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PREFACE

WORKNG TOGETHER FOR OUR GLOBAL RANGELANDS FUTURE

2-6 June 2025, Adelaide, Australia.

Welcome to the XIIth International Rangeland Congress (IRC), being held in Adelaide, South Australia!

This Congress is the first opportunity for the international rangeland community to meet face-to-face since 2016 when the Xth IRC was held in Saskatoon, Canada. In 2021 due to ongoing COVID disruptions, the XIth IRC was held in Nairobi, Kenya as an online event.

We are thrilled to be welcoming more than 700 delegates from 46 countries to the XIIth IRC, to share knowledge, experiences and ideas that will progress the management of the 56% of the world land mass that is rangeland.

We have more than 60 delegates are participating in pre-Congress Tours arriving in Adelaide from Perth, Alice Springs, Longreach and Sydney. Three pre-Congress Workshops are also being attended by more than 150 delegates and nearly 200 delegates will be celebrating the Australian Rangeland Society's 50th Birthday.

Interest in and support for the Congress Program has been high. These Draft Proceedings contain over 400 papers, that will be delivered at the Congress as either full oral or lightning presentations or displayed as posters. The papers are grouped into the seven sub-themes for the Congress:

1. Valuing rangelands and pastoral systems for their societal contribution
2. Co-design, partnerships, and incorporating traditional knowledge for more enduring rangeland outcomes
3. Technology, information systems, communication, and big data to aid monitoring and decision making
4. Integrating rangeland ecology into management
5. Managing risk – climate and other system shocks and trends
6. Livestock production systems in a world of changing drivers
7. Multi-functional land use in rangelands – moving beyond niche opportunities

These sub-themes reflect the increasing inter-connectedness between what is happening in the rangelands and what is happening in the rest of the world's economies, social systems and governance. They also recognise the need to integrate trends in technology, artificial intelligence and communication into the day-to-day lives of rangeland decision makers and residents. Finally, for too long the traditional indigenous knowledge of long-established rangeland cultures has been ignored, but no longer.

We encourage you to absorb the information contained in the papers presented in the Proceedings and to expand your knowledge through your interactions with the 700 people who have gathered from all parts of the world to attend the Congress. By working together, we can build better, fairer and more beneficial rangelands for all of humanity to appreciate and cherish.

At the conclusion of the Congress, the Proceedings will be augmented with contributions from the keynote speakers, the three pre-Congress Workshops, and the various Panel sessions being held during the Congress.

The Chairs of the Organising Committee for the XIIth International Rangeland Congress from 2021 to 2025 acknowledge the tremendous contributions of Dr Sarah McDonald (Chair, Publications Sub-Committee) and her team of people who reviewed papers; and Dr Alex Baumber (Chair, Program Sub-Committee) and his team who sorted Abstracts and arranged the Program for the Congress. We offer our grateful thanks.

Pieter Conradie, Chair, Australian Organising Committee, 2021-2022;

Dr Nicole Spiegel and Dr Andrew Ash, Co-Chairs, Australian Organising Committee, 2022-2024;

Dr Cath Waters and Dr Don Burnside Co-Chairs, Australian Organising Committee, 2024-2025

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PLENARY PAPERS

Stewards of the steppe: Khoid Mogoin Gol-Teel pastoral community institutions and their role in rangeland ecosystem conservation

Ulambayar, T[1]; Nergui, M[2]; Batkhuyag, B[3]; Davaasuren, O[4]

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Key words: community-based conservation; pastoral institutions; conservation outcomes; Mongolia

Abstract

Rangelands, covering over 50% of the Earth's terrestrial surface and providing essential ecosystem services, are experiencing severe degradation due to land conversion, overgrazing, invasive species and unsustainable land-management practices exacerbated by climate change. This degradation contributes to biodiversity loss, with habitat loss, resource decline, pollution and fragmentation posing serious threats to human society, including economic losses and food insecurity. This case study offers a positive perspective on Mongolian herders and their collaborative efforts to protect natural resources vital for their livelihoods and cultural identity. The Khoid Mogoin Gol-Teel Local Protected Area (KMGT LPA) in Central Mongolia, home to iconic species such as musk deer and snow leopards, supports over 400 herder households with 90,000 livestock (NSO 2023). Since Mongolia’s transition to a market economy in the mid-1990s, the KMGT LPA has faced rangeland degradation and declines in wild species due to overgrazing and illegal activities. This study evaluates outcomes of initiatives of the Union of Conservation Communities (UCC) over the past five years, which have led to a significant increase in community engagement and participation, enhancing biodiversity conservation and improving herders’ wellbeing. Specifically, participation in conservation training rose from 9% to 72%, and reports of illegal poaching and logging dropped to zero, highlighting the effectiveness of UCC efforts. These findings contribute important insights to the discourse on sustainable rangeland management and community-based conservation (CBC) strategies, supporting global efforts to achieve the Sustainable Development Goals and to promote ecosystem stewardship.

Introduction

Rangelands occupy nearly 70% of Mongolia's total area, directly supporting the livelihoods of almost 300,000 herders and over 64 million livestock (NSO 2023). Since Mongolia's transition to the market economy, with the collapse of state cooperatives and privatisation of livestock, the national herd has tripled in the past three decades (NSO 2023). This rapid growth has contributed to rangeland degradation, affecting 58% of the country’s pastures (Densambuu et al. 2018) amidst intensifying climate change. In the absence of effective rangeland management institutions and because of weak governance over natural resources, Mongolia has witnessed a rise in illicit activities, including poaching, illegal logging and mining, which have depleted wild species and their habitats. Currently, only 21% of the country is under state protection, leaving vast rangeland ecosystems unprotected and heavily exploited, adversely impacting on Mongolia’s natural capital. In this context, CBC could play a pivotal role in empowering herder stewardship to address the management gap and sustain ecosystem services vital to Mongolians. Since the introduction of CBC in the late 1990s, Mongolia has experienced varied outcomes, with positive results often failing to endure in the long term. This study aims to contribute to the broader research question of the key factors for successful CBC.

The KMGT LPA, located in Bulgan District of Arkhangai Province, covers 243,000 ha of mountain forest-steppe, with nearly 20% covered by forests (44,830 ha) that support rich biodiversity, including globally endangered species such as musk deer, saker falcon, steppe eagle, red deer and Mongolian marmot. The LPA's accessibility from the Arkhangai Province centre and the main road to the western region has led to challenges like illegal logging, poaching, forest fires and overgrazing. In response to these issues, the Bulgan District Government declared KMGT an LPA in 2017, and the Union of Conservation Communities (UCC) was established to unite the LPA herders with support from the Zoological Society of London (ZSL). This study aims to evaluate the initiatives undertaken by the UCC over the past five years, focusing on how these efforts have sought to address the dual challenges of rangeland degradation and decline in biodiversity. By assessing both the social and the ecological outcomes of UCC initiatives, the study will contribute to identifying the key factors that foster successful community-based governance and sustainable rangeland management, thereby enriching the discourse on effective strategies for conservation in Mongolia.

Methods

The study analysed data from two reports produced by researchers at the Independent Research Institute of Mongolia (IRIM) in 2019 and 2024, focused on assessing socio-economic surveys as well as separate biodiversity monitoring reports for three key species. The IRIM study employed a mixed-methods approach to assess social and ecological outcomes of KMGT LPA management. Research instruments included social surveys designed to capture herders' perceptions, alongside observations of natural resource conditions and changes, livelihoods (encompassing primary income and expenditures), housing, access to financial services, attitudes and participation in conservation initiatives. To evaluate herders' wellbeing, the study used the Multidimensional Poverty Index (MPI) (Alkire & Foster 2011), which integrates two critical components: the incidence of poverty, representing the proportion of individuals experiencing multiple deprivations, and the intensity of those deprivations. Ecological outcomes were measured through assessments of forest and rangeland conditions and the population status of key wildlife species. This involved the use of transects for musk deer monitoring, bird surveys and marmot counting, supplemented by herders' observations and reported sightings. For monitoring poaching and timber-logging activities, secondary data sources, including records of the Arkhangai Environment & Tourism Department (ETD), were also analysed.

Results

Social outcomes

The initiatives undertaken by the UCC have led to significant social outcomes within the KMGT LPA, enhancing community engagement, participation and governance structures among herders.

Community institutions established and governance process laid out. The baseline report indicated the existence of six registered Forest User Groups (FUGs), each comprising 6–7 member households; however, these groups were inactive because of a lack of leadership, organisation, collaboration, planning and financing (IRIM 2019). By 2024, the UCC had established 20 community-based organisations (CBOs) with membership ranging from 16 to 83 households (Yanjinpagma 2024). Each CBO is led by an elected leader and supported by two community rangers and a community-banking unit. The CBOs have defined territorial boundaries and signed management contracts with the District Authority, securing herders' tenure rights while clarifying their conservation responsibilities. Motivated by the successful management of the LPA, the District authority expanded the initial LPA area from 137,018 hectares to 242,887 ha in 2024, providing additional habitat for endangered species like the musk deer and increasing UCC membership to 592 herders. The UCC develops an annual management plan that incorporates individual CBO plans, which are discussed and reported at bi-annual UCC meetings. Each CBO also holds monthly community-banking meetings to facilitate loan disbursement and repayment among members and to discuss ongoing activities.

UCC member herders' access to information and participation increased. In 2018, only nine out of 28 FUG members reported participating in conservation initiatives, primarily focused on forest cleaning. By 2024, participation has significantly increased. The UCC, in partnership with organisations such as the Arkhangai ETD, the Ecological Police, the Zoological Society Luujin and the District Government Office, has provided herders with briefings and training on local biodiversity, rangeland management, forest management, biodiversity monitoring and SMART (Spatial Monitoring And Reporting Tool) patrolling. According to the endline report, 72% of survey respondents participated in various training sessions, attending an average of seven meetings over the past three years. In addition, 61% engaged in planning and conservation actions, on an average of four times during the same period, and 42% of respondents were involved in monitoring activities, averaging four instances over three years. These learning opportunities have led to a positive shift in attitudes among herders, transforming them from poachers and illegal loggers into protectors of the LPA.

UCC members engaged in collective conservation actions. Thanks to a positive change in attitudes, UCC herders are now proactively involved in various conservation activities, including waste clean-up, forest thinning, fencing to protect young trees from grazing, safeguarding springs and conducting SMART patrols. These collective efforts have contributed to improved ecological outcomes. In 2018, surveys indicated prevalent illegal logging, cedar nut collection and marmot poaching, often without detection by law enforcement. Records from the Arkhangai ETD in 2024 revealed zero instances of poaching or illegal logging, with herders reporting no knowledge of such activities in their areas.

LPA women: housekeepers of CBO affairs. Women play a vital role in conservation and community-banking activities, particularly regarding organisational and logistical tasks. They have equal rights to run for leadership positions within CBOs and community banks and to access learning and development opportunities offered to UCC members. In addition to their essential herding and household responsibilities, women ensure high attendance at CBO meetings, prepare meals and appropriate clothing for annual activities such as forest cleaning and tree planting, and manage household chores, which allows men to engage in conservation efforts. Women lead about 10% of CBOs and 60% of community-banking groups; 90% of community banks have female secretaries and 50% have female accountants. Although more physically demanding tasks, such as forest cleaning, SMART patrolling and waste management, are predominantly undertaken by men, women are indispensable in governance-related functions, including financial management, meeting documentation, CBO planning, monitoring and dairy marketing.

Ecological outcomes

The UCC initiatives have led to significant ecological outcomes within the KMGT LPA, demonstrating improvements in forest health, wildlife populations and rangeland management.

Forests. The KMGT LPA is predominantly covered by conifer forests, encompassing 78,631 ha or one third of the LPA. These forests provide critical habitats for endangered species and a diverse range of rare plants, herbs and berries. Compared to the 2018 baseline, forest conditions have significantly improved, with reduced logging and notable regeneration observed (Marshall-Stochmal et al. 2020). The UCC has implemented an annual forest-cleaning event, a signature initiative in Arkhangai, focusing on clearing 63 ha and rehabilitating 8 ha of forest. These efforts help eliminate debris, promote new growth, prevent wildfires and provide herders with additional income while supplying towns with affordable firewood. Additionally, constructing fences around young trees has effectively supported natural regeneration by preventing damage from livestock. These events serve as collective missions for UCC members, fostering team spirit and enhancing their contributions to community wellbeing while strengthening social capital. In 2023, the initiative engaged 70 members from nine forest CBOs and five partner organisations to clean a 10-h area, resulting in the harvesting of 960 cubic meters of firewood, benefiting 240 households with discounted prices, generating over US$14 thousand in income for participating herders.

Wildlife. The KMGT LPA is home to several globally threatened species, including the Mongolian marmot (*Marmota sibirica*), Siberian musk deer (*Moschus moschiferus*), snow leopard (*Panthera uncia*), Siberian ibex (*Capra sibirica*) and white-throated bush chat (*Saxicola insignis*). Notable bird species such as the Saker falcon (*Falco cherrug*) and Steppe eagle (*Aquila nipalensis*) also inhabit the area. The UCC's annual monitoring of musk deer, marmots and birds has indicated an increase in marmot populations, stable musk deer numbers and consistent bird survival, alongside herders reporting increased sightings of deer and marmots. Key factors contributing to these positive outcomes include the implementation of institutionalised conservation measures, such as regular SMART patrols by community rangers and annual joint patrols conducted with Arkhangai law-enforcement agencies and UCC rangers, which help prevent and detect poaching and illegal logging. The positive changes in herders' attitudes and increased public awareness within the UCC and neighbouring communities have further supported these conservation efforts.

Rangelands. The KMGT LPA's mountain forest-steppe ecosystem is home to 191 plant species, predominantly perennial herbaceous plants (87%), including 52 medicinal plant species and 22 that require protection. Notably, this includes one endangered species (*Gentiana macrophylla* Pall.), ten rare plant species, one endemic species (*Astragalus galactites* Pall.) and ten species classified as intermediate endemics.

However, the ecosystem faces significant challenges because of a doubling of livestock numbers over the past decade, such that carrying capacity is exceeded by 6–30 times in summer-autumn pastures and 2–5 times in winter-spring pastures across the LPA (Ariunsuren 2012). To address these issues, the UCC has organised various management training sessions and supported livelihood diversification activities aimed at reducing reliance on livestock products, such as tourism, forage planting and forest cleaning. While engaging private livestock holders has proven challenging, livestock numbers have decreased by 15.6%, with a notable decline in number of goats compared to 2018.

Discussion

This study illustrates the transformative impact of the UCC on the KMGT LPA. The findings indicate that improved organisation and community engagement empower herders to become environmental stewards, aligning with existing literature on the efficacy of local institutions in conservation efforts (Berkes 2007, Ostrom 1990). Significantly, the role of herder women emerges as essential in both conservation and pastoralism; their contributions, ranging from managing community activities to facilitating knowledge sharing, underscore the importance of empowering women in pastoralist societies for enhanced environmental stewardship and resource management. While UCC initiatives have led to improvements in forest health and wildlife populations, persistent rangeland degradation because of overpopulation of private livestock poses ongoing challenges. This highlights the necessity for continued efforts to address economic pressures contributing to overgrazing. Increased demand for underutilised livestock products (skin, hides, wool and hair) could incentivise herders to reduce their herd sizes. Currently, herders mainly sell cashmere, camel wool and meat, while byproducts are often discarded or low-priced. If demand for these additional products were boosted, herders could earn more from each animal, potentially reducing livestock numbers and alleviating overgrazing pressure. However, for this to succeed, stricter rangeland management regulations would be vital.

In conclusion, this study demonstrates the potential for CBC initiatives to bring about positive change while emphasising the need for adaptive strategies that consider socio-economic dynamics. Fostering resilience within pastoral communities is crucial for preserving the vital ecosystems they depend upon.

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Traversing transdisciplinary terrain: a journey from knowledge integration to decolonial awareness

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Key words: traditional knowledge; Indigenous methodologies; feminist research; participatory research; collaborative autoethnography

Abstract

Rangelands and the people who live and work in them confront growing complex and "wicked" challenges in the face of interacting environmental, demographic, socio-cultural, economic and political changes. To address these challenges, rangeland scientists increasingly turn to transdisciplinary research approaches—those that span multiple disciplines and engage diverse social actors in the research process—to co-produce actionable knowledge for living with complexity and managing wicked problems. We use a collaborative auto-ethnographic approach to tell stories of our 30-year journey of studying, collaborating and co-producing knowledge with pastoralists and ranchers across three continents. As we reflect on our learnings through the lenses of feminist, decolonial, and Indigenous research theories, methodologies, knowledges, and ethics, we ask how these approaches can be meaningfully applied to pastoral and ranching systems. We celebrate the inherent strengths of rangeland research as an applied and place-based science. Yet, both the literature and our experiences reveal limitations in current applications of transdisciplinary knowledge co-production, largely attributable to inequitable power relations and inadequate ethical frameworks. Such limitations appear rooted in the colonial and productivist paradigms and practices that continue to dominate mainstream academic and research institutions. To achieve more effective and enduring rangeland outcomes, mainstream institutions could transform in ways that enable rather than constrain boundary-spanning research partnerships that center genuine (not transactional) reciprocal relationships with pastoralist communities and Tribal Nations. We envision a future where such partnerships take root in ethical frameworks that respect pastoralists' rights and knowledge sovereignty, consider multi-generational implications of research practices and outcomes, and call for care-full research guided by a critical decolonial approach that considers Indigenous and community concepts of relevance, time, reciprocity, respect, appropriate communication and power relations.

Introduction

Over the past 30 years, rangeland science and management have increasingly recognized the wisdom of traditional pastoralist practices embedded in Indigenous and local knowledge systems (Sharifian *et al.* 2023). Always an inherently interdisciplinary field, rangeland science has also progressively turned to transdisciplinary research approaches that integrate social, ecological and physical sciences and bring together knowledge holders from varied sectors of society to co-produce knowledge for managing the wicked problems that rangeland and pastoral systems increasingly face (Tengö *et al.* 2014; Knapp *et al.* 2019; Reid *et al.* 2021). These diverse and intertwined streams of learning grow out of diverse theories and methodologies, including feminist (Haraway 1988; Harding 1991), Black feminist (Hill Collins 1986; hooks 2000; Hill Collins and Bilge

2016) and Indigenous and decolonial feminist (Lugones 2010; Kovach 2021) ones, and from our lived experiences as researchers and community members. In this keynote paper, we collectively reflect on the trajectory of transdisciplinary research approaches in rangeland science as represented in the lived experiences and publications of one rangeland social-ecological scientist (MFG). We use this series of collaborative autoethnographic vignettes to highlight successful strategies for combining knowledges from different disciplines, communities and sectors of society in ways that benefit rangeland peoples and landscapes, and to learn from past missteps. Feminist theories help us to consider the ways colonial scientific institutions condition transdisciplinary research approaches and Indigenous methodologies, and offer inspiration for institutional transformation toward a more equitable and relational transdisciplinarity. As Kovach (2021, p. 12) notes, "Indigenous methodologies are well positioned to unpack and unsettle the [Western] research-policy-practice cycle influencing Indigenous life."

Methods

We use collaborative autoethnography (Ellis *et al.* 2010; Lapadat 2017) to describe MFG's lived experiences of traditional knowledge, participatory, and transdisciplinary research and to analyse how they relate to wider cultural and social contexts of these experiences, including the settler colonial culture of US academia and rangeland science specifically, and the Tribal Nations, Indigenous and pastoralist cultures where her research often takes place. The three co-authors first co-developed a process for making meaning from MFG's research experiences, and identified key issues to focus on within and across project narratives: ah-ha moments, Indigenous and feminist insights, structural components, cultural and language barriers, lessons for transdisciplinarity, and visions for the future. Drawing from research memos, published accounts of the projects, and memory, MFG drafted vignettes of six projects spanning her 35-year research career and wrote short reflections on each. RB and CS asked further questions, guided MFG to consider the larger structural forces at work, and wrote responses to MFG's reflections, further contextualizing her experiences and framing them from Indigenous and feminist perspectives. MFG revised each vignette to integrate the most salient learnings, incorporating RB and CS's insights.

In keeping with qualitative and feminist methodologies, we briefly note our positionalities. MFG is a multi-ethnic (predominantly Spanish and Anglo-American), interdisciplinary rangeland scientist from a socio-economically and educationally privileged background, recently retired from her position as Full Professor. RB is a Native and Irish American scholar and a first generation Full Professor. She has worked with Native American organizations and Tribal Nations throughout the U.S. on child maltreatment and her recent work considers the impact and resistance of Native peoples living within a settler colonial state. CS is an AfroLatinx (Puerto Rican and Cape Verdean) first generation Associate Professor whose interdisciplinary work focuses on qualitative inquiry (critical ethnography, testimonio as method and methodology) and Decolonial and Intersectional Feminist theory.

Collaborative Autoethnographic Vignettes

Traditional Ecological Knowledge of Mongolian Pastoralists (TEK): My initial work in Mongolia involves ecological fieldwork and traditional ethnographic research, living alongside herders for months at a time. I want to understand how the major changes in Mongolia's political system and economy would affect herders' lives, livelihoods and land use practices, and how these in turn will impact the rangeland conditions. I am also very interested in the role herders' ecological knowledge plays in their decision-making. I have formal training in both ecology and anthropology. Through months of living with, interviewing and observing herders I come to understand that herders' ecological knowledge is reflected in their everyday practices and norms of pasture use. I find that my observations on pasture management do not fit with the neat conceptual categories in the existing theory about commons governance. Eventually, I realize I need to pay attention to what is, not what theory says should be, and use my observations to revise theory. As I reflect back, I see that the TEK aspect of my work was extractive, shaped by my training in siloed academic disciplines. I lacked a model of participatory research and training in research ethics. I did not co-design the research with herders and it had not clear and immediate benefits for them. I authored articles from my work alone or with my dissertation advisor. Yet I did learn that traditional knowledge is more than biophysical facts and observations, and that it encompasses ways of doing and thinking, skills and technologies, cultural norms and values, and social relationships like reciprocity. The significance of reciprocity in Mongolian culture became a through-line of my decades of work there, both in terms of its importance to understanding social-ecological dynamics, living relationality and in how it influenced my relationships and work with Mongolian individuals and institutions. Thirty years on, all my subsequent work has been co-authored with Mongolian researchers and much has been co-designed by with herders and products co-developed with and for communities. I have mentored many Mongolian students including three who earned PhDs at my university.

Participatory Rangeland Planning and Curriculum Development with the Tohono O'odham Nation (TON): The Tohono O'odham Nation spans the US border with Mexico and encompasses over 2 million acres of desert grasslands and Sonoran desert ecosystems. O'odham people incorporated livestock into their culture and economy during the Mission period, and cattle continue to play important roles in O'odham society today. In the early 2000s, the Tohono O'odham Nation is taking over management of its natural resources from the US Bureau of Indian Affairs (BIA) under the provisions of the Indian Self-Determination Act (PL 93-638). Unlike in Mongolia, in this case, the Tribe invites me to advise on grazing and rangeland management, and specifically the development of a Tribal grazing code. Our relationship starts with my participation in monthly meetings with the newly formed TO Natural Resources Department, and mostly listening. Two projects eventually grow from this, a pilot participatory rangeland planning project and later, a participatory curriculum development project. After six months, I suggest the idea of a pilot participatory community-based rangeland management project. Past efforts to impose top-down grazing regulations have met with resistance. Maybe working at the community-level with a single grazing district and helping the community come up with its own set of rules could lead to a more bottom-up process that communities would support. After Tribal Council approval, and with guidance and support from a key community member, the Sif Oidak district agrees to take part in this pilot. Masters student John Hays, formerly a working cowboy, serves as a critical link to the community. John participates in 19 round-ups in Sif Oidak over a year, building trust and demonstrating reciprocity by helping with a dangerous and labor-intensive task. He also helps each of Sif Oidak's 9 villages identify and map areas of resource concern and opportunities for restoration. We then help them apply for federal funds to implement restoration. The resulting resource management plan looks different from what we envisioned. It focuses on education and cooperation among villages instead of rules and by-laws (Hays and Fernandez-Gimenez 2005). We learn that support for cooperation and reciprocity is more important than attempting to solve issues through formal rules and sanctions that further fray inter-community relationships (Fernandez-Gimenez *et al.* 2008).

The community's interest in education leads us to apply for another grant in partnership with the TO Resource Conservation District, to develop a rangeland curriculum specific to the Tohono O'odham lands and culture. Another Masters student, Jennifer Arnold, leads the implementation and evaluation. A curriculum advisory committee composed mostly of O'odham cultural experts, ranchers and natural resource professionals guides the project. Thirty-nine individuals participate in the committee over a two-year period, and a core group of seven members are deeply engaged in all phases of the research, including developing the research goals and methods, interpreting the findings, and authoring publications. Instead of a TEK documentation approach, the curriculum committee incorporates O'odham traditional knowledge, values and priorities directly, by shaping the curriculum and participating in the delivery of the workshops. O'odham participants choose what they want to learn and from whom, including a mix of both local O'odham elders and experts and outside non-O'odham presenters, with nearly two thirds of the presentations given in O'odham. The workshop series begins with elders' stories of water and ends with an O'odham presentation about drought, the desert and the monsoon rains (Arnold *et al.* 2007). The advisory committee identifies a goal to "incorporate values of cooperation and community" and their importance for rangeland management into the curriculum. The importance of cooperation emerges in various ways, leading us as academic researchers to draw on the concept of social capital as an analytical lens. One O'odham elder objects to the use of non-O'odham theories to explain O'odham ways, and this leads to an extensive discussion about the project's goals and the role of research on the TON. Ultimately, we use a social capital framework and a core group of O'odham participants help refine the analysis and interpretations, which are supported by political leaders, elders and other community members (Arnold *et al.* 2007). As I reflect on this dynamic today, I wonder if we could have co-created an O'odham theoretical framework based on the importance of relationality instead of imposing a social capital framework (Kovach 2021).

Mongolian Rangelands and Resilience (MOR2) (Fernandez-Gimenez *et al.* 2019a): Back in Mongolia, it's now 2008, a decade and a half after my original work there in the early 1990s. Rangelands and herders are suffering from increasingly frequent droughts and severe winter storms, exacerbated by declining pasture conditions. To address declining livelihoods and rangeland health, herders, with support from international development organizations, have begun to organize into local community-based rangeland management (CBRM) groups to manage their rangelands, yet there is little communication or coordination among these efforts. Project leaders see the value in learning from diverse project experiences, and with their support we begin to design a research effort. Rangeland social-ecological changes in Mongolia are a wicked problem—one with high complexity, no simple solutions and multiple drivers within and across scales. We need a multi-disciplinary team of researchers with expertise in rangeland ecology, climate change, hydrology, human ecology, geography, policy and sociology. To design a relevant study that asks the right questions to produce information that is credible and usable, representatives from herder communities, conservation and development organizations and government must participate in shaping the questions and design. We bring together researchers from the US and Mongolia with diverse expertise and organize a two week research planning process in Mongolia that begins with a week-long field trip to build trust among members of the newly formed international team, and ground our science in on-the-ground realities. The second week we host a 5-day interactive workshop in the capital of Ulaanbaatar, where scientists, conservation and development practitioners, herders and government officials collectively identify and prioritize key issues affecting Mongolia's rangelands and herders, draw connections among these complex factors, and finally, agree on a primary issue and research question and outline an overall research design.

It takes several years to secure funding to implement our ambitious research plan across 36 districts (*soum*) in Mongolia's 4 major ecological zones. The quasi-experimental design compares the process and outcomes of community-based rangeland management (CBRM) in adjacent districts with and without formally organized CBRM groups. Almost half of our core team are Mongolians, including two PhD students and two post-docs. Each subteam is co-led by Mongolian and US scientists. We train over 50 young Mongolian researchers and students who participate in field teams alongside senior Mongolian and US researchers. We collaborate with other organizations to make the trainings in research design, social and ecological data collection, quantitative and qualitative data analysis, and scientific writing available to students and professionals beyond those on the MOR2 team. We hold annual all-members team meetings in Mongolia to discuss our progress and findings, and plan for the next phases. Our core team includes a social scientist who interviews or surveys each member annually and facilitates an annual reflective retreat that helps us identify and redress power imbalances and communication issues on the team, strengthening trust and mutual accountability and reciprocity. Later, we hold monthly informal day-long analysis and writing retreats that help break down disciplinary barriers and reduce power imbalances between graduate students and faculty.

Consistent with principles of reciprocity and data sovereignty, the expanded project team agrees that all team members will have access to the data collected by the project, and that it will be permanently archived and available for use by Mongolians and other scientists who request it. We develop formal guidelines for data use and authorship. To give Mongolian researchers the experience of peer review and opportunity to present their findings to an international audience, in the final year of the project we organize a major international conference in Ulaanbaatar. All the project participants have a chance to attend, present and publish a peer-reviewed paper in the fully bi-lingual conference proceedings

Following through with reciprocity to 36 different herder communities spread across Mongolia proves challenging. We develop community-specific brief written summaries of interim findings and deliver them in brochure form back to some but not all of the communities. One of the Mongolian post-docs works with one community to develop a book by and for community members. Finally, we organize four regional workshops for herders and local government representatives from each study community where we share findings, facilitate interactive discussions to "ground-truth" our scientific results with local knowledge, and engage participants in scenario-planning to consider what our findings might mean for their communities' futures.

Ten years after the project's end, the impacts of MOR2 persist. Many of the young Mongolian researchers who took part in our project and trainings went on the earn graduate degrees at top universities and today contribute their skills within Mongolia to teaching, research, entrepreneurship, and direct action with herder communities. MOR2 was a transformative experience for many of us. The team exemplified respect, responsibility, reflexivity and reciprocity among members. At the same time, the very aspects of it that made it powerful scientifically—the large sample size, quasi-experimental design and broad spatial extent—also made it impossible to develop meaningful long-term and truly reciprocal relationships with all of the participating communities. The funding source and institutional expectations also influenced the power dynamics such that Western science dominated our decision-making and outputs.

Collaborative Adaptive Rangeland Management (CARM) (adapted from Wilmer)***:*** On eastern Colorado's Great Plains, rangelands and ranchers face multiple environmental, social, economic and policy challenges from climate change to land-use change to demographic change and shifting public values related to rangeland ecosystems and animal agriculture. This broad expanse of shortgrass steppe from the foothills of the Rocky Mountains to the mixed grass prairies of Kansas and Nebraska are the traditional homelands of the Ute, Cheyenne and Arapaho Tribes, who were violently expelled during the process of Euro-American colonization and settlement in the 19th century. In the early 20th century, settlers attempted to plow and farm the area, with disastrous consequences, leading to the Dust Bowl, and subsequent creation of the National Grassland system and the US Department of Agriculture's Central Plains Experimental Range (CPER). Over 80 years, CPER generated a strong body of rangeland science, yet the conventional research approach had limitations. It excluded complex social dynamics and public participation and focused mainly on production problems, ignoring wildlife, conservation and social problems.

By the 2010s, challenges to ranch sustainability and conservation have intensified and CPER researchers recognize they need to work in a different way. They ask me to join their team as a social scientist. The team is dominated by ecologists, but also includes me and Hailey Wilmer, as social scientists. Later, a hydrologist and an economist join us. The research team invites a diverse group of stakeholders including representatives from federal and state natural resource agencies, conservation organizations and ranchers from the local grazing association, to participate as co-researchers. The project team designs and implements a comprehensive collaborative adaptive rangeland management (CARM) project with the stakeholder-defined goals of enhancing ranch profitability and drought resilience, bird and plant biodiversity, and social learning. The team divides the experiment station into two, ecologically paired ranches, and manages one with the "business as usual" season-long grazing approach common in the area, and on the other gives decision-making control to the stakeholder group, keeping the stocking rates the same on both halves. Scientists monitor and evaluate outcomes on both ranches, incorporating stakeholder-devised indicators as well as conventional rangeland and wildlife monitoring metrics. The stakeholder group and research team cycle through goal setting, stocking, grazing, prescribed fire and drought decisions, tracking learning as we go. The group commits to this ranch-scale experiment for 10 years. Plenty of time to learn and adapt.

The decade that followed is incredible, and incredibly challenging. Working and learning together in this context is entirely new for both researchers and stakeholders. From the first goal-setting workshop, we realize we face an uphill journey to understand each other's disciplines, goals, and communication styles. Researchers and stakeholders from different backgrounds find we come from entirely different social worlds, with different ways of knowing and learning. Trust – in people and in data – is not a given. Additionally, while everyone agrees on the overarching goals, the stakeholder-managed steers gain less weight than those managed conventionally, efforts to improve bird populations and plant diversity are inconclusive, and ranchers initially reject data that suggested prescribed fires could benefit rangelands, and vote against the use of fire. To top it all off, the roles of researchers as scientists, facilitators and decision-makers become confused. As researchers, aren't we stakeholders, too? How are we influencing the stakeholder group's decisions? Somehow, through a mix of courage, stubbornness and social cohesion that forms out of time together on the land and flexible, supportive leadership, the CARM process begins to work. Trust begins to develop as all the participants—stakeholders and researchers—learn about each other's social worlds and ways of knowing through informal interactions like a tour of one stakeholder's ranch. They become vulnerable, they listen, and try to understand one another's point of view.

Throughout the project we try to create more opportunities for these informal interactions, and empathy, curiosity and compassion start to build the key ingredient to CARM, trust. Trust supports a culture of flexibility and creativity, experimentation and learning, which in turn leads to scientific productivity and adaptive capacity. Because social science is integrated into the core of the project, we are able to document how the project facilitates social learning, and to reflect honestly on the challenges and opportunities of the approach. Some of the key ingredients to learning and enduring collaboration are: flexible, inclusive problem definition; respect for context and history; effective team leadership and power sharing; long-term investment in relationships and a long time horizon for the project; capacity for collaborative creativity; sufficient resource allocation; and a study design that invited diverse research methods and questions (Wilmer *et al.* 2018; Wilmer *et al.* 2022). CARM has inspired similar approaches in Nebraska and in Idaho, where Hailey Wilmer leads the Rangeland Collaboratory, focused on building relationships among diverse stakeholders and researchers to help ranchers, land managers and conservation organizations manage iconic landscapes for multiple species and values. Despite these successes, I now recognize that we failed to invite key rightsholders, Tribal representatives, to participate in CARM. I wonder how different might the process have been with their participation, and why we omitted them.

Co-Creating Knowledge for Action with Women Pastoralists in Spain (CCK): Extensive livestock management has shaped Spain's landscapes and cultures for 7000 years, but the 20th century saw major structural changes in agriculture that have led to industrialization of animal agriculture, rural depopulation, and transformation of these socially valued landscapes, the ecosystem services they provide and human communities that inhabit them. The number of women-led livestock operations is increasing, yet women pastoralists remain largely invisible in the public eye and absent from decision-making spaces. Inspired by work with women ranchers in the southwestern US (Wilmer and Fernández-Giménez 2016), and my recognition that my own research in Spain and Mongolia have largely overlooked the knowledge and experiences particular to women, I decide to mend this gap. On reflection my blinders here were due in part to disciplinary assumptions in rangeland science and in part to the culture of pastoralism in Spain, where I was told by many experts not to bother interviewing women because they are not directly involved in land and livestock management. This turns out not to be true.

Two colleagues, Elisa Oteros-Rozas and Federica Ravera, and I partner with networks of women pastoralists in Spain (Ganaderas en Red and Ramaderas.cat) to research the lived experiences of Spanish women pastoralists. We take a feminist research approach. For us, this means a rejection of simple binaries and universalizing claims about women's lives. Instead, we are interested in the diversity of women's experiences and how their multiple social locations interact to shape their power and access to pastoral resources and decision-making. We draw on our outsider within perspectives—as women in the male dominated field of rangeland science, and working with women herders in a culture where herding is understood to be a man's job. As feminist researchers, we value multiple ways of knowing and our research has emancipatory as well as scientific goals. We center care in interactions with research participants and co-researchers, and commit to reflexive practice where we regularly examine our process and power relations with one another and our research participants (Ravera et al. 2021).

In contrast to the MOR2 and CARM projects, we have no big funding sources to support the work, but also less pressure to meet funders' expectations regarding research publications. Building on Elisa and Federica's existing relationships with GER and ramaderas.cat, we gain support for the project and women in both networks agree to participate. We visit and interview women in southern, northern and eastern Spain on their farms, frequently in remote areas. We analyse the transcripts together, returning their transcript to each participant. We organize participatory workshops in each region where we share meals made from the women's products, interpret and refine interview themes, and facilitate discussions of women's priorities for action. During covid, we organize several follow-up virtual workshops with broader audiences. We send copies of our final report in Spanish to all participants and make it freely available on the web. One participant writes a companion essay to a book chapter we write about women pastoralists and climate change. Members of the GER network present at the Society for Range Management, are active in the IYRP, and help women in other countries to establish their own networks.

CCC Workshop: My continuing dis-ease about my positionality as a non-Indigenous researcher and the ways in which, despite a commitment to participatory research, my projects continued to privilege conventional Western scientific outputs over Indigenous science and lasting community benefits, motivate me to work with Center for Collaborative Conservation (CCC) director Robin Reid to organize a workshop on decolonizing collaborative conservation. We also recognize the wealth of knowledge, experience and adaptive capacity held by Indigenous communities and land stewards despite centuries of genocide, displacement and dispossession. We think we were ready to engage in decolonization of collaborative conservation. As we assemble a diverse organizing committee, bring in Indigenous facilitators to work with us, and invite Indigenous people from around the world to participate, we are forced to re-examine our readiness and to recognize that we didn't understand what decolonization means from an Indigenous perspective. Through the workshop, we begin to learn from Indigenous people what a decolonial perspective on collaborative conservation might look like.

The tone and content of the workshop changes immediately once an Indigenous facilitator joins the team, and Indigenous participants report feeling seen and validated based on the process and content of the workshop. The workshop spurs enthusiasm and willingness of the CCC and others at CSU to support and validate Indigenous researchers at CSU and elsewhere. I experience several ah-ha moments during the workshop. First, during the workshop, I am struck by the ongoing harms that Indigenous students experience within colonial education systems that devalue traditional knowledge and erase Indigenous communities and realize that my own work perpetuates the system that causes these harms. Second, I gain appreciation for the importance of history and the value of theory to understanding how and why Indigenous communities have been dispossessed and displaced, and their relationship to their land. Learning this history and theory is essential to being an effective non-Indigenous collaborator and ally. I learn that decolonization is not a metaphor (Tuck and Yang 2012); to decolonize conservation we need to work at practical and policy levels to return land, water and management authority to the original stewards and prioritize Indigenous life ways. Third, I learn the transformative power of holding space for people with marginalized identities to share experiences and support each other across genders and generations. Participants share solutions grounded in healing within Indigenous communities, restoring relationships to land, and developing equitable collaborative partnerships with external allies, governments and research institutions. The workshop leaves me more committed to and hopeful for the possibility of change, and with a deeper understanding of how to collaborate effectively with Indigenous communities.

Discussion, Conclusion and Implications

Feminist philosophers advance the idea that all knowledge is embedded in particular social, cultural, historical and political contexts, and reflects the lived experiences of those who produce it (Haraway 1988; Harding 1991). Decolonial feminist theory embraces the multiplicity of knowledges and experiences and values them equally (Tuhiwai Smith 1999; Kovach 2021). Indigenous methodologies are research by, for and of Indigenous researchers (Tuhiwai Smith 1999), including Indigenous epistemologies, theories, methodologies and methods (Tuhiwai Smith 1999; Kovach 2021).

As transdisciplinary approaches are mainstreamed within rangeland science and management, feminist, decolonial and Indigenous thought can inform and improve our approaches. In the vignettes above, we describe the lived experiences of MFG as a multi-ethnic woman and interdisciplinary researcher working in ecological and social sciences, whose positionality led her to become a boundary-spanner in multiple ways. Reflecting on her experiences through decolonial and feminist lenses underscores how institutional culture and structures in academia, steeped in colonial scientific ways of thinking and doing, promoted extractive research practices and created barriers to investing necessary time, resources and heart into building equitable and reciprocal relationships with pastoralist and ranching communities and Tribal Nations. Some of the ways this occurred are obvious in hindsight, such as insufficient graduate training in research ethics, an academic culture that rewards above all else research productivity measured in number of articles, impact factors, and the size and prestige of research grants, and the lack of models and resources for developing genuinely equitable and reciprocal participatory research relationships. Academic culture influences research practices in more subtle ways related to MFG's specific positionality as an interdisciplinary and multiethnic woman researcher. For example, as a junior scholar, more senior faculty discouraged her interdisciplinary aspirations, dismissed traditional Indigenous knowledge as a valid research interest, and questioned her qualifications and abilities, leading her to question herself and to double-down in her efforts to meet and exceed the academy's expectations for productivity. The primacy of Western science remains deeply engrained and internalized, as illustrated in the power relations that played out in the Mongolian TEK, TON and MOR2 vignettes. Twenty years on from the TON project, MFG now has examples of Indigenous theory-building that might have led us to a different approach (Kovach 2021). Thinking about the final vignettes presented here—Co-creating Knowledge for Action with Women Pastoralists in Spain and our workshop on Collaborative Conservation through a Decolonial Lens—we consider how they *felt* different—in the heart and in the body. This different affect, we reflect, results from a different approach—one that prioritizes *care* and *doing things in the right way*--and a different underlying ethic—an *ethic of generosity* that flows from a *philosophy of abundance* and incorporates Indigenous research ethics. This approach stands in contrast to the dynamic of competition in academia, based on a worldview grounded in scarcity.

The challenges outlined above are not unique to these specific vignettes, and are echoed in much of the recent literature on transdisciplinarity (Knapp *et al.* 2019; Reid *et al.* 2021) and knowledge co-production (David-Chavez and Gavin 2018; Chambers *et al.* 2021; Chambers *et al.* 2022). Yet despite the structural and cultural challenges and resulting missteps, the vignettes also highlight examples of positive outcomes, successful transdisciplinary research and constructive mutually beneficial research relationships with rangeland stewards and communities. The practices that supported these outcomes are highly aligned with principles of feminist (Haraway 1988; Harding 1991) and Indigenous research (Kirkness and Barnhardt 1991; Kovach 2021; Montgomery and Blanchard 2021; Tsosie *et al.* 2022; David-Chavez *et al.* 2024). Indigenous research, when it employs Indigenous methodologies, including Indigenous epistemologies and theories, is specific to particular Tribes and cultures, and at times may not be appropriate for all researchers. However, the practices associated with Indigenous and feminist methodologies can apply in a wide range of transdisciplinary and participatory research contexts.

1) "The process is the product" and the importance of *doing things in a good way*. Pragmatically, MFG navigated the productivity demands of academic culture by focusing research on the process of transdisciplinary collaboration. In most of the vignettes above a significant part of the learning came from building in a component of studying the collaborative process, which enabled us to publish widely about the processes of transdisciplinary and participatory research. In CARM, MOR2 and CCK, the learning resulted from a deliberate practive of *reflexivity*, the process of collective critical reflection on power relations in the research process (Ravera *et al.* 2023). An important aspect of Indigenous research and working with Indigenous peoples, RB emphasized the importance of doing things in a good way. In Indigenous research, this includes preparation of the research and the researcher, recognizing and following ethical and cultural protocols, connecting with community, reciprocity (sharing knowledge and food, giving back to the community) and respectfulness (Kovach 2021).

2) *Relationships* form the core of successful transdiscipilanary research. Ideally, relationships develop before research begins (Kovach 2021; David-Chavez *et al.* 2024) and outsider researchers come at the invitation of the community (TON). It takes time to establish trust, which often grows through informal interactions (e.g. shared meals, field trips as in CARM, CCK) and shared experiences like the researcher taking part in and contributing to community life and work (MON TEK, TON). Trust develops through mutual vulnerability—where individuals reveal feelings or ideas that put them at risk. Trust also depends upon respect,

honesty, and integrity. Researchers and community members must follow through with what they say they will do and not promise what they cannot deliver. From an Indigenous perspective, relationships include not only those with people involved in any aspect of the research process, but also understanding and respecting the wider web of relationships and kinship with ancestors, and other living and non-living more-than-human beings (Kovach 2021; Tsosie *et al.* 2022). Relationality thus extends beyond the human relationships to our interdependence with and responsibilities to all beings.

3) *Respect* is a foundation for relationship-building and includes respect for Tribal governance, cultures (Kirkness and Barnhardt 1991), individuals (Tsosie *et al.* 2022) and their social worlds (Fernandez-Gimenez *et al.* 2019b), and in an interdisciplinary context, for different epistemologies and methodologies associated with different disciplines (MOR2, CARM) (Fernandez-Gimenez *et al.* 2019a; Wilmer *et al.* 2022). For outsider researchers working in cultures different from their own, learning the language and cultural protocols is a sign of respect. Fluency in the language improves communication and reduces power differentials in research. Respect also encompasses respect for Indigenous communities' sovereignty, including their right to govern data generated from research (David-Chavez et al. 2024), and respecting methodological preferences and options that include participatory and Indigenous research methodologies. Along similar lines, Wilmer et al. (2021) suggest that respect for community and individual self-determination is a critical component of expanded ethical considerations for transdisciplinary research.

4) *Relevance* in an Indigenous research context includes the salience and appropriateness or research to the specific Indigenous community's experiences, perspectives, ways of knowing and doing, and priorities (Kirkness and Barnhardt 1991; Tsosie *et al.* 2022). In a broader transdisciplinary context, relevance relates the degree to which the research problem and approach are defined by relevant rightsholders and stakeholders (for example, as in TON, MOR2 and CARM), with outcomes that are likely to have a direct impact on managing "wicked" problems and improving community conditions.

5) *Representation* means that particular perspectives are present and included in the research process. For Indigenous communities, representation ensures that they share what is important and relevant to their community (Tsosie *et al.* 2022). Representation may be accomplished through advisory committees (TON) or direct participation by different rightsholders and stakeholders in research design and implementation (TON, CARM). MOR2 ensured that the research team included Mongolian researchers alongside US-based scientists in every discipline, and that the research problem, questions and methodology were co-developed and agreed upon by herders, conservation practitioners, government officials and researchers working together.

6) Responsibility includes honouring ethical and moral responsibilities both in in-person interactions and in with regards to data (David-Chavez *et al.* 2024), and accountability for people and knowledge put in the researcher's trust (Tsosie *et al.* 2022).

7) Reciprocity signifies giving back to a community or individual involved in the research process. It is a continual process of exchange essential to relationship-building and ensures that community members access benefits from the research (David-Chavez et al. 2024). As such, reciprocity can take many forms, but in transdisciplinary research, at minimum, it includes sharing data (e.g. transcripts), knowledge and learning with the community orally (e.g. workshops) and/or in written or other forms (e.g. film, photography) (TON, MOR2, CCK, CARM), or opportunities to co-author research articles or other products (TON, CARM). Other forms of reciprocity in a research context include organizing meals or social events for the community or research participants (CARM, CCK), helping the community with needed work (e.g. TON round-ups), or providing assistance during emergencies (e.g. during the 2023-2024 *dzud* MFG sent cash to Mongolian women in her study whose families were affected by the severe winter weather). We always offer a useful gift to research participants beyond the typical IRB incentive. True reciprocity is not transactional, but rather a demonstration of generosity in the context of an authentic relationship. From a practical standpoint, it is critical to include necessary resources in grant proposals to cover local hiring of community member experts and appropriate costs related to reciprocity (Kovach 2021).

8) *disRuption* represents the emancipatory aim of feminist research (Ulmer 2024). Transdisciplinary research aims to link knowledge with action to solve wicked problems, and participatory action research engages communities in analysing and addressing community-identified challenges. Feminist research contributes to these aims by disrupting patriarchal research institutions and processes, and by supporting research participants and community partners in fighting oppression and advancing their goals for social, economic or environmental change (CCK). CCK worked with existing networks of women pastoralists to support them in reflecting on their experiences of oppression and liberation, and in articulating goals for policy change. By doing research in a care-full way this project also disrupted established academic norms and

provided an example of an alternative research ethic. disRuption also occurs within an Indigenous intersectional lens when "An intersectional analysis becomes important to dismantle settler colonial logics to reveal moments of settler complicity" in classroom settings and also within Western research processes ((Bubar *et al.* 2022) p. 53), as occurred in the CCC workshop.
What kinds of institutions are needed to support research with Indigenous, pastoralist and other rangeland communities and Tribal Nations that is done in a good way, a way that respects these combined principles of Indigenous and feminist research? First, we clarify that, as Kovach (2021) notes, just as not all research with Indigenous Tribes and communities needs to use Indigenous methodologies, with pastoralist communities, a variety of different approaches may be appropriate, depending on the problem and questions. However, transdisciplinary research is often required to address the wicked problems facing pastoralist communities and rangeland systems. Some mainstream academic and research institutions are making incremental changes towards research that addresses some if not all of the 8 Rs above, for example through more and better training for junior scholars in inter- and trans-disciplinary and participatory research methodologies, including research ethics. Yet, the dominant competitive productivist academic culture persists; if anything the competition and pressures on faculty and graduate students grow steadily more intense. How can we work in a good way under these conditions? Kovach (2021) advocates that the academy develop appropriate criteria for evaluating Indigenous research, which would take into account not only peer-reviewed publications and grants, but other kinds of community-valued outputs and outcomes. While we (MFG) advise(s) young scholars committed to "engaged scholarship" to "make the process the product", publishing on participatory and transdisciplinary processes as well as the other types of learning from research captured in more traditional disciplinary publications, this strategy does not address other barriers to implementing research in a good way. We dream of academic and research institutions that invest in building relationships first—following the principles outlined above from Indigenous and feminist methodologies--where research priorities emerge organically from these relationships and the historical and environmental contexts and problems particular to these communities and places. Academics and researchers operate in a competitive environment, where we compete for funding, space, resources and recognition. These pressures to compete infect relationships between researchers and communities, often causing researchers to pressure communities in turn—this is especially true for non-Indigenous researchers who too often engage with Tribes and Indigenous communities in instrumental and transactional ways, rather than building relationships on a foundation of genuine respect, responsibility and reciprocity. This is the opposite of doing things in a good way, and it is driven in part by the productivist culture of mainstream academia, a culture rooted in an ethic of competition for scarce resources as opposed to an ethic of generosity and reciprocity arising from worldview of abundance. Our intent is not to homogenize, idealize or oversimplify diverse Indigenous ontologies or epistemologies. Nor is it to overlook the realities of many historically marginalized and disenfranchised communities. Rather, we ask for a radical rethinking of the ethical foundations for our work.

A year ago, at another rangeland conference, at the end of the Q&A in a concurrent session, a graduate student posed the question to the room—"but how do we engage with these communities?" referencing rural, often conservative, rangeland users in the Western US. I (MFG) responded, "Love is the answer." I did not mean this facetiously. I meant it genuinely, in the sense of Black feminist bell hooks (2000), who writes that love is an active choice and practice to nurture one's own or another's growth. Although saying this to such an audience made me vulnerabile, I did it to call in rather than call out our predominantly white and male field of rangeland ecology and management. Through the gaze of love we see each other's humanity, and that is a starting point. We may look at the world today and consider love is in short supply. War, genocide, dehumanizing treatment of humans by other humans, destruction of Earth. But this is a fallacy, a dangerous mistruth. Love is not a finite resource. Like the beauty of the grasslands, it is infinite. We direct care and generosity towards the objects of our love—including the self. I have had some degree of conventional academic success in my career, in no small part because the discrimination I faced motivated me to overcompensate in the research productivity department. This so-called success also threatened my physical and mental health and my family's well-being. Yet when I think of the most meaningful projects I have taken part in, and what gave them meaning, it has been the relationships with the research team and with our study communities, even more than the scientific insights, publications and broader impacts. Those relationships weren't just about making me, or other participants, feel good. In fact, a lot of the relationship building was difficult, even painful at times. It was the process of working through those difficulties and learning from them that made these projects work. The relationships, among individuals, communities and institutions were often the most consequential outcomes. At the most essential level, they were about love. Our shared love for rangeland landscapes, for the people that inhabit, steward and study them, and ultimately, for one another. That love is expressed through care, and through recognition, respect, commitment and trust (hooks 2000). Care for one another as individual human beings and communities, care for the rangelands and all their beings, and care for the research process. We do not look at the world through rose-colored glasses. This is hard work, but it is work worth doing. Moreover, because it is hard, this work is not worth doing in any other way than in a good way. We hope these stories from one researcher's life combined with insights from Indigenous and feminist methodologies provide both food for thought and actionable practices relevant to diverse rangeland and pastoral contexts.

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Big data and digital tools to support adaptive rangeland management

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Abstract

There is a growing thirst for data and digital tools to support adaptive rangeland management. Over the last two decades, adoption of standardized field monitoring methods has enabled unprecedented data collection across rangelands globally. Monitoring capability has been boosted by an explosion of remote sensing products and models that can leverage field datasets and cloud computing to extend predictions across space and time and produce new indicators of rangeland health. Integrating these datasets with decision-support tools has the potential to support the development of new knowledge systems and place data and interpretive tools in the hands of managers in the field. Here, we review examples of recent developments that are transforming how pastoralists, extensionists, scientists, and agencies make decisions about rangeland use and management. These developments leverage new perspectives on data quality, data harmonization and aggregation tools, models that produce new integrative indicators, standard frameworks for describing land potential, and applications of benchmarks to make objective and actionable decisions supporting adaptive land management. These improvements can dramatically simplify rangeland monitoring and assessment, in both developed and developing world contexts, in addition to increasing the decision-making value of rangeland monitoring.

Introduction

The world has now passed 1.5°C warming. As the climate continues to change, pastoralists and rangeland managers must adapt to novel growing conditions often exacerbated by interacting effects of invasive species, wildfire, drought, soil erosion and changing social and economic conditions. In this time of environmental change, monitoring the status, condition and trend of land health attributes is of critical importance for identifying threats, understanding risks, and anticipating change in rangeland ecosystem services and the sustainability of enterprises – and adaptively managing them. Monitoring land health indicators provides a means for pastoralists and other rangeland managers to objectively assess different attributes and the function of landscapes, whether they are changing, where, when and why changes are occurring, and evaluate the outcomes of management actions. Recent integration of large-scale monitoring datasets with digital tools for interpreting land health indicators offers new opportunities to develop approaches that provide pastoralists and other range managers with information and knowledge to simplify adaptive management decisions. Here, we review examples of big data and digital tools that are successfully transforming management decision-making on rangelands. We synthesize lessons learned from these developments that could support opportunities for new research, adaptive management approaches and international collaboration.

Standardize and upscale monitoring methods

Monitoring methods standardization has provided a foundation for using indicators to assess the status, condition and trend of ecological attributes that are important for understanding and adaptively managing rangelands. In the United States, the *Monitoring Manual for Grassland, Shrubland and Savannah Ecosystems* was developed collaboratively with rangeland scientists and managers to provide standardized methods for collecting data that can be used to describe soil and site stability, hydrologic function, the biotic integrity of landscapes, and derive other indicators of, for example, wildlife habitat suitability and biodiversity (Herrick et al. 2018). The standard methods include line-point intercept (LPI), which enables estimation of the fractional cover of vegetation by species and other ground cover elements, a vegetation height estimation method, the canopy gap intercept method which enables quantification of bare ground connectivity, and a method for conducting species inventory. Extensive training and observer calibration programs, supported by rigorous data quality assurance and quality control (QA&QC) approaches (McCord et al., 2021) and statistically valid sampling frameworks (Toevs et al., 2011; Stauffer et al. 2022), have enabled implementation of the standard monitoring methods by producers, land management agencies and research institutions at over 100,000 locations across privately and publicly owned and managed grazing lands in the United States since 2004. Similar standard methods have been developed and implemented elsewhere around the world, providing comparable opportunities for adaptive management informed by globally standardized land health indicators (Oliva et al. 2016; Tokmakoff et al. 2020; Dashbal et al. 2023). Recognizing the significant costs associated with implementing large-scale monitoring, the Land Potential Knowledge System (LandPKS) mobile applications (https://landpotential.org/ [Accessed 22 01 2025]) were developed to provide globally accessible and compatible field-based monitoring technologies (Herrick et al., 2017).

Harmonize monitoring data and models

A major challenge to the findability, accessibility, interoperability and reusability of large-scale monitoring datasets is that different monitoring programs tend to develop and use their own data collection tools and formats and data management systems. In the United States, the Database for Inventory, Monitoring and Assessment (DIMA) (Courtright and Van Zee 2011), Vegetation GIS Data System (VGS) and ESRI-based Survey123 apps, for example, are all used for data collection among users following Herrick et al. (2018). While data collection formats have been optimized to reduce errors in the field, they are not typically analysis friendly (McCord et al. 2023). Furthermore, databases and data management systems have tended to exist in isolation among user groups. Monitoring data may be collected and managed separately by different organizations and government entities, while cross-tenure management is not uncommon. Consequently, inference from indicator assessments has often been restricted to specific land use and tenure and the ability to make cross-scale assessments has been limited.

The Landscape Data Commons (https://landscapedatacommons.org [Accessed 15 01 2025]) uses modern cyberinfrastructure to harmonize and aggregate monitoring data, enabling unprecedented access to standardized monitoring data and calculated land health indicators (McCord et al., 2023). Open-source code and toolsets enable data harmonization and standardized indicator calculation (McCord et al. 2022), ingestion of raw monitoring data into staging and production databases, and data access through a web portal and application programming interface (API) – which are open to users globally. During data harmonization, a set of 58 common grazing land indicators are calculated that can be used to assess land health, prioritize land for restoration and rehabilitation, and assess outcomes of conservation practices and whether land use and management objectives are being met. A Rangeland Indicator Calculator (https://jornada-data.shinyapps.io/rangeland-indicator-calculator/ [Accessed 15 01 2025]) enables users to query or upload data and grouping variables to produce custom indicators of management interest.

Concurrent management for multiple ecosystem services, which is typical for rangelands, requires a broad set of indicators and the ability to assess their interactive responses to drought, climate change and disturbances, in addition to responses to management practices sought to improve the sustainability of rangeland social-ecological systems. Harmonizing and aggregating monitoring datasets has provided opportunities for the scientific community to develop, in partnership with pastoralists and managers, new indicators that can broaden data use in decision making, and to develop predictive models that extend the kinds of quantitative indicators available to users (e.g., wind and water erosion) and their spatial and temporal coverage through remote sensing applications (Jones et al. 2018; Allred et al. 2020). The Rangeland Hydrology and Erosion Model (RHEM) (Hernandez et al. 2017) and Aeolian EROsion (AERO) model (Edwards et al. 2022) were developed for standard monitoring data applications. Running the models on aggregated monitoring datasets has enabled public release of quantitative erosion indicators that are interpretable alongside other indicators of land health and biodiversity – transforming how soil erosion can be considered in management decisions across watersheds and airsheds (Webb et al. 2017). For example, AERO has been used to assess how invasive annual grasses can accelerate and suppress sediment transport across rangeland wind erosion hotspots depending on wildfire interactions (Tremino et al. 2024). Such models also present new opportunities to evaluate relationships between land degradation processes and the ecological dynamics of rangelands, with identification of critical eco-geomorphic thresholds providing a basis for identifying early warning indicators of ecological state change (Webb et al. 2024) and insights into where and why restoration practices are/are not likely to be successful (Schaeffer et al. 2025).

Data analysis and interpretation frameworks to build a shared understanding of ecosystems

Collecting standardized monitoring data provides a foundation for using data to inform adaptive management. However, interpreting data in a reproducible (and defensible) way can be challenging. Setting and applying benchmarks has emerged as a practical way that managers can interpret big indicator datasets and make objective and actionable decisions about rangeland management (Webb et al. 2020). Benchmarks have been defined as indicator values or ranges of values that establish goals for resource conditions, such as land health (Kachergis et al. 2020). Benchmarks can simplify data applications in adaptive management to 1) make land health assessments to determine whether objectives, standards, or regulations are being met; 2) identify and prioritize land for restoration treatments; 3) assess the efficacy of conservation practices, restoration, reclamation, and rehabilitation; and 4) compare management strategies to inform adoption of new management approaches (Webb et al. 2024).

A critical consideration for setting land use and management goals, and selecting management practices, is how effective they are likely to be given the land potential and ecological dynamics of a site. Using information about land potential is an effective way of establishing realistic benchmarks that reflect local ecosystem dynamics – including responses to drought, climate change, disturbances and management. Land potential describes the potential productivity, degradation resistance and resilience of sites as influenced by soil properties, climate and landscape position (Herrick et al. 2013). Ecological states represent contrasting land conditions as influenced by land management and climate variations interacting with land potential. Benchmarks can be established for monitored indicators by identifying indicator values that represent desirable ecological state characteristics. Benchmarks can also be set based on knowledge of thresholds between states at which certain processes, for example soil erosion, impact ecosystem function and result in state change. Collaborative benchmark setting involving natural resource managers, scientists and pastoralists has been an effective way of engaging managers (often for the first time) in exercises to interpret indicator datasets and think critically about their use to inform management on-the-ground. These activities have been supported by development of the Ecosystem Dynamics Interpretive Tool (https://edit.jornada.nmsu.edu/ [Accessed 15 01 2025]) and State Transition Classifier (https://webapps.jornada.nmsu.edu/transition-classifier/ [Accessed 15 01 2025]), which provides a global framework for developing and sharing state-and-transition models (STMs) (Bestelmeyer et al. 2016). Producing quantitative STMs, and establishing indicator value ranges for states and transitions, has become a major research interest to support big data interpretation in decision making to meet land use and sustainable development goals, avoid, reduce and reverse land degradation, and minimize spending on practices that are unlikely to be effective or have undesirable outcomes (Heller et al. 2022; Duniway pers. comment.).

Discussion: Big data-informed adaptive rangeland management

Building accessible knowledge systems from big data and digital tools is already having impact on management decisions, pastoralists livelihoods, and management outcomes on rangelands. Further improving data access will enable more insights that can increase capacity to adopt adaptive management approaches to avoid, reduce and reverse land degradation and support sustainability and planned transformation of rangeland social-ecological systems in the context of drought and climate change. By linking big monitoring datasets with models and interpretive tools that support applications of land potential concepts and benchmarks, simple workflows can be developed that enable pastoralists to prioritize actions based on their management objectives, local knowledge and data. One successful example is the Land Treatment Exploration Tool (https://www.usgs.gov/apps/land-treatment-exploration-tool/ [Accessed 16 01 2025]), which provides a one-stop-shop for managers to access historical land treatment data, monitoring indicators and erosion predictions from the Landscape Data Commons, remote sensing data on vegetation cover, and drought forecasts to plan rangeland restoration and rehabilitation. With such tools in hand, managers can use data to help identify resilient land and management options that support resilience, identify land at risk of degradation and loss of ecosystem function, and apply that knowledge to assess landscapes, learn from their condition and the outcomes of management actions, and adjust management where and when needed to meet land use and management goals. Early identification of where there are risks or threats to the status, condition and trend of rangelands can support identification of land use and management approaches that are sensitive to the drivers of ecological state transitions and assist pastoralists and other rangeland managers in anticipating and preparing for more systemic impacts of climate change.

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Mind the gap: Integrating rangeland ecology into management requires more than just knowledge dissemination

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Key words: International Year of Rangelands and Pastoralists; knowledge co-creation; local knowledge; rangeland ecology; rangeland management

Abstract

Rangelands are social-ecological systems that provide multiple ecosystem services, including livestock production. To sustain the services rangelands provide, it is crucial to integrate rangeland ecology into their management. However, the reality is complex, as rangeland management reflects human choices and values, is informed by different kinds of knowledge, and is constrained or enabled by various policy, governance, environmental, social and economic factors. In this context, how can rangeland ecology contribute more effectively to sound rangeland management? For ecological knowledge to guide management, it must be communicated effectively, accepted as valid, and viewed as trustworthy. However, what constitutes "true" knowledge and appropriate management of rangeland systems is very often contested. Reconciling and integrating local or indigenous knowledge with scientific knowledge is important for a shared understanding of management challenges and solutions, but tends to be challenging and unfamiliar for both rangeland ecologists and land managers. Historical legacies and biases among researchers and land managers can also create significant barriers to the acceptance and implementation of new ecological insights. The inherent uncertainty and debate within ecology, while necessary for advancing knowledge, can lead to confusion or mistrust among managers and policymakers. Additionally, the management implications of ecological knowledge in a system may not align with the values, objectives, and perceptions of land users or decision-makers. Integrating rangeland ecology into management thus requires dedicated work and collaboration between scientists and practitioners at all stages of the process from identifying problems, through co-creating and integrating knowledge, to finding solutions.

Introduction

Rangelands are social-ecological systems that provide essential ecosystem services, including livestock production, biodiversity conservation, and carbon storage (Briske & Coppock 2023). Their long-term sustainability thus requires management based on appropriate ecological principles. Rangeland ecology and related ecological fields (e.g., vegetation dynamics, herbivore population and behavioural ecology) are well-developed, and much of this research is motivated by the need to understand and manage the ecological dynamics of rangelands better. Yet many rangelands across the globe and under a variety of tenure and management systems are described as mismanaged, degraded and vulnerable to global change, despite concerted efforts at informing, resourcing and developing their stewardship (UNCCD 2024). The long and ongoing debate around desertification in arid rangelands is a case in point, with powerful crisis narratives persisting and driving the policy agenda, and interventions aimed at stabilising inherently variable systems, despite mounting evidence that the reality is more nuanced (Behnke & Mortimore 2016). I argue that this disconnect is not simply a matter of communicating knowledge or educating land users, but reflects deeper issues related to how knowledge is produced, perceived, applied, and valued by different stakeholders. Scientific knowledge must not only be disseminated but also accepted, trusted, and considered relevant by those making management decisions Wilmer et al. 2021). Historical biases, institutional inertia, competing values and interests, and substantial power differentials between role players further complicate the process of integrating ecological knowledge into practice (Utter et al. 2021).

When rangeland ecology fails to inform appropriate management
A number of possible scenarios can account for misalignment between rangeland ecology and management. The first step towards better alignment is to identify which scenario we are dealing with, and the reasons for it.

1. Lack of uptake because the knowledge is flawed

There is a long and growing list of cases where the ecological knowledge guiding interventions is inappropriate to the local ecological dynamic, land users' objectives, or altogether. This includes applying models developed for different ecological contexts without testing their validity, or applying altogether outdated and disproven knowledge. For example, the notion that drylands are the result of deforestation by nomadic pastoralists, which resulted in their climate aridifying, was widely held in the 19th century (Davis, 2016). The solution was "reforestation" and other interventions such as irrigation to "green" the deserts. These actions have often caused salinization of soils, lowering of water tables, and invasion of fast-growing exotic tree species such as Prosopis. Ironically, more often than not the "solution" to the resultant resource degradation consists of more cycles of the same misguided interventions (Davis, 2016). Land users resist because the proposed interventions do not work in their context, or because scientists and policy makers make the wrong assumptions about problems that need to be addressed. Often the historical origin of these pervasive narratives has long been forgotten but careful analysis reveals flawed logic that has been transmitted uncritically over generations (Davis 2016; Davis and Robbins 2018).

2. The knowledge is sound, but it is not applied

This is often assumed to be the case when scenario 1 is actually the explanation. In other cases, however, the ecological dynamic and its management applications are well understood and agreed on, but not applied by land users. Possible reasons include lack of trust, or misunderstanding; but very often there are economic, institutional, policy and/or logistic impediments. For example, while flexible stocking approaches are ecologically appropriate in variable climates, the relative optimality of fixed vs tracking strategies depends on a range of factors including climate variability, access to markets, property rights regimes, market stability and prices (Campbell et al. 2006), and requires a supportive policy environment. Land users and policy makers may also prefer simple, rule-based approaches that aim for stability over adaptive strategies that require continuous monitoring and adjustment.

3. The knowledge is poorly supported but popular among land users and policy makers

When knowledge is poorly supported, land users are generally less likely to embrace it than policy makers and advisers; but there are examples where land users adopt management based on poorly or incompletely supported science. Again, reasons for such a scenario can vary. It may be a case of very persuasive and dedicated proponents or incentives. The practice may have proven successful in some contexts and applied in contexts where it is not appropriate; or rooted in tradition but no longer suited to current contexts.

For example, despite scientific criticisms, holistic planned grazing (Butterfield et al 2006) remains popular in many regions. Its compelling narrative offers a hopeful solution to land degradation, it aligns with ranchers' economic interests, and it appeals to conservationists and agriculturalists (Bennie et al 2024). Anecdotal success stories from individual practitioners have reinforced its credibility, even in the absence of consistent scientific validation (Hawkins 2017). The success of this approach in gaining widespread acceptance highlights the role of active promotion, personal experience, and economic incentives in shaping management decisions.

4. The appropriate solution is unknown or uncertain

Sometimes management problems defy current understanding of the system. Fires are known to suppress woody vegetation, yet a regularly burned rangeland is steadily becoming more encroached. An invasive species has taken over and nothing seems able to bring it under control. Years of resting have failed to improve the condition of a rangeland dominated by unpalatable grasses and shrubs. Often the reason is that the situation is novel – for example, elevated atmospheric CO_2 has changed the frequency and intensity of disturbance required to suppress shrubs (Bond & Midgley 2012; Ripley et al. 2022), and the formerly open grassy vegetation would require management actions that are no longer feasible or economical.

When rangeland ecology informs management

For all of the above possibilities, there is also the possible – and ideal – scenario that the available knowledge is ecologically sound and is applied successfully, whether in the form of a traditional system that has managed to maintain its desired features, or in the form of management consciously adapting in response to changing conditions and scientific input. This raises the question of what the factors are for success, especially if applying such knowledge means changing land users' practices substantially.

In the ideal scenario, the land manager understands and trusts the proposed management actions, a scenario that becomes more likely if they played an active role in identifying the problem and co-producing the knowledge underpinning the solutions (Wilmer et al 2021). This scenario is also more likely if management draws on land managers' existing practices and own knowledge, or is at least compatible with their knowledge system, and less likely if the management intervention is provided by outside experts with little local knowledge. Local knowledge can also help bridge separate and at times antagonistic fields of scientific knowledge, as in a case where herders' knowledge of cattle foraging behaviour helped integrate rangeland ecology (concerned with animal nutrition) and conservation ecology (concerned with avoiding biodiversity loss) by developing herding strategies that harmonized these different objectives (Molnár et al 2020).

The inherent uncertainty and debate within ecology, while necessary for advancing knowledge, can lead to confusion or mistrust among managers and policymakers. Success in solving management problems is more likely if risk and uncertainty are (or are perceived to be) low, or at least balanced by the benefits; land users in an already precarious economic situation, and who lack reliable safety nets are likely to be more risk averse and wary about adopting management practices that they have no direct experience of. Land users who have the agency and resources to implement the changes are more likely to adapt and succeed; communally managed rangeland with poorly functioning governance institutions, or where conflicts over land use exist, face much greater challenges, especially where factors such as dispossession, resettlement or constraints to mobility have heightened local conflicts over resources (Vetter 2013).

Ideally, management actions yield benefits quickly, providing the feedback that stimulates their continued implementation. The unpredictable and climatically variable nature of many rangelands tends to obscure trends and can cause setbacks (or apparent success in a good year that is not sustained in other years) and this can make evaluating and adapting management challenging. Rangeland ecologists can draw on data and literature from long-term studies to provide evidence while designing local studies and the communication around them in ways that are appropriate to their dynamic nature.

Integrating knowledge systems, knowledge co-creation and transparently negotiating trade-offs

Despite this complexity, a few general important lessons emerge.

1) It is important to be clear about the objective(s) of the land management and to ensue that the solutions actually aim to achieve these. This requires a common shared understanding of the social and ecological dynamics and constraints of the rangeland system, and achieving this requires sustained engagement, trust, and knowledge co-creation (Wilmer et al 2021).

2) Trade-offs are inevitable (e.g. plant biodiversity vs beef production vs carbon sequestration) and need to be transparently addressed. Misleading narratives of unrealistic win-win scenarios may impress donors and the

global public but can leave pastoralists losing out to carbon forests or "fortress" conservation (Fleischman et al. 2021).

3) Different stakeholders and role players often have very different objectives and understandings of the ecological dynamics of the system; differentials in economic and political power often influence which objectives and paradigms hold sway, and these are very often not the pastoralists' own objectives or knowledge system, leading to failed or unsuccessful implementation (UNCCD 2024).

Reconciling and integrating local or indigenous knowledge with scientific knowledge is important for a shared understanding of management challenges and solutions, but tends to be challenging and unfamiliar for both rangeland ecologists and land managers. Rangeland users – such as pastoralists, ranchers, and indigenous communities – rely on experiential and traditional knowledge systems that may differ from scientific interpretations. These knowledge systems may be rooted in cultural practices and long-term observations of the land, but which almost everywhere have had to adapt to drastically changing circumstances including climate change, land dispossession, restriction of mobility, stock reduction schemes and other interventions. Successful integration of ecological insights into practice thus requires active collaboration starting with problem identification, an openness to multiple knowledge systems, and an appreciation for the values and constraints that influence land users' choices (Utter et al. 2021; van Ewijk and Ros-Tonen 2021). The International Year of Rangelands and Pastoralists (IYRP) aims to address these issues, through raising awareness of the diversity and value of different pastoralists systems, and by giving greater voice and prominence to pastoralists and the organisations that represent and support them.

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Rangeland conservation: courage and resiliency in the face of climate adversity

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Keywords: Rangelands; ecosystems; climate change; resiliency; courage

Abstract
As climate change continues to impact rangelands worldwide, threatening the livelihoods of millions and the ecological integrity of these vital ecosystems, community-driven action has emerged as a powerful force for building resilience. Adapting to and mitigating the effects of climate change on rangelands requires courage from individuals and larger society and determination to overcome these challenges and drive positive change.

The integration of innovative management practices and technologies is essential for enhancing the resilience of these ecosystems. Digital technologies, such as monitoring databases, mobile applications and AI power, offer new insights and a way to enable land managers to adaptively manage rangelands amidst rapid changes. However, empowering communities to lead rangeland adaptation requires more than just technical solutions. It requires a fundamental shift in how we approach conservation and development, one that values local voices, respects traditional knowledge, funds research in region that are not deemed 'profitable', and fosters sincere partnerships embedded with trust and mutual learning. Courage and resiliency are crucial – to challenge entrenched power structures, to embrace uncertainty and experimentation, and to work in solidarity with local rangeland communities that are on the frontlines of these challenges.

It is time we welcome a new paradigm for rangeland management – one that recognises the value of these ecosystems goes far beyond economics, the inherent resilience of local people, and the transformative power of collective ambition to take care of precious rangeland environments.

Rangeland Significance
Rangelands represent far more than agricultural landscapes or locations for extractive industries – they are critical ecosystems that teem with biodiversity when in a healthy state, and that require shared stewardship and collective responsibility for their future. These vast territories, covering approximately 30-40% of Earth's land surface and supporting 1-2 billion people (Sayre et al., 2013), embody the intricate relationship between human communities and natural systems. Yet, despite their extent and importance, rangelands are often neglected in research and funding for development, whilst becoming increasingly vulnerable to climate change due to their low and variable rainfall, and poor soil fertility.

In Australia, rangelands occupy about 70% of the country, approximately 6 million km^2 (Guerin et al., 2017). Many rangelands support pastoral activities, contributing significantly to global food security (Herrero et al., 2016). They hold critical importance to global ecosystem services, including carbon sequestration and biodiversity conservation (Sala et al., 2017).

Climate Change and Rangelands

For rangeland managers, climate patterns form the cornerstone of decision-making processes. Temperature and rainfall guide crucial determinations on stocking rates, grazing rotations, and land management strategies (Briske et al., 2015; Eldridge and Beecham, 2018). This dependency on natural rhythms makes the disruption of traditional climate patterns particularly concerning for rangeland communities. Increasingly, generational knowledge passed down through communities no longer aligns with current conditions. These observations are validated by scientific evidence: anthropogenic greenhouse gas emissions have disrupted global climate systems, with rangelands experiencing warming at rates above global averages (IPCC, 2022).

Rangeland managers, working in close connection with natural systems, serve as front-line witnesses to climate change impacts. Rising temperatures manifest in more frequent and heatwaves, while increased evaporation hastens soil moisture loss, leading to droughts (Howden, 2017). Due to the ancient and weathered nature of Australian soils, rangelands are particularly susceptible to degradation processes such as erosion, compaction, salinization, acidification, and contamination, ultimately leading to fertility loss, increased desertification, and thus a decline in agricultural production and food security, which are exacerbated by climate change (Dadzie et al., 2023). Native vegetation communities are shifting in rangelands, affecting livestock nutrition and habitat availability for native species (Godde et al., 2020). These disruptions are reshaping viable agricultural activities across regions. Globally, mounting pressures on rangeland communities drive rural-to-urban migration, deepening socioeconomic inequalities among those who maintain these vital landscapes (Herrero et al., 2016).

The implications extend far beyond local communities. Rangelands function as crucial carbon sinks, storing approximately 30% of global soil carbon (Wang et al., 2016), while serving as biodiversity hotspots and essential components of global food security. Their deterioration threatens not just local livelihoods but larger planetary health. In recent decades, rangelands worldwide have faced mounting pressures from climate change, overgrazing, feral animal explosions and other land-use changes. Human-driven degradation of the Earth's land surface is affecting the well-being of over 3.2 billion people, accelerating the planet toward a sixth mass extinction of species, and leading to biodiversity and ecosystem service losses amounting to over 10% of the annual global GDP (IPBES, 2018).

Courage for Rangeland Conservation

A central challenge emerges: how can societies simultaneously achieve good ecological health and community resilience in rangelands? One answer lies in cultivating what can be termed "climate courage" - the moral and practical strength to confront and act against climate change challenges, despite the uncertainty and anxiety they invoke. This concept encompasses both individual determination and collective action, building on social-ecological resilience (Folke et al., 2016). Climate courage moves beyond mere adaptation to actively promote positive environmental change, positioning planetary health as a central determinant in decision-making and action. It manifests through community-driven initiatives that combine traditional knowledge with innovative solutions, fostering resilience while acknowledging the deep interconnections between human wellbeing and ecosystem health.

The relationship between humanity and the biosphere is fundamentally reciprocal - we shape our environment and it in turn shapes us. This interconnection has led to growing recognition that development strategies and scientific research must account for the deep links between human welfare and the health of our planet's living systems, as exemplified in frameworks like the Sustainable Development Goals. By viewing these challenges through the lens of interlinked social-ecological resilience, we see that human development must be grounded in and compatible with the biosphere's capacities and finite resources (Pedro et al., 2024). The recognition of our dependence on Earth's living systems will help in stewarding human development in harmony with the biosphere - a crucial requirement for both sustainable development and maintaining human dignity, particularly in fragile rangeland ecosystems.

The magnitude and urgency of climate change impacts on rangelands demand more than incremental responses or business-as-usual approaches. Climate courage means acknowledging that conventional management practices and policy frameworks are insufficient for the challenges ahead. It requires embracing transformative changes in how we manage, value, and protect these landscapes. This includes supporting innovative practices that may challenge current approaches, advocating for policy changes that prioritise long-term sustainability over short-term productivity, building new partnerships that bridge the divide between scientific and traditional knowledge systems, and supporting community-led co-creation (Lavhelesani et al., 2024).

Looking to the Future

The path forward demands a fundamental shift in how we think about rangelands and their management approaches. We must move beyond viewing these landscapes solely through the lens of production or extraction, recognising their vital role in climate regulation, biodiversity conservation, and cultural heritage (Stafford Smith et al., 2020). To appreciate these precious landscapes and look after them in the manner required, there must be empowered local communities who are active decision-makers, who integrate traditional and scientific knowledge, and who build supportive networks that transcend individual properties to catchments and outwards to reach business and policy.

Success are stories are emerging. Pastoral networks share knowledge about drought-resistant native species and innovative water management techniques, improving resilience to climate variability (Marshall et al., 2018). National Drought Resilience Adoption and Innovation Hubs have been established to help with this. The national farmer movement, Farmers for Climate Action, exemplifies climate courage, uniting farmers and agricultural leaders across Australia to advocate for climate solutions while building resilient farming communities. There are research teams working in remote rangeland locations. The Wild Deserts field site, covering 35,000 ha in north-west New South Wales, aims to bring back seven locally extinct mammals. Similarly, Arid Recovery, an independent not-for-profit running a 123 km^2 wildlife reserve in South Australia's arid north, is pioneering conservation science to help threatened species thrive across the Australian outback. Nearby, Boolcoomatta is a 63,000 ha former sheep station now conservation reserve.

One more controversial topic in Australia's rangeland management is that of dingos. Recent studies suggests that dingoes, Australia's largest terrestrial predator, can play a crucial role in maintaining healthy rangeland ecosystems while potentially increasing profits for farmers. Dingoes suppress populations of kangaroos and feral animals, reducing unmanaged grazing pressure that contributes to landscape deterioration (Campbell et al., 2022; Letnic et al., 2013). This effect from dingo presence can lead to increased pasture biomass, improved livestock condition, and higher profit margins for pastoralists (Prowse et al., 2015; Pollock, 2021). Additionally, dingoes may indirectly benefit small mammals and vegetation by controlling invasive species like foxes and cats (Letnic et al., 2013; Newsome et al., 2015). While dingo reintroduction has been proposed to restore degraded rangelands, it remains controversial due to concerns about livestock predation and conservative community views (Newsome et al., 2015). This is indeed an area for further research and community education – coupled with courageous conversations – so that there is greater understanding of dingoes' ecological impacts and to develop management strategies that balance predator conservation with livestock production.

These are just some of the many examples and areas for research throughout Australia's rangelands that are both encouraging and inspiring and that are helping to protect rangelands in our climate challenged world.

Conclusion

Despite the grand and complex challenge that climate change presents, there are people who are stepping up and speaking out to look after rangelands. Climate courage means facing hard truths about environmental change while taking decisive action. This type of courage isn't just about bravery or rose-tinted optimism - it's about maintaining hope and taking practical action in the face of serious environmental challenges, all while preserving the cultural and ecological heritage of rangeland systems now and for future generations.

Securing a resilient future for rangelands requires cultivating climate courage within individuals and communities. It depends on us truly acknowledging our dependence on healthy, thriving natural ecosystems and the relationship of reciprocity. This determination to care for the planet's precious rangelands can radiate from local initiatives, the amplification of traditional knowledge, the embracing of innovation, and fostering collective resilience in the face of change. Through coordinated action and shared determination, communities can enable positive transformation in rangeland management and conservation.

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THEME 1. VALUING RANGELANDS AND PASTORAL SYSTEMS FOR THEIR SOCIETAL CONTRIBUTION

Cultivating knowledge among pastoralists' children, students, rangeland professional, and broader society

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Modifying the education system for children of migratory pastoralists of Jammu and Kashmir State of India for equitable growth

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Key words: migratory pastoralists, education system, mobile schools, equitable growth

Abstract
Children whose elders are actively engaged in pastoralism are becoming more and more demanding when it comes to their schooling. Poverty-stricken households view education as a means of escaping their situation, whereas pastoralist households view it as a means of sustaining their system of production in a world that is becoming more interconnected. Education systems, on the other hand, are still focused on "educating pastoral children out of pastoralism" and are failing to adapt to this change in demand. Programmes for education intended for sedentary individuals are typically expanded to include pastoralists, and they are predicated on a straightforward modification of sedentary models to account for some elements of nomadic living. The greatest transhumant population in the world is found in Jammu & Kashmir. The *Gujjars* and *Bakarwals* make up the majority of the population in this part of the Himalayan valley and are the third largest ethnic group there. *Bakarwals* are people who herd sheep and goats, whereas Gujjars raise big ruminants like cows and buffaloes. The *Chopan*s are a group of semi-nomad people who traditionally raise sheep in Kashmir for their meat and wool. For four to six months, the pastoralists migrate to the southern regions of the state, where they can find suitable climate conditions for their livestock to graze. Their children's education is their main issue because of the disparities in the curricula. A study was conducted on the possibility of opening mobile schools to provide children from migrant populations with a uniform education. Children from mobile schools outperformed those from stationary schools in terms of intellect. When compared to sedentary schools, the dropout rate from mobile schools was noticeably lower. In addition, a number of other socio-economic and ecological factors were investigated for overall welfare of the ethnic groups.

Introduction
Pastoralists have had difficulty sustaining their way of life (Waller 1999). They are traditionally semi-nomadic and nomadic herders who rely on their livestock as a source of income, cultural prestige, and sustenance (Gustafson et al. 2011, Lybbert et al. 2004). Although pasture and water availability has received much of the attention in research on the drawbacks of the traditional pastoral system, education for children is also essential to sustained livestock production and livelihoods. The need for education is growing quickly among pastoralists, particularly children who work directly in the field. In an increasingly globalised society, households actively engaged in pastoral production saw education as a means of sustaining their production system, while impoverished households view it as a means of escaping poverty (Siele et al. 2011). However, educational systems continue to focus on "educating pastoral children out of pastoralism" and through formal schooling, failing to adapt to this change in need. Education programmes for pastoralists are often based on a straightforward adaptation of sedentary models to certain characteristics of nomadic living, and they are typically an extension of those created for sedentary people. Productive households are thus forced to choose

between continuing the family business and obtaining access to formal education, which is a detrimental trade-off. Historically, pastoralists have been marginalised. "The greatest poverty rate and the least access to essential social services are found in nomadic pastoral areas (Allen 2017)". Therefore, a study was conducted to examine the significance of mobile schools for the children of pastoralist Mobile schools were established by the Jammu and Kashmir government for children from pastoral families, however they are only operational for around six months during the winter when pastoralists are not at home. Short-term teachers receive a set wage that is significantly less than that of their permanent counterparts.

Methods

A study was conducted on the possibility of opening mobile schools to provide pastoralist children from migrant populations with a uniform education. As a case study, 50 pastoralist children were selected, at random, 25 each from mobile and stationary school. The study was conducted from 2019 to 2023 for five years. Both formal and informal questionnaires were utilized to gather information from the elders, temporary teachers, and schoolchildren about the pastoralists' migration and educational system. To gain a thorough understanding of the migratory system, previous research publications and existing literature were examined.

Results

Dropouts and passing rates

The findings revealed that, compared to mobile school children, the number of dropouts among pastoralist schoolchildren was substantially greater if they were stationary schoolchildren (Fig. 1). Children attending mobile schools tended to pass more often (Fig. 2). It was discovered that the dropout rate for children attending mobile schools was one student in each of classes three and four, and two in class five. In contrast, at the class 2, 3, 4, and 5 levels, the dropout rates were 1, 8, 3, and 8 pupils, respectively, in sedentary schools. In mobile schools, the passing percentage was 100, 98, 96, 92, and 90, whereas in sedentary schools, it was 100, 96, 76, 68, and 50. Children who dropped out of school were viewed as failing pupils.

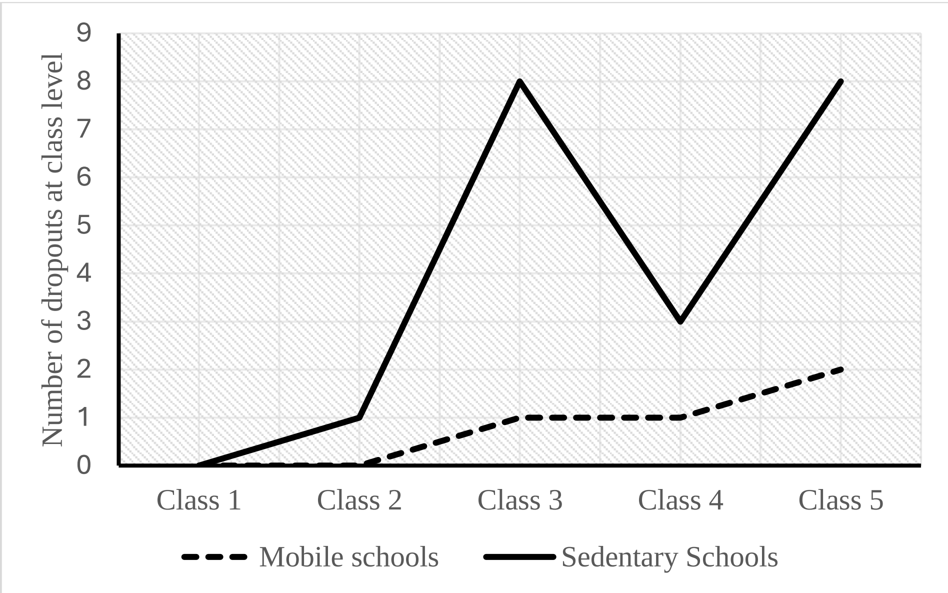

Fig. 1. Number of dropouts at class level

New mobile schools

The state government began mobile schools, though they are still in their infancy, after realising the difficulties faced by pastoralist schoolchildren. According to the information that is currently available, the guidelines in this regard are as follows: (i) the teacher will be an educated member of the moving tribe with the highest qualification; (ii) he or she will receive INR 10,000 as a salary for only six winter months; (iii) the teacher should have his own livestock and move with the other tribe members; and (iv) the government will provide a tent, a table, a chair, a mat, and books to facilitate the teacher and the students at the start of the session. It was also difficult for the parents to leave their kids emotionally and without proper care at home. Because there were no mobile schools, the kids who accompanied their parents didn't go to school. Many studies show that the domination of the school-based system itself is to blame for the historically dismal record of offering pastoralists access to high-quality education.

Major constraints

Parents, teachers, and school children brought attention to the challenges they encounter while switching from mobile to stationary schools, and vice versa. The main limitations were things like different curricula, dealing with new teachers, admissions processes, altered school environments, etc

Discussion [Conclusions/Implications]

The primary cause of the increased dropout rate among children of mobile pastoralist from sedentary schools was their insistence on going with their parents when they moved to the plains in the winter. Leaving their children at home, emotionally and without adequate care, was difficult for the parents at the same time. In the lack of mobile schools, the children who went with their parents did not pursue further education. A large body of research indicates that the historically poor record of providing pastoralists with access to high-quality education has been caused by the dominance of the school-based system itself. To date, the school-based system's structure and culture have been restricted to the "classroom" model of instruction and have not provided education as an alternative to pastoralism. A needless obstacle to learning is created for children in pastoralism by school-based services. They do not, however, want to replace pastoralism or undermine it because of its basic requirements. There isn't currently a service supply to meet this type of demand. This must be adjusted.

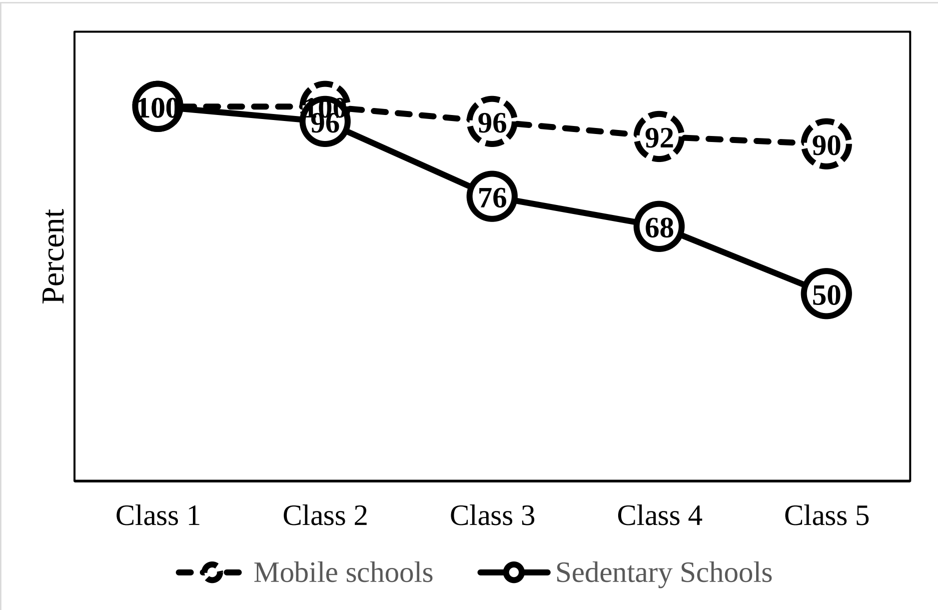

Fig. 2. Passing rate from mobile and sedentary schools
Note: Considered dropouts also.

A deeper comprehension of the role that mobility plays in pastoral production is necessary for effective educational inclusion measures. This must entail avoiding the disadvantageous trade-offs pastoralists face when their sole choice for obtaining "modern" education is a school-based model of provision that requires them to make concessions with pastoral produce and eliminates their means of subsistence within pastoralism. Instead of creating new avenues for advancement, this strategy restricts them. Putting the blame on pastoralists for their poor school attendance has diverted policymakers' attention from the fact that the educational system is, by definition, keeping prospective students out of the pastoral system.

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Prairie Project on Zooniverse: citizen science and inquiry-based learning for promoting rangeland literacy

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Key words: authentic inquiry; STEM education

Abstract

The Prairie Project aims to promote pyric herbivory and mixed species grazing as climate-smart agricultural practises for sustaining livestock production and other ecosystem services of rangelands in the Great Plains. Key to fulfilling such a shift of management paradigm is effectively engaging land managers and professionals, future professional and decision makers, and the public through integrated research, education, and extension efforts. Leveraging citizen science as an effective tool for research and education and outreach through crowdsourcing, we have been developing citizen science projects on the Zooniverse platform for engaging secondary and undergraduate students as well as the public, based on research data collected at our research and demonstration ranches across the Great Plains. In one of these projects, students and the public engage in identifying animal species and their activities as captured on camera-trap photographs from a research ranch. The data generated are essential for studying the spatial and temporal distributions and behaviour of livestock and wildlife in different vegetation communities and with different burn histories. Crowdsourcing the data classification also presents educators with a platform for designing and implementing high-impact learning activities in classrooms and extension programs. Importantly, this also allows us to reach a broader and more diverse audience outside the traditional range management and ecology community. We have developed and implemented learning activities in an introductory ecology course at a research university and are developing learning activities for additional educational settings. During the last two years, over 950 students have engaged in this Zooniverse project as part of an authentic inquiry project to explore the effect of fire on animal distribution and behaviour in different vegetation settings and developing critical thinking and communication skills. Assessment data show that these experiential learning activities resulted in significant gains in understanding the scientific practice and rangeland literacy.

Introduction

The future of productive rangelands requires management practices that promote conservation of systems and education on the importance of rangelands for agricultural products and ecosystem services. The expansion of woody plants into grasslands of the North American Great Plains is a threat to the productivity, biodiversity and function of these rangelands (Archer et al. 2017, Londe et al. 2022). A secondary concern is the challenges presented by a growing urban population making policy decisions affecting rangelands (Sayre 2023).

The Prairie Project is a collaboration among researchers and extension specialists from the University of Nebraska-Lincoln, Oklahoma State University, and Texas A&M University. The project aims to increase the ecological and economic production of Great Plains rangelands by combatting woody plant encroachment with pyric herbivory and multispecies grazing. As part of the research into the effects of these treatments, we have placed camera-traps on a research ranch in Texas to record the movements of livestock and wildlife. To assist us in classifying the animals and their activities, we have employed the public through the citizen science platform Zooniverse. Photographs are grouped into six categories based on the locations' burn status (burned or unburned) and vegetation community (herbaceous-dominated, small woody-dominated, or large woody-dominated).

Authentic inquiry-based learning engages students by allowing them to investigate real-world, open-ended problems using critical thinking and the research process (Crawford 2000, Herrington and Kervin 2007, Krajcik and Blumenfeld 2006). To this end, we have developed a Zooniverse-based authentic inquiry activity for students of an introductory ecology class at an R1 university. We investigated the effectiveness of this activity by analyzing students' self-assessments on interest, ability, and knowledge of ecology and the scientific process (Wu et al. 2021).

Methods

The activities of this inquiry-based project were given to students of an introductory ecology course titled 'Fundamentals of Ecology' at Texas A&M University in the fall semesters of 2022 and 2023. This sophomore-level class has enrolment of 400 – 500 students. During the first week, students were taught the concepts of pyric herbivory and multispecies grazing and their use in combatting woody plant encroachment and increasing quality forage production. They learned about the study site and were assigned 100 photo classifications through the Prairie Project Zooniverse page. Students completed a survey by rating themselves on the following prompts on a Likert scale of 1 (very low) to 5 (very high): 1) interest in ecology, 2) ability to formulate a testable hypothesis, 3) understanding of the research process, and 4) ability to evaluate a scientific report. Working individually, students began identifying patterns in the photographs during the second week to develop a testable hypothesis and design the needed methodology to gather evidence to test their hypothesis. Students collected and analyze their data and submit a report during week 3. Peer reviews were conducted during the fourth week followed by revisions and final submissions during the fifth week. The project concluded with students again rating themselves on the same survey.

To test students' self-perception of learning, we analyzed pre-project and post-project responses to survey questions using a Wilcoxon signed-rank test. We evaluated effect size using Cliff's delta with the measures of $\delta = 0.11$, 0.28, and 0.43 to indicate small, medium, and large effect sizes, respectively (Vargha and Delaney 2000). Additionally, we applied Wilcoxon signed-rank test for each survey question by student categories. These groupings were male and female students, upperclass and lowerclass students, underrepresented minority students (URM) and other students (non-URM), and students taking the course as a degree requirement (major) or science elective (non-major). For purposes of this study, first- and second-year students were classified as lowerclass and students in their third year or beyond were classified as upperclass. Students from university departments of ecology and conservation biology; rangeland, wildlife, and fisheries management; environmental studies; landscape architecture; and recreation, park, and tourism sciences were required to complete this course. Finally, Hispanic, black, American Indian, mixed race or ethnicity, and international students were classified as underrepresented minorities. We used Mann-Whitney U-tests to detect differences in learning gains (calculated as pre-survey response subtracted from post-survey response) between male and female students, upperclass and lowerclass students, URM and non-URM students, and major and non-major students. Again, we evaluated effect size using Cliff's delta.

Results

A total of 568 students consented to participating in our study during the autumn 2022 semester ($n = 325$) and the autumn 2023 semester ($n = 243$). Based on our demographic groups, there were 231 male and 337 female students and 199 URM and 369 non-URM students. There were 248 upperclassmen, 320 lowerclassmen, 369 major students, and 199 non-major students.

Overall, students' interest in ecology did not differ between pre-survey and post-survey responses ($W = 3572.5$, $p = 0.9112$). We detected significant differences in students' ability to formulate a hypothesis ($W = 5687$, $p <$

0.0001), understanding of the research process (W = 2737, $p < 0.0001$), and ability to evaluate a scientific report (W = 5353.5, $p < 0.0001$). Effect size for these responses were medium (δ = 0.387), large (δ = 0.551), and medium (δ = 0.429), respectively.

When broken into groups, we again did not detect a difference between pre-survey and post-survey responses for students' interest in ecology (Table 1). Differences were detected across all groups for the remaining survey responses. All groups exhibited a medium effect size for hypothesis formulation except male students with a small effect. A large effect size was observed across groups for understanding the research process. Finally, all groups exhibited a medium effect size for evaluating scientific reports except female students with a large effect.

Table 1. Differences in students' self-perception of learning before and after participation in an authentic inquiry project as tested by Wilcoxon signed-rank test (W) with effect size measured by Cliff's delta (δ).

Student Group	Interest in ecology			Ability to formulate a hypothesis			Understanding of the research process			Ability to evaluate a scientific report		
	W	*p*	*δ*	*W*	*p*	*δ*	*W*	*p*	*δ*	*W*	*p*	*δ*
Male	1695	0.858	0.001	1735.5	<0.001	0.315	652.5	<0.001	0.538	1082	<0.001	0.357
Female	3234	0.754	0.009	893.5	<0.001	0.437	676	<0.001	0.558	1577	<0.001	0.480
URM	1535.5	0.676	-0.003	734.5	<0.001	0.386	297.5	<0.001	0.556	526.5	<0.001	0.466
Non-URM	3469.5	0.643	0.010	2340.5	<0.001	0.388	1222	<0.001	0.548	2535.5	<0.001	0.409
Upperclass	1345.5	0.434	0.021	1386.5	<0.001	0.356	689.5	<0.001	0.511	1268	<0.001	0.388
Lowerclass	3615.5	0.622	-0.006	1405.5	<0.001	0.416	648	<0.001	0.581	1389	<0.001	0.462
Major	4623	0.804	-0.002	2380.5	<0.001	0.400	1116	<0.001	0.572	2691	<0.001	0.431
Non-major	905	0.582	0.022	711.5	<0.001	0.364	358.5	<0.001	0.512	458.5	<0.001	0.427

None of the results of the Mann-Whitney U-tests showed a significant difference between learning gains of any of the groups across all 4 survey responses.

Discussion

Assessment showed that participation in this authentic inquiry project promoted students' self-perception of learning the scientific research process. This methodology has been shown to promote knowledge retention and academic performance in the STEM fields, enhance student engagement and motivation, supports development of self-regulated learning, and increases student confidence in their academic abilities (Savery 2006, Zimmerman 2002). Furthermore, inquiry-based learning promotes systems thinking in ecology and can inspire students to engage with ecological issues (Gormally et al. 2009, Tanner 2009).

By using our citizen science project on Zooniverse, we were able to provide students with exposure to actual data from research in a rangeland setting. The course curriculum provided a wide-range of students with lessons in rangeland ecology, management practices, and problems facing rangelands. The majority of the students taking this course do not study rangeland ecology and management nor come from rural backgrounds or demographics of past rangeland managers. Thus this is an important outreach interface. Rangeland literacy can promote positive outcomes by educating voters and future policy-makers whose decisions often affect the stewardship of these lands (Launchbaugh et al. 2012). Two noteworthy challenges to current rangeland curriculum include shifting demographics and organizational shifts within university programs (Tanaka et al. 2012). Our results indicate that we were able to provide rangeland literacy across all demographic groups from an introductory ecology course not housed within a rangeland ecology and management department.

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Bridging academia and outreach: mentorship programs for future rangeland scientists

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Key words: Extension, framework, graduate students

Abstract

Integrating graduate students into mentorship programs that encompass teaching, research, and Extension/outreach is essential for developing a skilled workforce capable of addressing the multifaceted challenges of rangeland management. Although many graduate programs focus on developing academic skills necessary to conduct rangeland research, students often enter the workforce unprepared to engage with diverse stakeholder groups that comprise the rangeland community. We explore how outreach specialists can collaborate with academic researchers to create deliberate, comprehensive mentorship frameworks that enhance graduate education and professional development. This paper directly responds to Theme 2 of the 2025 International Rangeland Congress as we present a model that involves a synergistic approach to incorporating stakeholder engagement with student training. Specifically, this model integrates the expertise of outreach specialists, who provide practical, field-based insights, with academic researchers, who contribute theoretical and methodical rigor. The resulting collective collaboration ensures that graduate students gain a holistic understanding of rangeland science, encompassing both traditional and innovative practices. Critical components of the mentorship program are 1) co-designing research projects that address real-world, producer-driven problems, 2) engaging students in community-based outreach activities, and 3) fostering partnerships with local stakeholders. The hands-on approach both enhances students' technical skillsets and builds capacity for effective communication and collaboration - essential for future leadership roles in rangeland management. By embedding graduate students in multidisciplinary teams and providing opportunities for participatory research, this mentorship model aims to strengthen the academic-research-outreach paradigm and further embed graduate students in the rangeland community. A holistic mentorship approach ultimately contributes to more resilient and sustainable rangeland outcomes and prepares the next generation of rangeland scientists to tackle the complexities of global rangeland ecosystems.

Introduction

Rangeland science can address some of the most pressing global challenges, including food security, climate change adaptation, biodiversity conservation, and sustainable land use. Rangelands cover 54% of the global terrestrial surface, amounting to approximately 79.5 km^2 (Rangelands Atlas 2021). Consequently, they support key ecosystem services (Macfadyen et al. 2012) such as carbon storage, wildlife habitat, and water filtration, while simultaneously providing a foundation for livelihoods based in agriculture. Effective management of rangelands is critical, then, and requires science and practice to be integrated to address complex challenges and "wicked" problems, from climate change to biodiversity loss.

Although rangelands have a significant role in global sustainability, a gap exists between academic research and practical application. The results from research generated by universities and research institutes can sometimes stay in the "ivory tower" and fail to reach practitioners, policy makers, and local stakeholders who depend upon and manage rangelands across the globe. Contributing factors include limited communication among groups, different priorities between academics and managers, and limited training opportunities that integrate outreach and applied applications. Consequently, it is important to bridge this divide to ensure that rangeland science effectively addresses real-world challenges.

Mentorship programs create the potential to serve as the crucial bridge between academia and outreach, helping to prepare the next generation of rangeland professionals to apply their knowledge in practical settings. Mentorship – the guidance of a less experienced individual (mentee) by an experienced professional (mentor), creates a collaborative framework for knowledge transfer, skill development, and professional growth (Allen et al. 2004). Within the context of rangeland science, mentorship can connect students and early-career professionals with experienced researchers, outreach specialists, and land managers, fostering a well-rounded understanding of both scientific principles and their application in diverse landscapes.

This paper explores the role of mentorship programs in bridging the gap between academia and outreach in rangeland science graduate education. We first examine the challenges that contribute to the academic-outreach divide, and then discuss gaps in rangeland graduate curriculum. Finally, we offer recommendations for designing and implementing mentorship programs that are tailored to the unique needs of rangeland science. By integrating cross-disciplinary mentorship into the broader framework of professional development, the field can cultivate a workforce that is not only scientifically literate, but also skilled in outreach, communication, and collaborative problem-solving.

Challenges Between Academia and Outreach

Several challenges are inherent when discussing the disconnect between academia and outreach in rangeland science. Among them are divergent priorities and goals, communication barriers, a perceived disconnect between theory and practice, time and resource constraints, the complexity of rangeland systems, and a decline in integrating traditional ecological knowledge (TEK). Academics tend to prioritize research advancements, publishing peer-reviewed articles, and securing grant funding. This can result in not fully understanding the needs of stakeholders, such as helping them adapt to climate change (Briske et al. 2015). Further, the pressing needs of stakeholders may not align with those outlined in funding requests for applications (RFAs). Communication between academia and outreach can be fraught, with research findings often published with technical jargon. Reed et al. (2014) examine principles for effective knowledge exchange in environmental management and suggest that knowledge exchange needs to be designed into research questions; the needs of both academics and stakeholders should be systematically represented in research; and finally, that long-term relationships must exist and be built on trust to construct a dialog between academics and stakeholders to ensure co-generation of new knowledge. Drawing parallels to rangeland science, if both academics and outreach professionals incorporate these principles, together they can increase the cross-pollination needed between theory and practice.

This cross-pollination can be hindered by time and resource constraints, as well as the complexity of rangeland systems, and lack of TEK. For example, faculty members are tasked with balancing research, teaching, advising, and service, leaving little time for outreach. Outreach is often underfunded and understaffed, leading to reduced capacity to facilitate knowledge transfer between academia and stakeholders. Further, granting agencies usually do not require outreach, reducing the impetus to include it in proposals. Thurow et al. (2007) explain that in the United States, a shift has occurred in funding from a baseline support formula to one that relies on competitive research grants that don't support management-oriented research. Engle and Wailer (1993) express frustration that the increase in competitive grant funding moves rangeland professionals away from long-term research priorities and instead has them focus on grantor priorities. In addition, rangeland systems are complex and face many "wicked problems," such as invasive species and climate change (Briske et al. 2015); this can result in disciplinary silos instead of cross-pollination between research groups. Lastly, modern research can overlook TEK, despite it being developed throughout time with rangeland systems (Berkes et al. 200). This can result in stakeholder groups feeling that academics are untrustworthy and further reduces collaboration between academia and local communities.

Gaps in Rangeland Science Curriculum

Research to date of rangeland science curriculum is not exhaustive; however, the research and commentaries that do exist underscore the need for a more comprehensive education that includes formal mentorship and collaboration between academia and outreach. Buckhouse and Powell (1985) express that undergraduate students in rangeland resources at Oregon State University (United States) are increasingly coming from more urban/suburban backgrounds; the same has been shared anecdotally among rangeland professionals recently and holds true for both undergraduate and graduate students. The authors further conclude that a student can have strong academic skills, but "if he/she cannot open the pasture gate, the knowledge may never be shared with the landowner" (Buckhouse and Powell 1985). It is not only practical skills that may be lacking in today's students, but lack of stakeholder involvement in rangeland curriculum development. For example, Taylor and Andrews (2012) describe a complete restructuring of rangeland graduate curriculum in Australia, which entailed a strategic approach that combined focus groups with stakeholders, course scoping workshops, and research on learning. The focus groups identified current and future issues and challenges; through the course scoping workshops, the authors detail that a significant outcome was "the learning and insights the scientists and academics gained about real-world contexts, local knowledge, and the emerging issues perceived by a wide range of stakeholders" (Taylor and Andrews 2012). This has led to increased awareness and ownership of the program by stakeholders, ultimately helping the program be recognized as "best practice" (Taylor and Andrews 2012).

Rangeland curriculum has a direct impact on the abilities of graduates entering the workforce. Thurow et al. (2007) surveyed Society of Range Management (SRM) members and undergraduate students at the University of Wyoming (United States) to investigate what aspects of rangeland curriculum were perceived as important. Within the top ten skills needed by professionals, an average score of 4.3 ± 0.8 (1 = grasp of general concepts to 5 = highly detailed proficiency) was given by survey respondents on public interaction (listening/collaboration/mediation skills), 4.0 ± 0.9 was given for technical writing, and 3.9 ± 0.9 was given for public speaking. Further, resource management (scientific application and techniques) and communication skills were listed as the top two things that respondents indicated a rangeland science program should provide to students. The authors conclude that employers that enact management objectives (e.g., state and federal land management agencies) are likely to be frustrated by the lack of focus on management and low proficiency in communication and quantitative skills (Thurow et al. 2007). Although this study addressed undergraduate students, collectively, we as range professionals who train students have not purposefully addressed these issues that arise in undergraduate rangeland curriculum and focus our research efforts – and therefore, the graduate education of our students – on fundamental (e.g., 'basic') research instead of emphasizing rangeland management and the proficiency of our students to communicate about it.

A Comprehensive Mentoring Framework For Rangeland Graduate Students

Using the knowledge gained from the existing research outlined above, we provide a comprehensive mentoring framework for rangeland graduate students that strives to address both the challenges between academia and outreach and the gaps in rangeland science curriculum. There are three mentorship components (MC) to the framework: MC1) addressing producer-driven problems, MC2) community-based outreach activities, and MC3) partnerships with local stakeholders (Fig. 1). The framework further outlines both *who* and *how* these components can be accomplished. Across all MC are graduate students, cross-pollinated researchers, and outreach specialists. Cross-pollinated researchers are those that cultivate a rich, inter-disciplinary "intellectual ecosystem." These researchers actively integrate ideas from other specialities to foster innovation and holistic approaches to rangeland management. An example would be a rangeland scientist who collaborates with an economist to evaluate the financial implications of sustainable grazing practices or with sociologists to understand the decision-making processes of producers during drought. Outreach specialists are trained and have the technical expertise in rangeland management, but also have a breadth of interpersonal skills such as relationship and capacity building, as well as the adaptability to tailor their educational approaches to different audiences. It is critical throughout the three steps of the framework that graduate students are trained by both cross-pollinated researchers and outreach specialists.

The focus of MC1 is constructing a strong foundation with producers. Researchers and outreach specialists can work collaboratively with graduate students to engage producers through several different avenues. One avenue would be to conduct focus groups and listening sessions with producers, with the purpose of understanding their perspectives on rangeland management and what challenges they face. Another avenue would be to conduct a formal needs-assessment to identify gaps between current states and desired outcomes, as well as to prioritize identified needs. Both methods will help promote knowledge exchange and the co-development of potential solutions, such as alternative grazing methods, that can then be researched. This not only helps facilitate trust, ownership, and collaboration with producers, but it demonstrates that their input is valued. A facilitator is likely to benefit these methods and can help remove the emotion that often surrounds critical rangeland management threats. Finally, integrated grants – grants that require outreach, in addition to research – are grants that provide several benefits. One, they are competitive and often have higher funding caps (e.g., $750,000 to several million USD) that will be viewed favourably by university administration. Two, because they require research *and* outreach to occur on the same project, there is ample opportunity to provide graduate students with training and experience in both aspects. Three, integrated grants typically allow for an interdisciplinary approach between researchers and outreach specialists, helping to underscore the importance of both to graduate students.

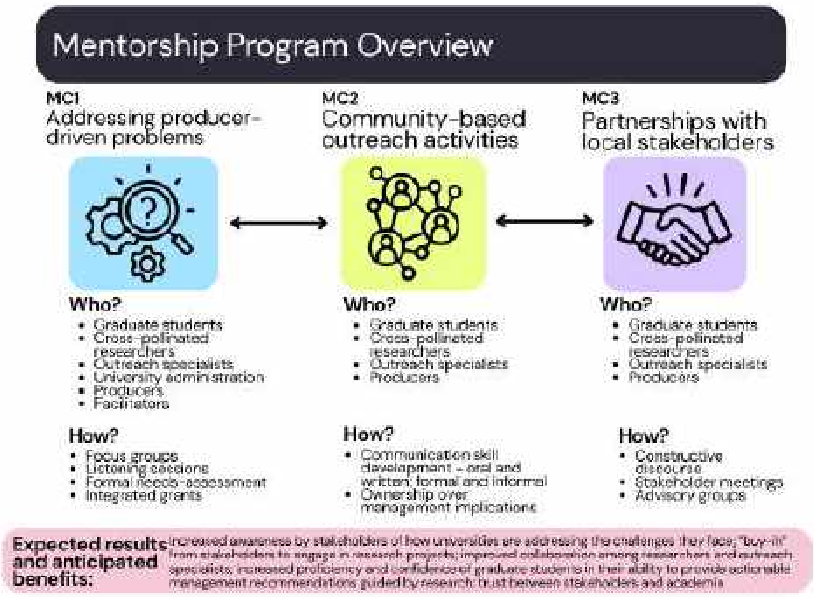

Figure 1. A mentorship program overview with three mentorship components (MC): MC1, addressing producer-driven problems; MC2, community-based outreach activities; and MC3, partnerships with local stakeholders. For each MC, a description of *who* and *how* is provided, along with overall expected results and anticipated benefits.

MC2, community-based outreach activities, provides mentorship for graduate students that is often disregarded. Outreach activities provide several informal opportunities for graduate students to develop their skills, particularly in both oral and written communication. This can be in addition to any formal (e.g., classroom-based) communication training that the university may offer. Graduate students can contribute to outreach activities and learn how to translate complex scientific concepts into accessible language for diverse audiences, through presentations and outreach articles for producers and the public. Another benefit of mentoring graduate students through outreach activities is that they will see the real-world application of their scientific knowledge, by helping to solve practical, producer-driven problems. Further, graduate students will feel empowered through participation and take ownership over the potential management recommendations suggested by their research. Finally, producers can also provide mentorship through these activities, by fostering relationships between academia and outreach, helping to expose students to diverse viewpoints and experiences.

The last piece of the mentorship program is MC3, partnerships with local stakeholders. This emphasizes and expands the groundwork that is laid in MC1 with producers. Specifically, MC3 helps graduate students enhance the success, relevance, and sustainability of their research. Partnerships further help graduate students learn the real-world application, as well as the social, cultural, and economic contexts of their research. These contexts often result in discourse that can be applied constructively and either developed into future research questions or used to create outreach programs that address stakeholder concerns. Some research projects – particularly those supported by integrated grants – benefit from an advisory group of stakeholders. By attending stakeholder meetings or leveraging an advisory group, graduate students can further develop their communication skills and help foster trust between academia and producers. Additionally, these interactions with stakeholders help graduate students increase career preparedness. By understanding the multi-faceted nature of rangeland management, students will be better prepared for interdisciplinary careers. Lastly, the involvement and familiarity with stakeholder groups explicitly demonstrates experience in applied research, outreach, and collaboration, thereby helping make students more competitive on the job market.

Implications

As outlined above, challenges exist between academia and outreach; these challenges can be overcome by mentoring the next generation of rangeland scientists to be 1) cognizant of the challenges, and 2) have the capacity to address them. We recommend that this is best achieved through mentorship of rangeland graduate students, via a three-component mentorship program that overcomes a common concern that the ivory tower of academia is "producing too much of the wrong kind of information" (McNie 2006). In addition to the benefits to graduate student training, the mentorship program we outline has several benefits for research/academia and stakeholders. Specifically, research quality may increase, as the increased collaboration with stakeholders ensures that research is aligned, and it may also improve access to local resources. Further, collaboration among researchers and outreach specialists will broaden perspectives on rangeland management, ultimately encouraging innovative and interdisciplinary approaches to problems. Stakeholders will gain access to emerging knowledge, ideally benefiting their operations. They will also benefit from the mutual learning that will co-occur with the academic insights the graduate students provide and the practical, hands-on knowledge they use daily. Overall, the mentorship program we outline has the potential to move the needle in rangeland graduate curriculum, bridging the gap between academia and outreach, while simultaneously fostering a new generation of leaders that are adept at collaborate, interdisciplinary, and impactful work.

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Going beyond the choir: an arts-based approach to informing the public about rangelands, grasslands and grasslands peoples in the International Year of Rangelands and Pastoralists 2026

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Key words: art-based education; rangeland/grassland exhibits; valuing rangelands/grasslands

Abstract

Rangelands and grasslands are highly productive and valuable perennial-based ecosystems that provide a multitude of benefits for society. Yet they are highly threatened throughout the world which was the impetus for the UN designating 2026 as the International Year of Rangelands and Pastoralists. In North America alone, these ecosystems have contracted by 60-80% due to conversion to intensive agriculture, urbanization, power development, and other causes. While causes of loss vary, wide agreement exists that these biomes are undervalued by society despite their ecological, socio-cultural, and economic significance. This has led to increasingly urgent calls for wide-reaching education campaigns to raise awareness among the public and policymakers, and spur action to stop and reverse losses. In response, we look to the approach of Indigenous Peoples who have and continue to use art as a means of educating and are designing and deploying a pilot mass communication effort. Specifically, we aim to "go beyond the choir" and use "more than facts and figures" by developing 25+ creative, multi-media public exhibits to test the efficacy of arts-based education. We will use a mixed methods research design to evaluate the effectiveness of art in public settings (specifically variables of exhibit venue, media type, and messaging strategies) to increase awareness and knowledge, and drive behaviour change regarding support for rangelands and rangeland communities. We assembled a team of 30+ professionals across 12+ US western states and the Pacific Islands, Canada and Mexico who will help to recruit, design, and deploy content and exhibits. Content will be digitized and curated in collaboration with the Rangelands Partnership and key subject matter specialists including land stewards, Indigenous communities, rangeland scientists, Extension professionals, an evaluation researcher, and artistic directors. Outreach efforts are a key need identified by diverse groups working and living in rangelands and a clear guide for where limited resources will be most effective will be a critical factor in helping to preserve these lands.

Introduction

Rangelands (grasslands, shrublands, tundra, savannahs and woodlands) are threatened ecosystems around the world. Their services and relationships provide carbon sequestration, soil stabilization, water filtration, habitat, and human food. However, in North America alone, 60-80% have been converted to crops or non-agricultural use (Nature Conservancy Canada 2024, USFWS 2024, USGS 2023). While causes of loss vary, agreement exists that these biomes are undervalued by society despite ecological, socio-cultural, and economic significance (Bengtsson et al. 2019, Birdlife International 2024, Sayre et al. 2013). Rangelands have been mapped as "leftover areas" (Sayre et. al 2013), marginalizing their influence on public perception and land-use decisions.

Inadequate knowledge of rangelands has negative environmental, economic, and social consequences, including conversion (Lark 2020, Briske et al. 2024), desolated cultural landscapes (Rattling Hawk, Pers. comm.), and rural economic decline (Bardgett et al 2021). Consequently, producers and range professionals have called repeatedly for education going beyond the "choir" and using more than facts and figures. A promising avenue for the range-grassland community to explore that may prove effective is art-based education, which is known to provoke reflection and expand awareness through the 'affective' or emotional domain (Drumm et al. 2013, Lawrence 2008, Thompson et al. 2023). Indigenous Peoples have for many years utilized art as a means of sense-making, educating and documenting, creating dynamic and engaging expressions of knowledge and understanding (Sorenson 2013). At present, there is a lack of structured coalitions for mass communication to explain how different approaches may have different impacts across diverse populations (Devine et al. 2023, Lesen et al. 2016). As such, we have developed a coalition that seeks to explore the impacts of different art-based education approaches across diverse demographic populations. Our goals with this project are to:

1. Develop a western region network of 24 to 36 educational art exhibits to evaluate the effect of ecological context, city size, venue type, and exhibit openings on public comprehension of and engagement with critical rangeland and grassland issues.
    a. Evaluate the impact of art-based rangeland exhibits on public audiences not historically familiar with grass/rangelands by locating exhibit venues in non-rangeland ecological contexts and larger metro-urban areas.
    b. Evaluate our ability to reach new audiences with rangeland messages by partnering with and displaying arts-based educational content at novel exhibit locations such as airports, city halls, libraries, and shopping malls.
    c. Evaluate the impact of social gathering (i.e. public opening vs. no public opening) on level of engagement of attendees.

2. Investigate the potential for arts-based learning to enhance a sense of connection among Indigenous and non-Indigenous youth to their range/grassland landscapes
    a. Evaluate the effect of farm-based art-education workshops on comprehension of range/grassland topics among Indigenous and non-Indigenous youth.
    b. Evaluate the effect of classroom-based art-education workshops on comprehension of range/grassland topics among Indigenous and non-Indigenous youth.

Methods

This is a multi-year project with major portions of the effort being deployed in 2025 and 2026. Our first goal of developing a network, and then creating and disseminating educational art packets, is currently in progress. A network has been established with 24 confirmed venues and another 12 venues with conversations actively happening on logistics, including major venues like the Port of Seattle and the City of Los Angeles. We will continue to build on our network over the coming year and with installations put up in 2026. The educational art exhibit packets will contain 10-15 exhibit items (photography, mixed media, painting, etc) from around the world and we will start to compile materials for these in the beginning of 2025. We will develop a publicly accessible digital and physical library in collaboration with Rangelands Gateway consisting of at least 100 submissions of artistic audio-visual resources that are paired with one of ten priority messages about grass/rangeland issues in addition to the pre-composed exhibit packets. Exhibits will be installed in diverse venue types and at diverse geographic and demographic locations across the US, Canada and Mexico (Table 1) with active and passive surveys conducted at the different locations.

Table 1. General study framework for educational art exhibits.

Treatments (independent variables)	City size, venue type, ecological context, exhibit opening/no opening
Knowledge indicators	What rangelands/grasslands are; ecological, economic, and social importance; extent and decline; ecosystem services including habitat, C sequestration, biodiversity, water; services provided by producers
Attitude indicators	Expressed desire to learn more about grass/rangelands and increase support for producers, interest in meeting and purchasing from producers
Practice/behavior change indicators	Access information on policy, range issues; participation in community collaboration or association; purchasing intentions of grassland-based product; participation or facilitation of urban-rural cross-cultural exchange
	Speak out on behalf of rangelands; promote policy to include grasslands in climate response strategies;
Survey tools (passive)	QR codes on content, paper response questionnaires
Survey tools (active)	QR codes on content, participant observation, exit interview with venue host
Survey tools at case study sites	QR codes on content, participant observation, exit interview with venue host, intercept surveys, follow-up interviews with willing viewers

For our second goal, we will test two methods for educating youth about rangeland/grassland landscapes. The first method (a) is getting youth to the landscape (school-to-landscape), and the second is (b) taking the landscape to the youth (landscape-to-school). The first approach will utilize existing programs and programs in development where professionals host youth in a rangeland/grassland landscape and use art workshops (including photography, film, or other) to teach youth about the ecology, culture, and agriculture of the area. The second method is a less time and resource intensive endeavor wherein educational packets will be created for a multimedia experience about rangelands/grasslands that can be enjoyed in the classroom. This approach is tailored to the US primary and secondary education system to meet criteria required of teachers for science and art. While the experience will likely be less profound than actually going to a rangeland/grassland biome to learn about the ecosystem and the types of land uses that exist, we believe the opportunity to reach a larger population of youth is important. This approach will provide students with an opportunity to learn about rangelands/grasslands, while fitting within the time limitations of teachers and instructional requirements.

Results Thus Far

This project is currently in progress with the full deployment set to occur during the 2026 International Year of Rangelands and Pastoralists (IYRP). Efforts associated with the educational art exhibits are scheduled to begin in 2025 and while this effort is currently North America focused, we welcome the participation of our global rangeland communities. Material developed for this project will be made available on the Rangelands Gateway website (https://rangelandsgateway.org/). An overview of exhibit information and materials will be given in this presentation.

Program development for school-to-landscape events and material packet creation for landscape-to-school efforts are currently underway. In this presentation, we will be giving examples of how collaborators are developing school-to-landscape programs and we will be presenting examples of the landscape-to-school materials. These materials will also be available on the Rangelands Gateway website and the US based teachers-pay-teachers website (https://www.teacherspayteachers.com/). These materials are being designed with adaptive capacity in mind: people will have different needs in terms of art-based educational material and we want to create content that can be used broadly, with individuals having the opportunity to add their own local flair.

Discussion

The goal of this project is to provide diverse groups of people in rangelands/grasslands with ideas and materials to help educate people in non-rangeland areas and instil a sense of value and appreciation for the lands that many of us call home. While the direct impacts of efforts of this nature can be difficult to quantify, we know that talking amongst ourselves will not provide a solution to the current challenges that many of us face. As such, we need to reach beyond the choir and find diverse ways to reach diverse audiences. Findings from these studies will be shared through podcasts, extension products, webinars, conferences, manuscripts and partner networks. Our hope is to not just provide an outreach campaign for the 2026 IYRP, but reach beyond 2026 and create a culture of caring for rangelands into the future.

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Education and experience to empower the next generation of rangeland professionals

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Key words: Career; University Degrees; Workforce Development; Youth Education

Abstract

The challenges facing rangelands and the human communities that rely on them are increasingly intense and variable. Management of the modern threats of damaging fire regimes, invasive plants, variable climates, and desertification of rangelands across the globe requires a skilled and knowledgeable workforce. Historically, most rangeland management professionals came from agricultural backgrounds, obtained a rangeland degree through educational programs that provided extensive hands-on field experiences, got real-world experience through internships or summer jobs, and/or received extensive training and mentoring through their employers.

Many emerging rangeland professionals today, however, come from urban backgrounds, often with little or no direct exposure to rangelands. Time constraints on established rangeland professionals, due to increased workload and limited personnel, result in less opportunity for emerging professionals to learn from experienced rangeland management trainers and mentors. A proposed emphasis on recruiting, embracing diversity, engaging modern educational practices, and fostering intentional mentoring is needed to empower emerging rangeland professionals to develop a full complement of important knowledge, skills, and leadership traits to successfully manage rangeland resources. The Society for Range Management is committed to supporting and promoting the full continuum of educating, training, and mentoring future rangeland management professionals. Programs include those targeting high school and college students as well as a new program for early career rangeland professionals called the Academy for Rangeland Career Success. While these efforts are largely focused on the United States, ideas and engagement are needed worldwide. Effective programs will be presented and opportunities to share ideas and successful approaches from across the globe will be highlighted to support the theme of valuing rangelands and pastoral systems for their societal contributions.

Introduction

Slightly more than a century ago, the discipline of rangeland science emerged with the primary goal of addressing the significant challenges associated with livestock production on grasslands, shrublands, and woodlands (Sayre et al. 2012). This development gave rise to the profession of rangeland management, which brought together scientists, government land administrators, and livestock producers in a collaborative effort. From the early stages of the profession, it was recognized that sustaining rangeland productivity and values depended on recruiting and educating skilled personnel to handle the complex challenges of rangeland management (Sampson 1954). To support this emerging profession, courses and academic programs were established at Colleges and Universities to train professionals able to manage grazing, fire, and invasive species, and thereby ensure the sustainability of rangelands worldwide (Abbott et al. 2012; Taylor et al. 2020).

Global challenges such as climate change, food security, water sustainability, energy production, biodiversity loss, and desertification are increasingly critical to society and pose significant threats to rangelands. Addressing these issues requires a robust and well-trained rangeland workforce, yet the persistent shortage of skilled professionals jeopardizes the health and sustainability of these ecosystems. The demand for rangeland professionals who possess both strong academic knowledge and practical experience has never been greater, underscoring the urgent need to cultivate and expand this essential workforce. To address this workforce shortage, we argue that those dedicated to sustaining rangeland health and productivity must: (i) identify and recruit a diverse group of rangeland professionals, (ii) transform rangeland training and education, (iii) mentor and support early career professionals, and (iv) foster networks of life-long learners.

Identify and Recruit Rangeland Professionals

Building a strong, well-educated rangeland workforce starts with recruiting individuals to pursue advanced degrees essential for a career in rangeland management. One of the primary reasons prospective students do not choose degrees in rangeland ecology and management (REM) is simply a lack of awareness that such programs exist (Abbott et al. 2012). When exploring degree options through university websites, which often feature hundreds of majors, degrees, and certificates, students are unlikely to come across REM programs unless they are already familiar with the profession. Students may be more likely to encounter REM degree options if they are bundled with broadly recognized fields such as wildlife management, forestry, or environmental science. On-campus recruitment efforts, such as visits by rangeland faculty or students to introductory courses in biology, botany, or chemistry, or presentations to freshman interest groups, have proven effective in raising awareness. Additionally, exposure to the profession through youth range camps, interactions with rangeland professionals, or guidance from parents, teachers, or high school counsellors also play an important in influencing students to choose an REM major. Anecdotal evidence from reviews of several REM programs accredited by the Society for Range Management (SRM), suggest that university Range Club tabling and peer-group ambassador programs are an effective way to recruit students to REM programs. These outreach efforts are critical for attracting the next generation of rangeland professionals.

In 2020, a survey conducted for the Range Science Education Council (RSEC) explored rangeland degree choices at U.S. colleges and universities. Male and female students were nearly equally represented among the 228 respondents and about 75% of respondents were range majors. The survey revealed that 43% of range majors across the western U.S. initially enrolled as REM majors, while 57% switched to the REM major later. Among those who changed majors, 66% did so before taking a range course, while 37% switched after taking one. The top three reasons for changing to an REM major were perceived career opportunities (72%), the uniqueness of the major (40%), and the potential work locations (46%). The survey also showed that about 60% of REM majors entered as freshmen, while 40% were transfer students. These students came from various backgrounds: very rural areas (26%), towns with populations between 2,500 and 25,000 (38%), cities with populations over 25,000 (30%), and other locations (6%).

When asked how colleges and universities could increase enrollment in range-related majors, 87 respondents provided suggestions. The majority (78%) emphasized the importance of outreach to communities, schools, and other students, while fewer respondents mentioned the need for curricular or programmatic changes (29%) and highlighting employment opportunities (25%). Universities need to sharpen and expand their recruiting efforts as the demand for rangeland graduates continues to be high. In the U.S., 124 students per year graduated with an undergraduate degree in REM between 2011 and 2022 (Educational Digest, Tables 318.30) and the average demand for Conservation Scientists (of which range management is a part) is projected at 140 per year between 2023 and 2033 (U.S. Bureau of Labor Statistics Occupational Outlook Handbook).

Programs aimed at deepening and diversifying the rangeland workforce should also consider avenues to attract and support non-traditional students seeking REM degrees. Developing 2-year technical programs and building relationships with faculty in community colleges could increase the number of students seeking rangeland degrees and provide options that are more affordable to a wider array of students (Bullard 2024).

Transform Rangeland Education

Rangeland education is predominantly delivered through traditional, on-campus classes led by university faculty. Over recent decades, the reduction in faculty with specialized expertise in rangeland science, coupled with a growing emphasis on research over teaching, has significantly diminished the coverage of rangeland topics in many academic programs. This decline comes at a time when the demand for graduates in REM is increasing. Furthermore, many prospective students are geographically constrained, limiting their ability to access the traditional coursework essential for career advancement. To address these challenges, it is imperative to modernize rangeland curricula and adopt innovative instructional methods that broaden access, support student participation, and enhance professional development opportunities.

Advances in communication technologies over the past 25 years have created significant opportunities to serve place-bound students, enhance teaching resources for educators, and facilitate collaboration across universities and continents. Currently, several asynchronous web-based courses provide rangeland education to students. However, effective rangeland management requires strong skills in social interaction and the ability to engage stakeholders with local knowledge and solutions (Sampson 1954; Roche et al. 2021; Taylor et al. 2024). To address this need, distance-accessible courses could incorporate structured discussions involving topic experts or practitioners with deep local knowledge. Students might be tasked with investigating livestock operations, ecological challenges, wildlife habitat programs, or rangeland improvements in their communities, sharing findings with their peers. Laboratory activities could be designed to have students collect specimens or data, analyse results, and present their findings collaboratively. Professors could also collaborate to create innovative assignments and documentary-quality class presentations, moving beyond reliance on outdated or inconsistently prepared notes and presentations.

To better prepare the next generation of rangeland managers, it is essential to explore innovative approaches to course delivery. For instance, distance-accessible postgraduate programs have been designed to offer flexible educational pathways, enabling students to progress from graduate certificates to master's degrees (Ferguson 2021). Another promising approach is the use of workshop-style courses, such as those offered at the University of Nevada-Reno, which combine online learning with intensive field workshops to provide hands-on, practical knowledge. Additionally, workshops and courses could be developed to serve both degree-seeking students and professionals pursuing continuing education, fostering an inclusive learning environment that meets diverse educational and needs for career advancement.

Support Early Career Professionals

Offering early-career rangeland employees support and professional development is crucial after recruiting and training individuals for careers in rangeland ecology and management. In 2010, the U.S. Bureau of Land Management published a "white paper" highlighting concerns about the agency's shortcomings in providing adequate training, mentoring, and onboarding for early-career rangeland management specialists. The paper identified widespread issues with retaining early-career employees and ensuring they could effectively serve both the rangeland resource and its stakeholders across various offices and regions. It warned that without meaningful development strategies for new employees, these challenges would worsen. Fifteen years later, those predictions have materialized. At the 2023 International SRM Meeting more than 20 employers, including agency representatives and private non-government organizations, confirmed that these issues remain pervasive.

Several factors contribute to the challenges facing rangeland professionals today, including shifts in their backgrounds, changes in academic preparation, and limited training and onboarding by employers. Historically, many rangeland professionals came from agricultural backgrounds, completed rangeland degree programs with extensive hands-on field experiences, gained real-world exposure through internships or summer jobs, and received comprehensive training and mentoring from employers. In contrast, many emerging professionals now come from urban backgrounds with little to no direct exposure to rangeland management. Hands-on field experiences are increasingly limited, even in high quality REM programs, and fewer professionals gain practical experience through internships or summer jobs. Additionally, time constraints on established professionals, caused by heavier workloads and staffing shortages, reduce opportunities for mentorship. To ensure effective rangeland management and retention of employees in the field, it is vital for emerging professionals to develop essential knowledge, skills, and leadership traits.

The Society for Range Management created the Academy for Rangeland Career Success (ARCS) to address the professional development needs of early-career rangeland management professionals. ARCS aims to enhance participants' knowledge, skills, and leadership in four key areas: Professionalism, Working with People, Understanding Cultures, and Subject Competency. Over the course of a year, participants engage with experts through a combination of remote and in-person mentoring and training. The curriculum focuses on addressing skill gaps, strengthening existing competencies, and leveraging individual strengths for mentoring others. While ARCS has shown promising results in its first year, agencies and employers must also invest in programs to ensure the retention and success of early-career professionals.

Foster Networks of Life-Long Learners

An essential strategy for supporting the future of rangeland management is fostering networks of lifelong learners. Building strong connections among land managers, ranchers, scientists, extension educators, and conservationists is critical to addressing the challenges facing rangelands today. Diversifying the rangeland workforce is also key to attracting new professionals and equipping them with the tools needed to succeed. This diversification should encompass various stages of career development, creating an inclusive environment for continuous learning and innovation (Taylor et al. 2020).

To achieve this, the Society for Range Management has established programs and initiatives that emphasize professional development throughout career stages. SRM's network spans from high school youth programs to collegiate students participating in the Student Conclave, and from early-career graduates in the Young Professionals Conclave (YPC) and the Academy for Rangeland Career Success, to mid-career and seasoned professionals. These networks not only help individuals transition through different career phases but also foster a culture where professional development is recognized as a critical component of career growth. However, there is evidence that we need to reach more rangeland professionals to help them develop the mindset that professional development is key for their continued career progression.

Members of the YPC and ARCS program benefit from targeted mentoring and networking opportunities, helping them build connections with other rangeland professionals within the SRM As they transition to regular membership, their continued professional growth depends largely on self-motivation to engage with peers and actively contribute to the profession. At every stage, SRM focuses on fostering a passion for rangelands and enhancing members' technical skills by introducing emerging tools like drones and artificial intelligence (AI).

Professional development opportunities are not limited to SRM annual meetings and section gatherings, which provide forums for research dissemination, extension updates, and producer engagement. The importance of lifelong learning in rangeland management extends globally, as evidenced by the Australian Rangeland Society (ARS), which has played a central role in professional development both within Australia and internationally (Taylor, et al. 2020). Such efforts highlight the value of continuous skill enhancement and the critical role these opportunities play in developing leaders within the rangeland profession.

By fostering a robust network of lifelong learners and emphasizing professional development, SRM, ARS and other rangeland organizations ensure that rangeland professionals remain equipped to address evolving challenges and lead the way in sustainable land management.

Conclusions/Implications

It is urgent to provide educational opportunities for students of REM and support for career professionals to succeed and excel in the management of rangelands as rangelands face unprecedented challenges to their ecological resilience and the human communities they sustain. The future of rangelands lies in the hands of the next generation. Our commitment to fostering and supporting these students and early-career professionals will either pave the way for or hinder the sustainable management of rangelands across the globe.

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Utah range camp: helping youth value rangelands

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Key words: Rangeland; Youth; Education; Camp; Management

Abstract

In Utah, there are nearly 45 million acres of grazing land; 73 percent federally owned, 9 percent state owned, and 18 percent privately owned (GOPB, 2011 as cited in UDAF 2019). Rural economies benefit from livestock grazing on these rangelands, many of which are managed for multiple uses including recreation, mineral extraction, timber harvest and other practices. Political and public sentiment toward livestock grazing on public lands is becoming less positive as the attention turns from livestock and conservation to recreation and preservation. In 1973 Utah State University and the Utah Society for Range Management started Utah's Range Camp for high school youth in an effort to help the rising generation see the value of rangelands and livestock grazing. Up to 25 high school youth are allowed to participate in this program each year. The camp teaches youth about the basics of rangelands and natural resources. Youth learn about poisonous plants, noxious weeds, wildlife, livestock, and how to identify plants. If possible, the camp is changed to a different location each year to give returning youth new perspectives. Youth experience each ecosystem available in the area from desert shrubland to alpine tall forb communities. Professors, agency land managers, and ranchers are brought together to share with the youth about their jobs and different issues they face in their careers and ways to manage rangelands. Many young adults come to camp because they want to work in a range related field or because their family is involved in range, while others come because it gives them an edge at FFA (Future Farmers of America) competitions. Some attendees may never be involved in a range related career, but they are taught the importance of natural resources and multiple uses and become vital to the future of rangelands as educated community members.

Introduction

In 1954, the Utah Section of the Society for Range Management (Utah SRM) decided to begin holding youth Range Camps to speed up the adoption of rangeland management practices and principles among Utah ranchers (Smith, 1981). Range Camp is still used to help the public adopt rangeland principles but it is also used to help the students to network, expose them to potential colleges and careers and succeed in FFA competitions. The first camps were held from 1958-1962 and, starting in 1973, have been held annually ever since. While attendance has not been accurately counted prior to 2016, an average of 20 individuals attend each year making an estimated total of 1,100 youth that have participated in the Utah Range Camp since its start.

Methods

Originally, when Range Camp began, it was the responsibility of the Utah State University Rangeland Extension Specialist to direct the camp. This has evolved over time, the only real consistency being that the Range Camp Director was a member of the Utah SRM and was chosen by the previous Camp Director.

Each summer, up to 25 Utah High School youth between the ages of 14 and 18 who are interested in Rangeland Management and Natural Resources apply to attend Range Camp. Camp is usually held for one week (Monday-Thursday) in the summer, when most plants have finished their growing cycle. A site is chosen to base the camp out of for the entire week. Each year, it is the intent to change the location of the camp to give repeat students the chance to experience different areas. Depending on the venue, young women sleep in a cabin and young men camp in tents. Usually there are bathroom and kitchen facilities provided. Leaders for the camp are invited by the Camp Director and include Range Specialists from Federal and State Agencies, Universities and institutions, and the private sector.

Throughout the week, students learn about, collect, press, and correctly label 20 plants on their plant list. They are graded off of neatness and accuracy. Plant ID tests are held at several locations each day in which the student must properly identify the plants common name, growth form (grass, forb, woody), life span (annual, perennial), origin (native, introduced), forage value (desirable or undesirable for grazers and browsers), and whether the plan is toxic. Students should take notes and complete worksheets to receive full credit for participation. Worksheets include; forage production estimation, line point intercept, line intercept for shrubs, soil stability, and grazing utilization. These are filled out while a professional helps them complete these hands-on monitoring activities. At the end of the week each student must give a prepared two-minute oral presentation on something they learned at camp. Students are judged and graded and the combined winner and runner up are chosen to represent the Utah SRM by competing at the High School Youth Forum at the National SRM Meeting. The winners are given financial aid by the SRM to attend. To maintain high standards, students who do not achieve 50% or greater are not welcomed back to attend camp the next year. Previous winners may attend the next year but will not compete.

After attendees are checked in, they are given a plant press, a grass and forb identification field guide, water bottle, swag bag provided by a sponsoring college, pencil and pen, and a camp binder. The binder contains; the camp agenda, the Western National FFA Range CDE practice worksheets, ideas for a career in rangelands, instructions for writing an effective resume, the Western Rangeland Career Development Event Manual, several Ecological Site Descriptions that match locations the group will visit during camp, and several plant ID test sheets and rangeland monitoring forms. The first day is spent giving lectures and trainings on Introductions to Rangelands, Plant Identification, and Soils.

Each day begins with showers and breakfast and then the group travels to a range location using vans. Each day focuses on a different zone. The group is able to familiarize themselves with the low brush desert, semi desert, foothills, mountain brush, mountain grasslands, and alpine tall forb zones anywhere from 2000 to 11,000 feet in elevation throughout the week. Rangeland principles are discussed, monitoring is practiced, plants collected, and students are tested on plants in each zone. Students are able to learn from local land managers about current issues and practices and ask questions about their jobs. Time is taken to discuss toxic plants, noxious weeds, soil texture, aspect, climate, precipitation, vegetation, wildlife, and livestock in each zone.

Each evening is spent with dinner and more lectures and trainings in a classroom setting. Lectures are usually given by a representative of a college or range related career detailing their jobs or research. Other topics include discussions on livestock stocking rates, wildlife conflicts, noxious weeds, toxic plants and innovations in rangelands such as virtual fencing. Evenings are finished up with the students preparing for their oral presentations and labelling and pressing plants collected that day. At the end of the week, winners are selected and camp is cleaned up.

Results

To show the long-term impacts of Range Camp, a survey was created and sent out to all previous students on file, and distributed to members of the Utah SRM and State and Federal land management agencies within Utah. The 49 survey respondents previously attended Range Camp as a youth. 100% responded that it was important that youth attend Range Camp and would recommend that other youth attend. Respondents noted that it is a great way to teach the rising generation the importance of rangelands, it prepares youth to participate in FFA Contests, prepares youth for employment, and it is a great networking tool to introduce students to colleges and career paths. Those who attended Range Camp noted that they loved gaining knowledge of rangelands and the friendships they built through the program. 58% of the attendees attended the camp more than once. Those who only attended the camp one year noted that they would've attended more than once had they been able to. The top two reasons for not attending the camp a second time was that the students had either aged out or their Agriculture Teachers did not notify them of the activity. Figure 1 shows which years the survey participants attended Range Camp. Figure 2 shows the reasons youth attended Range Camp.

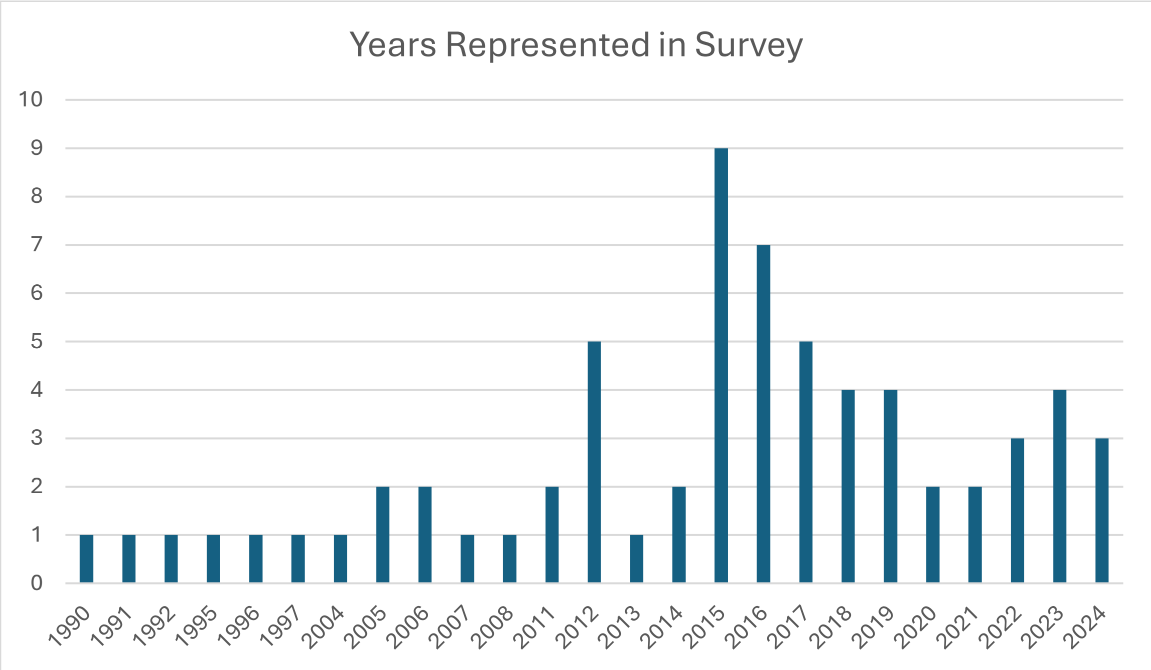

Figure 1

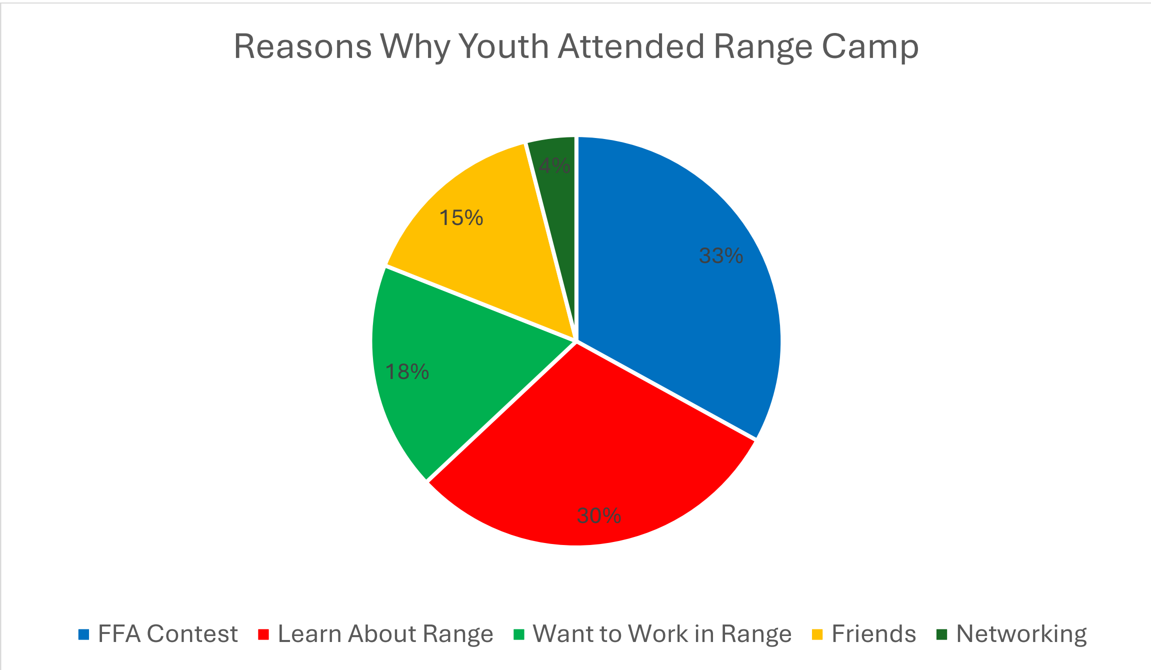

Figure 2

All survey participants rated the quality of the instruction and quality of the instructors as very good or excellent. 54% of youth said that Range Camp influenced their decision to pursue a college degree in Rangeland or Natural Resources and 56% said that it influenced which university they chose to attend. Utah State University, Southern Utah University, and Snow College were the higher institutions that Range Camp Participants attended. 39% of respondents said that they applied for a range related internship because of Range Camp. 83% of those who completed a range internship went on to work in a range related field and 73% responded that range camp influenced who they chose to work for. The employers listed are the United States Department of Agriculture, Bureau of Land Management, United States Forest Service, National Park Service, Natural Resource Conservation Service, and private ranches. 100% of those working in a range related career noted that Range Camp helped them be a better rancher or range manager. 100% of survey participants responded that Range Camp has positively influenced their current career choice and has helped them to positively contribute to society and the rising generation. All survey participants noted that they still use knowledge gained from Range Camp.

Discussion

Only an estimated 5% of Range Camp attendees completed the survey. Until 2016, data was not collected from the participants and the majority of the attendees contact information listed were school emails that became invalid after the students graduated. Most of the results were gathered by locating previous attendees via Facebook Messenger. Some survey applicants were reached through the Utah SRM email list serve, however, this would only reach individuals that are currently involved in rangeland management within the state of Utah. Moving forward, camp participants will be asked to fill out contact information using their personal emails in hopes to gain more long-term data on the camp. Although part of Range Camp is to help students do better on FFA competitions, very little information is had as to whether Range Camp has consistently helped with this goal. At the 2024 Utah Range FFA Competition, seven of the top ten individual winners and 5 of the top ten teams participated in Range Camp. At the 2024 Western National FFA Competition, one of the top ten individuals and one of the top ten teams attended Range Camp. These results will be followed more closely in the future. Range Camp has proven to be an important recruitment tool for colleges and employers. Only the employers and colleges that frequently send a representative to Range Camp benefit from recruiting these students. This information will be used to help increase participation from other employers and higher institutions. Another key note is that those students who pursued a range related internship clearly had more success in obtaining a career in range management, this underlines the importance of internships. In conclusion, Range Camp has successfully aided students in pursuing higher education and range related careers and has positively represented range management practices to individuals not involved with rangelands.

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Drylands Summer School: a pathway from training to a community of professionals

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Key words: drylands; school; monitoring; agrosilvopastoralism; global

Abstract

Forests and agrosilvopastoral systems in drylands contribute to landscape resilience and environmental sustainability. They support species adapted to harsh ecological conditions and provide essential goods and ecosystem services, as well as enhanced resilience for dryland communities. When sustainably managed, they can alleviate poverty, ensure food security and improve livelihoods worldwide.

Drylands and rangelands are home to over 2 billion people globally but face significant challenges, including land conversion, climate change, unsustainable practices and poorly designed restoration programmes. The Food and Agriculture Organization of the United Nations (FAO) Drylands Programme, under the mandate of the Committee on Forestry Working Group on Dryland Forests and Agrosilvopastoral Systems (COFO WG), addresses these challenges by promoting good practices for the sustainable management, protection and restoration of drylands.

The only subsidiary body of the Committee on Forestry working specifically on dryland forests, the COFO WG is fostering resilient dryland ecosystems by training experts to drive transformative policymaking and management through its Drylands Summer School initiative, which builds a global community of practice through its participatory training programmes.

The Dryland School initiative explores transformative approaches to building climate-resilient dryland systems. The inaugural Drylands Summer School, held in Amman, Jordan, in 2023, equipped 22 participants from diverse dryland regions with tools to enhance resilience, focusing on context-specific solutions and monitoring progress through cross-cutting indicators. The second edition, hosted at the CIFOR-ICRAF (Center for International Forestry Research and World Agroforestry) Campus in Nairobi, Kenya, on 12–15 September 2024, expanded this effort with an enriched curriculum and a field trip to showcase practical applications of monitoring drylands and agrosilvopastoral systems towards climate change and sustainability.

Introduction

The Dryland School series addresses the critical need for transformative management of drylands. Currently, the dry areas of our planet are becoming increasingly vulnerable to climate change and unsustainable practices, leading to decreased production and land degradation. By training experts to drive policy, management and restoration shifts, the initiative fosters a shared vision for resilient dryland systems.

The Second Drylands School, titled “Monitoring Restoration in Agrosilvopastoral Systems for Sustainability and Ecosystem Services”, aimed to enhance participants' capacities to monitor, evaluate and provide feedback on sustainable dryland management practices. Its specific objectives were to: (1) deepen understanding of challenges and participatory approaches in managing dryland agrosilvopastoral systems; (2) adapt and apply monitoring frameworks for sustainable management and restoration; (3) co-define indicators with local stakeholders and gather field data; and (4) promote knowledge exchange and establish a long-term community of practice.

Methods

The Second Drylands School was a dynamic four-day programme, held on 12–15 September 2024 at the CIFOR-ICRAF Campus in Nairobi, Kenya. It included a one-day field trip and was facilitated by a dedicated CIFOR-ICRAF team with technical support from FAO and partner organisations. Emphasising experiential learning, the course placed participants’ knowledge and experiences at the core of the curriculum, following a well-structured “storyline” to ensure logical progression and continuity.

As part of the selection process, participants submitted case studies of their work, which were further developed during the course. Participants were also required to complete FAO's e-learning course on dryland forests and agrosilvopastoral systems. The curriculum blended theoretical knowledge with practical, hands-on activities, incorporating diverse formats such as technical lectures, group discussions, individual exercises, peer-to-peer learning and outdoor activities. This variety created an engaging and interactive environment, with the programme’s technical focus fostering in-depth and productive discussions.

The programme comprised seven dedicated sessions led by experts, addressing critical issues in dryland monitoring and management. These included monitoring frameworks, tools and approaches, design and implementation of indicators, and adapting monitoring strategies to pastoralist communities. The first day introduced the principles of monitoring drylands, during which participants shared their individual case studies and action plans. The second day focused on sustainability indicators and frameworks, with participants working in groups to refine their plans.

The third day featured a field trip led by the Kenya Forestry Research Institute’s (KEFRI) Dryland Eco-Regional Research Centre in Kitui. Participants visited the KEFRI Tiva Woodland Conservation site to learn about dryland restoration technologies, a commercial forest farmer in Kabati, and the Kyawean Community Forest Association’s restoration efforts in the Kyawea Forest Landscape. This hands-on experience highlighted practical application of dryland monitoring and restoration techniques.

On the final day, the programme explored scaling-up monitoring from local site-level efforts to global surveillance, featuring citizen data-collection practices. Participants shared their refined action plans and visions during group sessions, culminating in a discussion of future opportunities, such as the International Year of Rangelands and Pastoralists (IYRP2026), the upcoming International Rangeland Congress in Adelaide, Australia, and the third edition of the Drylands School.

The Second Drylands School was strategically scheduled before the Global Landscapes Forum (GLF) Africa event on 17 September 2024 at the CIFOR-ICRAF campus. During GLF Africa, the FAO team presented the outcomes of the Drylands School, showcasing its success.

The course fostered a positive and collaborative atmosphere, encouraging innovative and forward-looking discussions. Participants from diverse institutional affiliations and professional backgrounds actively shared experiences, enriching discussions and fostering mutual learning. Structured sessions enabled critical reflection on personal projects, promoting the enhancement of participatory monitoring practices.

Networking and experience-sharing were central to the programme, with participants exchanging insights and receiving peer feedback. These efforts aimed to build a global community of practice in dryland restoration, supported by the adaptation of established participatory monitoring and evaluation (M&E) protocols. By equipping participants with actionable tools and methodologies, the Drylands School strengthened their capacity to address the complex challenges of dryland restoration and management.

The Second Drylands School itself followed an M&E procedure led by the organisers and supported by a daily session of recap and reflection, with a final evaluation session completed by means of an online survey sent after the school ended. The evaluation survey was structured into five categories: ‘Global item’, ‘Organization’, ‘Methodology and program’, ‘People’ and ‘Logistics’ (see Figure 1).

Results

The Second Drylands School marked a significant milestone in a larger, long-term initiative to foster transformative dryland management. Participants developed personal action plans during the course, tailored to apply the knowledge and skills gained, and were encouraged to implement these plans in their work. The programme emphasised sustaining momentum by encouraging participants to apply their learnings actively and to champion dryland restoration efforts.

The results of the evaluation survey show how the participants considered the Drylands School to have been a memorable and fruitful experience. The organisation and efforts to make the stay enjoyable were highly appreciated. The event was rated as well organised, and the attendees appreciated the selection of participants based on diversity of backgrounds and experiences, which allowed deep exchange in the sessions and networking. Participants expressed pride and satisfaction, noting improvements in their project management skills and understanding. Figure 1 summarises the results.

Figure 1. Results of the evaluation survey, based on answers by 19 participants

To support continued engagement, plans are underway to establish an alumni network, linking participants in the second Drylands School with those in the inaugural one. This network aims to foster ongoing collaboration, knowledge sharing and professional growth. Participants were also encouraged to leverage their participation in the Drylands School to enhance their professional profiles and advocate for improved dryland management practices globally.

Discussion and conclusions

The 2024 Drylands School highlighted the complexity of dryland ecosystems and emphasised the importance of a landscape approach that integrates both physical and socio-economic dimensions of resource management. Effective dryland management requires consideration of diverse factors, including plants, soil, water, tenure security, livestock and economic dynamics, with careful negotiation of trade-offs between production and conservation.

A focus on monitoring emerged as a critical yet complex component of sustainable management. Participants were introduced to a wide array of tools, methodologies and communities of practice spanning local to global levels. The selection of appropriate monitoring tools depends on the specific challenges being addressed and the geographic scale of application. Participatory monitoring was particularly emphasised for its role in fostering ownership and ensuring relevance. Developing SMART (Specific, Measurable, Achievable, Relevant, Timely) indicators remains a challenge, particularly for integrating indigenous knowledge, which often informs local decision-making and management practices. Transparent organisation of data and information was underscored as essential for effective monitoring.

Field observations, validation and verification were identified as integral to successful monitoring efforts, alongside the involvement of local communities to ensure ownership, validate findings and align priorities with local needs. The course also underscored the need for combining top-down and bottom-up approaches to dryland management, ensuring that national and provincial policies are informed by field realities and that grassroots initiatives are scalable within policy frameworks.

The deliberations emphasised that addressing livelihood aspects of sustainable dryland management is often more complex than managing physical components. However, building on lessons learnt and success stories offers significant opportunities for progress. Ultimately, achieving resilient and sustainable dryland ecosystems requires an integrated, participatory and adaptive approach that bridges local realities with broader policy frameworks.

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As well as being a partner, the UNCCD G20 Global Land Initiative was the main sponsor of the Drylands School, and the Community Jameel funded the field trip.

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Color country natural resource camp – teaching high school students about natural resource career opportunities

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Keywords: Natural Resources, camp, career, outdoors

Abstract

The overarching goal of Color Country Natural Resource Camp (CCNRC) is to give participants an opportunity to learn, in a hands-on environment, about career paths in the natural resource field. At the five-day camp, participants spend four hours every day in "Investigations" over the period of five days, these investigations facilitate learning about the areas of vegetation, soils, land use, aquatics, and wildlife with an instructor who works in these fields. This camp has been evaluated every year, with results showing positive youth development in all the investigation areas with a greater appreciation for recreational activities. In 2024, participants were evaluated on their intent to pursue a natural resource career and revealed significant increases in campers' understanding of natural resource topics and familiarity with career paths in the field. However, there was no significant change in immediate career interests, with the exception of increased interest in soil-related careers.

Introduction

CCNRC was created in 1993 and currently just completed its 31st year. This camp is managed by Utah State University (USU) Extension in partnership with the Utah Division of Natural Resources, Red Cliffs Desert Reserve, local Bureau of Land Management and Forest Service representatives, and other specialists at USU Extension from around the state of Utah. The purpose of this camp is to help participants explore career fields in natural resources in the areas of land use, aquatics, wildlife, soil, archaeology, soil, and vegetation. Currently in the United States, these careers are not taught or highlighted in our high schools (secondary schools). The National Science Board (2014) noted that the number of college students enrolled in the sciences has been steadily declining since 2010. Conversely, the demand for more scientists and experts in natural resources, particularly renewable energy, continues to grow (Frey and Parent 2019). From our work in other fields and youth camps, we know that youth's interest in a subject matter often improves once they have hands-on opportunities in those areas. CCNRC also educates participants on outdoor recreation opportunities, depending on the year and location, can include archery, rifle shooting, horseback riding, rock climbing, rappelling, hiking, wilderness survival, mountain biking, and orienteering. This camp hosts up to 35 high school-aged youth and is held at one of three remote campsites for five days each year.

The objectives of the program, starting in 2024 are:

1. Evaluating changes in participants' knowledge of natural resources before and after attending the camp.

2. Measuring the level of interest in natural resource-related higher education and careers among campers.
3. Determining the influence of camp experiences on career and educational decisions.

Methods
To evaluate the camp's effectiveness, we implemented a Pre- and Post-Camp Survey Design. Surveys were administered at two points: (1) before the camp began (pre-camp survey) to establish a baseline and (2) after completing all camp activities (post-camp survey) to assess changes in knowledge, interest, and career aspirations.

The **Pre-Camp Survey** measured participants' initial understanding, interests, and aspirations in natural resources using a Likert scale to gauge agreement with key statements. The **Post-Camp Survey** mirrored this structure, enabling direct comparisons to identify shifts in attitudes and knowledge.

Both surveys combined quantitative and qualitative methods. The Likert scale responses provided measurable data, while open-ended questions captured deeper insights into participants' interests and experiences. Example questions included: *"What specific natural resource fields interest you?"* and *"What did you hope to gain from the camp experience?"*

Data analysis involved descriptive statistics (means, standard deviations) and inferential statistical tests (p-values) to determine significant changes over time. A **95% confidence interval** was used to assess statistical significance. Qualitative responses underwent thematic analysis to identify recurring themes in participants' interests and career aspirations.

The study aimed to determine whether the camp significantly influenced participants' understanding of natural resource topics, interest in higher education, and career aspirations. Survey questions were categorized into three areas: **(1) Personal Statements, (2) Subject Understanding, and (3) Interest in Natural Resource Careers.**

Results
Personal Statements The interest in pursuing higher education showed a slight increase from a pre-camp mean of 3.83 to a post-camp mean of 4.04, with a mean difference of 0.21. However, this change was not statistically significant (p-value: 0.4264), suggesting that the camp did not substantially impact this aspect. Similarly, the interest in a career in natural resources increased marginally from a pre-camp mean of 3.50 to a post-camp mean of 3.57, with a mean difference of 0.07, and this change was also not statistically significant (p-value: 0.77). In contrast, there was a significant increase in familiarity with career paths in natural resources, from a pre-camp mean of 3.46 to a post-camp mean of 4.13, with a mean difference of 0.67 and a p-value of 0.014. This indicates that the camp effectively enhanced campers' awareness and understanding of career opportunities in this field.

Qualitative Data Analysis
Summary of Pre- and Post-Survey Results To assess the impact of the camp on participants' knowledge and interest in natural resources, we compared pre- and post-survey responses. Statistical significance was determined using a **p-value threshold of 0.05**, indicating meaningful changes in participants' understanding and interests. (See Table 1).

Key Findings: Several areas showed statistically significant increases in knowledge:

- Familiarity with career paths in natural resources ($p = 0.0139$)
- Environmental science ($p = 0.0074$)

- Natural resource conservation principles (*p* = 2.201E-05)
- Outdoor recreation management (*p* = 0.0041)
- Soil (*p* = 0.0306)

Table 1

Comparison of Pre-Survey and Post-Survey Responses on Campers' Knowledge and Interest in Natural Resources

Question	Pre-Survey	Post-Survey	Difference	P-Value
I want to pursue higher education	3.83	4.04	0.21	0.4263
I am interested in a career in the field of natural resources.	3.50	3.57	0.07	0.7682
I am familiar with the various career paths available in the field of natural resources.	3.46	4.13	0.67	0.0139
Environmental science	3.12	3.88	0.76	0.0074
Natural resource conservation principles	2.84	3.96	1.12	2.201E-05
Outdoor recreation management	3.04	3.92	0.88	0.0041
Water	3.76	3.92	0.16	0.4493
Wildlife Biology	3.76	3.96	0.20	0.4285
Plants/Vegetation	3.52	3.58	0.06	0.8362
Soil	2.84	3.54	0.70	0.0306

The survey also assessed campers' interest in natural resource activities (e.g., clubs, volunteering) and careers, with responses categorized as Yes, No, or Unsure. Results showed a significant post-camp increase in participation interest: campers interested in natural resource activities such as volunteer work, clubs, camps, and recreation, doubled from 8 to 16, while those uninterested dropped from 13 to just 1, indicating a strong positive impact (Figure 1).

However, career interest followed a different trend. The number of campers interested in natural resource careers decreased from 4 to 2, while those uninterested dropped from 8 to 4. Notably, the number of "Unsure" responses increased from 12 to 17, suggesting that while the camp deepened awareness and understanding, it also exposed the complexities of these careers, prompting some campers to reconsider their options (Figure 2).

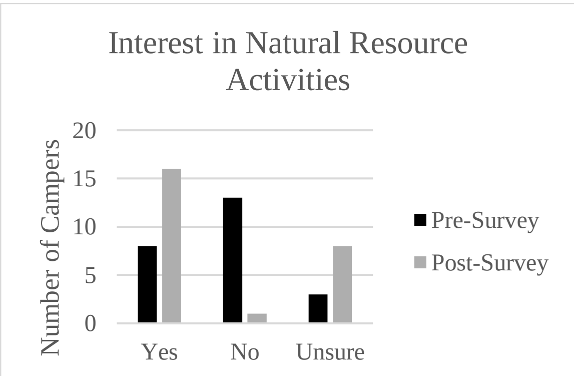

Figure 1: Evaluation results for interest in natural resource activities, such as volunteering, clubs, and recreation.

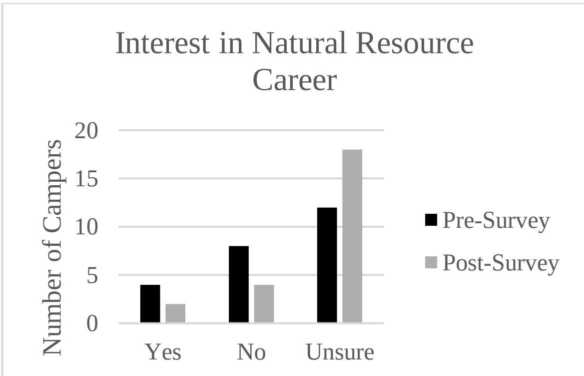

Figure 2: Evaluation results for interest in natural resource careers

Discussion

These results suggest that the camp effectively enhanced participants' understanding in these subject areas. However, changes in interest in higher education, career aspirations in natural resources, and knowledge of water, wildlife biology, and plants were not statistically significant ($p > 0.05$). While some areas showed slight increases, the results indicate that further engagement or long-term exposure may be needed to influence career and educational aspirations. Some ideas that we have had about camp as we move it forward is to involve more public speakers/demonstrations at camp that would showcase the various public land management organizations in the United States and incorporating more engaging hands on activities for the areas that scored lower.

Overall, the findings suggest that the camp successfully improved participants' knowledge in key natural resource topics, reinforcing its educational value. It is exciting to see that participation in this camp helps to change perceptions on natural resource careers in an overall positive way.

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Informed policy & governance + women empowerment and leadership in rangelands

XII INTERNATIONAL RANGELAND CONGRESS AUSTRALIA 2025

Policy engagement to enhance future American rangeland systems: implications for the IYRP 2026

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Key words: Loss of rangeland social-ecological systems; rangeland-relevant legislation; Society for Range Management

Abstract

The purpose of this paper is to explore issues that American rangeland professionals regard as most important in supporting sustainable rangeland systems. Impetus for this work is provided by the pending International Year for Rangelands and Pastoralists (IYRP), to be celebrated in 2026. One of the goals of the IYRP 2026 is to raise awareness about the challenges facing global rangelands. The American situation described here provides one example we can learn from. The objectives of this work include: (1) Summarizing recent findings from surveys and workshops conducted during 2022 to 2024 where the participants—largely members of the Society for Range Management (SRM)—ranked priority rangeland problems to be tackled; (2) reviewing historical and current aspects of policy environments that affect contemporary problem-solving on American rangelands; and (3) clarifying how progress in policy-related problem solving could be linked to the IYRP 2026. Findings are summarized as follows: (1) American range professionals see loss of rangeland systems as the key challenge, and interventions are needed to preserve open spaces and support new generations of resource users; (2) improved policy making and stakeholder collaborative processes are the main interventions to address these key challenges; (3) recent policy opportunities abound at local, state, and federal levels that could promote sustainable rangeland systems, but how best to engage policy making and document impacts remains somewhat of an enigma; and (4) in the context of action planning for IYRP 2026, it is proposed that a process of generating political proclamations that underscore the multiple values of rangelands to society are a useful first step that can better connect SRM sections to local and state-level political entities.

Introduction

Policy can be defined as "a course or principle of action adopted or proposed by a government, party, business or individual" (Anon 2024). Policy is complex and embraces many levels of engagement. In the USA, this includes players such as the federal, state, and local governments. Various policy objectives can be complementary or contradictory. Despite that policy is very important for rangeland preservation and stewardship, attention devoted to policy by stakeholders is surprisingly limited, especially in the world's more affluent nations (Holechek 2013). One major reason for this is the strongly eco-centric orientation of range science and management. Tertiary education in natural resources at American Land Grant universities has been founded on conveying technical aspects of vegetation assessments and livestock production; policy is typically left to social science departments rarely engaged by applied ecologists.

In the run-up to the International Year of Rangelands and Pastoralists (IYRP) 2026, a multi-faceted approach has been embraced by rangeland advocates and change agents tackling a wide array of ecological and social issues (IYRP 2024). Awareness-raising among key stakeholders, the public, and political decision makers is a prominent goal. As part of this effort, work was undertaken here to help clarify a policy environment for American rangelands so that an action agenda can be formulated in support of sustainable rangeland systems for the future.

Methods

Materials summarized here were created from 2022 to 2024 based on several approaches. Modest numbers of email surveys and several workshop deliberations, largely involving members of the Society for Range Management (SRM), were mined for policy-relevant information. Text from key aspects of draft federal legislation was reviewed. State-level perspectives have been focused on Utah, a classic example of a western, public-land entity where a small percentage of the landscape is under private ownership; the Bureau of Land Management (BLM), US Forest Service (USFS) are the federal stewards of most of the remainder (Leydsman-McGinty 2009). These efforts in tandem represent only a very preliminary, exploratory, qualitative synthesis that may help rangeland stakeholders chart a way forward for more effective policy engagement.

Results

National SRM Email Surveys and Workshop Deliberations

An email survey was sent to all 21 SRM sections (SRM 2024) during September and October 2022. In theory, this survey reached hundreds of potential respondents. Questions were open-ended and asked people to identify priority challenges facing rangelands as well as priority interventions to address the challenges. There were only 13 completed surveys submitted by Americans, with another 23 from Canadian and Mexican SRM members. Key results from the Americans are shown in Table 1. While the survey response rate was poor, results were broadly validated by over 50 participants at a follow-up workshop in February 2023, held at the annual SRM conference at Boise. Furthermore—although not emphasized here—data collected from Canadian and Mexican respondents were generally similar as well. In sum, it was concluded that the prominent gaps overall focused on the need for more effective policies, expanded outreach, education, and strengthened stakeholder networks.

Table 1. Top five challenges and intervention priorities (ranked) for American rangelands as revealed by 13 SRM stakeholders in 2022

Priority Challenges	Priority Interventions
1 Loss of rangeland systems	1 Policies preserving rangelands and livelihoods
2 Public and policy makers uninformed	2 More public and policy outreach needed
3 Climate change and ecological problems	3 Strengthen management at local levels
4 Better manage expanding recreation	4 Need to update federal regulations
5 Engage more resource users	5 Need to improve stakeholder networks

Utah Section SRM Group Discussions

Another effort to seek feedback on priority actions needed to sustain rangelands more locally was provided by an annual meeting of the SRM Utah section during November 2023. Forty-five attendees were assigned into nine groups of five people each for 30-minute discussions. Results were ranked with up to three categories, scored from most to less important (i.e., 3, 2, 1), and summarized. The top two needs for action in Utah were: (1) Developing more effective stakeholder networks on projects of mutual concern (16 ranked points overall), and (2) improvement of state and federal collaborations (15 ranked points). Four other needs followed more distantly, including: (1) Improved management of outdoor recreation (8 points); (2) expansion of public education concerning rangelands (6 points); (3) improvement of internal agency management processes (i.e., staffing and priority setting) for the BLM or USFS (6 points); and technical aspects of rangeland management and resource monitoring (5 points).

Historical Policy Environment

The foundational policies that still influence contemporary resource access and use in the rangelands of the western USA were first enacted over 150 years ago (Holechek et al. 2011). A vast, unsettled landscape governed by territories comprised most of the national endowment West of the Mississippi River. Federal Acts from congress relevant to rangelands began with the Homestead Act (1862) that allocated 160-acre parcels to people to encourage farming and the acquisition of private land. The Transcontinental Railroad Act (1862) promoted rural development, emigration, and market development. Government was slow to realize, however, that only small segments of land in the West were suitable for cultivation, hence grazing issues per se received little attention until later. Attempts to amend policies to enlarge homestead sizes or incorporate stock-raising on farms led to resource degradation because fodder resources were mismatched with livestock production needs.

The Forest Reserves Act (1891) and the Taylor Grazing Act (1934) enabled newly minted federal entities to control access to remaining public lands by curbing indiscriminate logging and overgrazing. Today, for example, ranchers in the western USA often graze livestock on a combination of private and public lands. Access to the latter is governed by permits for the use of allotments that are regulated to promote more sustainable utilization of forage. Agencies that oversee this resource use include the US Forest Service (USFS) at higher elevations and the Bureau of Land Management (BLM) at lower elevations. The USFS and BLM remain very influential in Utah.

Current Policy Environment

Using the State of Utah as an example, it is fair to say that there is considerable political tension today between state interests and federal interests concerning access to, and use of, rangeland resources. This occurs over a backdrop where the State of Utah controls roughly 20 percent of the state's land area and the US government controls most of the remainder. To illustrate conflict, for example, the State of Utah has recently sued the federal government for control over BLM lands (Schoenbaum and Brown 2024). This effort is a rekindling of past litigation; legal experts contend that the current lawsuit has little chance for success. There are other avenues for federal policy intervention for Utah rangelands. A prominent example is the omnibus Farm Bill, renewed every five years since the 1930s (Myers 2022). Traditionally the Farm Bill has not given much attention to rangeland, but this is changing. SRM submitted remarks in 2023 for the current update of the Farm Bill that is still ongoing (Reini, pers. comment). Requests from SRM include more Farm Bill support for: (1) Range conservation programs—including federal match for establishing land trusts; (2) innovative management technologies; (3) specialized education for range users including facilitation of intergenerational transfer of ranch operations; and (4) strengthening federal land-management agencies. Other range-relevant federal legislation has recently received attention, including the bipartisan North American Grasslands Conservation Act, introduced in the US House of Representatives in October 2024 (NAGCA 2024). The goal of the NAGCA is to foster landowner driven, voluntary, incentive-based programs to help conserve and restore over 125 million acres of critically imperiled grasslands and associated ecosystems, also with attention to livelihoods that includes farmers, ranchers, recreationists, and Native Americans. The focus of the NAGCA is on private lands. Administrative details of the NAGCA remain under debate. Extended congressional delays for both the Farm Bill and NAGCA are expected under the current atmosphere of political uncertainty (Reini, pers. comment).

Again, using Utah as an example, there are state- and local-level policies and actions targeted towards rangelands. The UGIP (Utah Grazing Improvement Program) funded by the Utah Department of Agriculture and Food, has provided support for ranch-level resource management innovation for almost 20 years (UGIP 2024). The UGIP is also under consideration for expansion into neighboring states given the success in Utah. Recent Utah legislation illustrates a novel embrace of ecosystem-level perspectives concerning sustainable management of the Great Salt Lake (GSLR 2024). Efforts to divert more water to the lake will ultimately have implications for water conservation on rangeland landscapes for both public and private lands. The need to recruit the next generations of ranchers seems to be addressed, at least in part, via educational outreach programs sponsored by the Utah Farm Bureau Federation, an NGO (UFBF 2024). Finally, local (county level) actions in the form of voter-approved bonds have recently taken hold in a few areas where peri-urban or ex-urban development threatens open space. Bond funds are used to purchase conservation easements (CC 2024).

Discussion and Conclusions

Feedback from national and local (Utah) sources suggests that dominant challenges for rangelands are social rather than technical in nature. The national input amplified policy and outreach to promote sustainable rangeland systems. The Utah input, in contrast, noted more need for improved stakeholder networks and inter-agency collaborations on-the-ground. This distinction between national and Utah perspectives makes sense. Honing this down further one might surmise in a synthesis that interventions are needed to preserve working rangeland landscapes, because failure to do so means that social-ecological systems will collapse. Policy-scale actions can help conserve land and fortify a new generation of resource users. Local-scale actions like stakeholder engagement and improved inter-agency collaborations play support roles in this process.

If we “connect the dots” between the synthesis above and elements of the current policy environment, several aspects of each seem to match up; it appears there is momentum towards increasing policy awareness about rangelands in the USA. Recent efforts at the federal level to raise the profile of rangelands in the Farm Bill as well as submission of a Grasslands Act are both timely. Of note is the potential provision of more money in the Farm Bill for the purchase of conservation easements via match from the McAllister Fund; lack of such resources makes open-space acquisition in Utah a struggle (Snider, pers. comment). The possibility of funding support for grassland conservation more broadly in the context of the Grasslands Act has even greater national implications. That state legislators in Utah now debate regionally scaled management of the Great Salt Lake is also encouraging.

How do these findings relate to the IYRP? A major goal of the IYRP is to raise awareness about rangelands worldwide among policy makers and the public (IYRP 2024). One impression from this work is that while rank-and-file SRM members appreciate the need for helpful policies to better navigate the future, there are few examples of SRM members actively engaging policy makers. Documenting policy impact thus becomes difficult at best. Policy engagement, rather, is left to NGOs and special interest groups. At the February 2025 annual meeting of SRM at Spokane, WA, a symposium will craft an IYRP action plan for North America. One of the key components of the action plan will focus on creation and delivery of short proclamations for political leaders in local and state governments. Editable templates will celebrate rangeland values for the public. Each SRM section will connect with policy makers to enable this process to occur, helping to build policy-relevant capacity for SRM. Other efforts are being made to bridge gaps between policy makers and SRM at state and federal levels (Reini, pers. comment). This all captures the spirit of the IYRP.

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Adapting decent work (SDG 8) for sustainable pastoral systems: meanings and challenges of decent work for Mongolian herder women

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Key words: gender; International Labour Organization (ILO); pastoralist identity; sustainable pastoral systems; herder women's empowerment

Abstract

The UN Sustainable Development Goal 8 includes "decent work for all" as a sustainable, inclusive economic growth component. The International Labour Organization (ILO) defines decent work as productive in conditions of freedom, equity, security and human dignity. Yet, almost no research or development initiatives have considered how decent work applies to pastoral systems. Therefore, we explore the meanings of "decent work" for women herders in Mongolia and compare these meanings with the ILO's criteria. We facilitated two workshops with women specifically focused on decent work (n=34) in 2023. For Mongolian herder women, "decent work" means "meaningful work" related to their cultural heritage, pastoralist identity, personal satisfaction, and the interdependent health of land, livestock, and people. "Opportunities for learning and professional development" also emerged as a key meaning not captured in existing ILO standards. Herder women face numerous barriers to decent work conditions, including long working hours, caregiving responsibilities, social isolation, domestic violence, lack of social and health services support, and limited alternative employment opportunities. Yet, ILO's decent work indicators and Mongolia's legal frameworks fail to address these issues adequately. This exploratory research highlights the mismatch between ILO's generic decent work criteria and indicators and the lived reality of pastoralism. Given the paucity of decent work research in pastoral systems, this study has broad relevance to pastoral systems globally as governments, donors and NGOs consider how to support socially just and sustainable pastoralism.

Introduction

The concept of "decent work" is defined as "productive work for women and men in conditions of freedom, equity, security, and human dignity" (Oya 2015, p.8). According to the ILO (2018), promoting jobs and enterprise, guaranteeing rights at work, extending social protection and promoting social dialogue are the four main pillars of decent work. With the help of these pillars, all workers should be able to access social security, fair pay, safe working conditions, and the opportunity to influence decisions that impact their professional lives (Aufderheide et al. 2013). Yet, putting these ideas into practice can be difficult, especially in the rural and agricultural sectors. Employment in rural areas is often seasonal and informal, so the ILO's indicators and standards frequently fail to adequately address these conditions. These difficulties are made worse in the case of mobile pastoralism, especially among women. Women pastoralists are responsible for reproductive labour (child rearing and household management) and productive labour (herding and processing livestock products), as well as community roles. These overlapped responsibilities are frequently unacknowledged and unpaid, which makes it more difficult to implement decent work standards (Köhler-Rollefson 2012). At the same time, the growing global emphasis on sustainability in rangeland management is making the issue of decent work for pastoralists increasingly relevant. Furthermore, both the International Year of Rangelands and Pastoralists (IYRP2026) and the newly adopted International Year of the Woman Farmer (IYWF2026) highlight the challenges and importance of women's roles in pastoralism.

In this article, we address a gap in the literature on decent work in pastoral settings, focusing on Mongolian herder women. This study uses qualitative research methods to illuminate what decent work means to Mongolian women herders and the challenges to achieving it. We also aim to contribute to a deeper understanding of the lived experiences of herder women in Mongolia and to suggest actionable implications that respond to their specific needs in achieving decent work.

Methods

We organised participatory workshops with 34 herder women aged 20–70 in two provinces, Arkhangai and Bayankhongor, each with distinct ecological environments. Arkhangai lies in the Khangai Mountain region, with rich pastures and dairy production. In contrast, much of Bayankhongor lies in the Gobi desert-steppe zone, where cashmere from goats is a primary source of household income. In the workshops, we used the World Café method (Löhr et al. 2020) to foster deeper discussions on specific questions related to decent work. Discussions were audio-recorded, transcribed, translated into English and analysed using grounded theory (Charmaz 2006). Data analysis began with open coding, generating 165 initial codes, redefined to 291 after a second review of coding. We then conducted axial coding, connecting codes to create key concepts that define "decent work." In the final stage, we organised axial codes to identify a theoretical framework with nine main meanings of decent work as explained by herder women.

Results

The nine key meanings of "decent work" for Mongolian women herders identified through participatory workshops reflect cultural identity, a sense of responsibility for herd and pasture health, and economic and social aspirations.

1. **Meaningful Work:** Meaningful work for women herders is work that inspires pride in one's occupation and provides physical and mental enjoyment of one's herding lifestyle. During workshops, a woman herder expressed "*Decent work is work that fulfils the mind, body and economy of the household"* (Bayankhongor, May 2023). Pastoralism is a way of life, identity, culture and tradition, and these meanings are critical to a sense of purpose and dignity.
2. **Healthy Land:** The health of livestock, herders' livelihoods, and the long-term persistence of their nomadic lifestyle depend on healthy and productive pastures. This dedication to environmental sustainability includes avoiding excessive grazing by moving seasonally, safeguarding nature, and guaranteeing the land's ability to sustain its herds in a healthy pasture. Furthermore, healthy land is deeply connected with the Mongolian cultural concept of *nutag* (homeland) as an interconnected web of land, livestock, people and other more-than-human beings (Baival 2012, Ichinkhorloo 2017). Moreover, in contemporary Mongolian, the word *nutag* also fluidly embodies a much wider range of things and ideas, such as the environment, nature, resources, history, origin, authenticity, identity, sovereignty and spirituality (Bumochir 2019). Women herders acknowledge their cultural role in the countryside and identify themselves as custodians of the land.
3. **Healthy Livestock:** The health of their herds directly impacts herders' economic stability, as healthy livestock produce high-quality products that lead to a stable income. For centuries, herder women have been taking care of their livestock, preparing for natural disasters, tending baby animals and maintaining the overall wellbeing of their livestock. Additionally, most of their household income comes from livestock products, including dairy products and cashmere, which are made by women herders. During the workshop, participants stated *"…Our livestock should be fat and strong [healthy] so that the prices will go up"*; on the other hand, another participant said "*These cattle are your cash; sheep are your pennies*."
4. **Sufficient and Stable Income:** A sufficient and stable income is a key element of decent work globally, including for herder women in Mongolia. Herder livelihoods depend on environmental conditions and are

vulnerable to drought and winter weather disasters, and livestock income is highly seasonal. Herder women emphasised their interest in adding value to raw livestock products to market them at higher prices. To facilitate this, appropriate training and, in some cases, machinery (e.g., butter churns, knitting machines) are essential. Women also spoke of the need to diversify rural economies to include alternative, non-herding jobs, especially for young people.

5. **Human Health and Safety:** Women herders mentioned having a healthy body is essential to their daily lives. Ensuring a healthy body and human safety requires the ability and resources to care for personal and family health, such as regular medical check-ups and access to adequate community health services, including local hospitals, and safe working conditions.
6. **Social Safety Net and Welfare:** The existing legal framework in Mongolia characterises herders as self-employed individuals, accommodating them in the voluntary social insurance scheme (ILO 2024). To get unemployment benefits, pensions and other social protection services, herders must pay their taxes accordingly. However, in 2020, the social insurance coverage rate for Mongolian herders was 16.4%, and health insurance coverage was 25.1%, although mandatory (ILO 2022). According to women herders in both workshops, an incomplete understanding of social and health insurance schemes leads to a lack of enrolment and payment, resulting in a lack of coverage and social protection services.
7. **Opportunity for Professional and Personal Development:** Women herders seek professional and personal development opportunities that allow them to improve their skills in value-added product processing, adapt to new technologies, and face daily challenges. Many mentioned that "*khorshoo*" (cooperatives) play a key role in supporting herders to work together and overcome challenges. Women also expressed interest in leadership and literacy training.
8. **Social and Cultural Participation:** Many herder women experience social isolation due to their remote locations and home-based care work. Participating in community social and cultural activities helps women feel engaged with society and a part of their community. Participating in these events also gives them the chance to network with other herders to accomplish common goals, like preparing hay and feed together, and exchanging livestock and human health-related traditional and practical knowledge.
9. **Herders' Rights:** Last but not least, herder women highlight legal protections for herding communities, including the rights to education, healthcare, pension support and protection of pastures. They advocate for government investment in local economies, ensuring fair rights and opportunities for all herders. Furthermore, culturally nomadic people move seasonally to keep their pasture and animals healthy; thus, they highlight the right to move freely in the countryside. One woman mentioned: "*We have freedom. We can move wherever we want"* (Bayankhongor, 2023). Therefore, it is important to acknowledge their cultural and human rights at the same time to maintain sustainable pastoralism.

Discussion

Mongolian herder women hold a holistic view of decent work that integrates the health and wellbeing of humans, livestock and the environment as interdependent elements. Furthermore, women herders' experiences highlight the need for gender-sensitive approaches within decent work standards. Pastoral women's triple-burden workload—care for home, including children and family members; care for animals and product processing; and care for the community—significantly impacts women's health and may contribute to rural gender imbalances that threaten pastoralism's future (Köhler-Rollefson 2012, FAO 2023, Fernández-Giménez et al. 2024). Our findings align with research that emphasises the challenges many pastoralist women face, including limited access to productive resources, adaptation to climate change and the undervaluation of their work, and therefore the need for gender-sensitive policies that address the inequities (Anbacha & Kjosavik 2019, Po & Hickey 2018, Wangui 2014, Flintan 2008). Literature on rural social protection emphasises the importance of adapting social safety nets to the unique risks faced by rural women, whose contributions to pastoralist households often go unrecognised (Po & Hickey 2018).

To conclude, Mongolian herder women's understanding of decent work extends beyond ILO's four pillars—productive work, rights, social protection and dialogue—by highlighting *meaningful work,* the *interdependence of healthy land, livestock and people* in pastoral work settings, and women's desire for life-long *professional development opportunities.* These additions highlight the importance of intertwined occupational and cultural identities. In supporting herders' holistic vision of decent work, we recommend that ILO standards reflect the interconnected health of people, livestock and land and address social issues specific to herding community cases, as there is a broader challenge in operationalising decent work standards and indicators in rural and smallholder agricultural systems throughout the world (Oya 2015).

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Developing a community-based rangeland health system in Ethiopia

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Key words: Pastoralism, Participatory approach, One Health/Unit, selection criteria, Piloting

Abstract
Rangelands are the cornerstone of African pastoral production systems and rangeland health (RLH) is vital for the health of livestock and the people who depend on them. RLH is integrally linked to actions of livestock, humans, climate and management applied. Cognisant of this, the HEAL (One Health for Humans, Environment, Animals and Livelihoods) project has been demonstrating how RLH can be integrated into One Health interventions at a local level in pastoral areas of Ethiopia, Kenya and Somalia. HEAL, a 12-year project started in 2019 with funding from Swiss Development Cooperation, reshapes service delivery into One Health Units (OHUs), which provides a sustainable, demand-driven and cost-effective integrated human, animal and RLH services. Key actors in implementation of OHUs are community-based health workers. In Ethiopia, these include the well-established systems of community-animal health workers (CAHWs) for livestock and health extension workers (HEWs) for humans, but there is no equivalent system for rangeland. In response to this, HEAL is developing a community-based rangeland health workers (CRHWs) system. A central pillar of this is piloting CRHWs, following a review of current practice, lessons learned from CAHWs and HEWs, and consultations with experts and communities. Initially, CRHWs are providing information and raising awareness on invasive species and establishing community RLH monitoring system for these. To instil opportunities for CRHWs to be self-supporting, nurseries for growing and selling grass and tree seedlings were established in agreement with community leaders. This paper shares experiences of piloting CRHWs and how this contributes to broader development and investment in RLH. Collaborative design from the beginning was important for increasing likelihood of uptake by government and communities besides considering sustainability and financing. Research played important role in assessing opportunity and application of CRHWs, developing support training materials and for sharing lessons learned.

Introduction
Rangelands are cornerstone of African pastoral production systems (ILRI et al. 2021). Thus, rangeland health (RLH) is vital for livestock and human health and is integrally linked to actions of livestock, humans, climate and management applied (e.., sustainable grazing; build soil organic matter). Nevertheless, East African rangelands face many problems like climatic fluctuations, drought and others. Ethiopia also has critical shortage of qualified rangeland experts with a high staff turnover (EIAR, 2017). One Health (OH) has also received increasing attention in recent years as an integrated approach bringing together human, animal and

ecosystem-environmental health (Cunningham et al. 2017). The HEAL (One Health for Humans, Environment, Animals and Livelihoods) has been demonstrating how environment/rangeland health can and should be integrated into One Health (OH) interventions at local level in pastoral areas of Ethiopia, Kenya and Somalia. The HEAL was established in 2019, with funding from Swiss Development Cooperation and is a 12-year project that seeks to establish sustainable, demand-driven and needs-based One Health Units (OHUs), as cost-effective, innovative, integrated service delivery models. Key actors in the implementation of the OHUs are community-based health workers, which provides cost-effective and integrated human, animal and rangeland health services to local communities. In Ethiopia, there is a well-established system of CAHWs for the livestock health and a strong and well-functioning system of HEWs for human health at community level. However, there is no equivalent structure for rangeland health. A study was undertaken to assess possibility of establishing a system of CRHWs and its operational modality in Ethiopia.

Methods

The study was carried out in HEAL project areas of Somali and Oromia Regional States of Ethiopia (Liben, Dawa and Borana zones). The study comprised rapid assessment; validation of assessment findings through participatory workshops; training and follow up of CRHWs for implementation. The rapid assessment included literature review with focus on HEP/HEWs, CAHWs and CRHWs which was followed by key informants interviews (KIIs) using checklists with qualified, and knowledgeable individuals in livestock, humans and RLH. The KIIs were undertaken with community elders, heads/experts of Tuft University and Vétérinaires Sans Frontières (VSF), researchers/ national rangeland coordinator, livestock /pastoral extension heads at different levels, HEAL field coordinators and Amref Health Africa staff. A total of 28 KII interviews were conducted. Two workshops were undertaken to validate assessment findings, agree on next step including selection of CRHWs, income sources of CRHWs etc. Preparation of training materials and selection of CRHWs in each kebele (lowest administrative unit) was undertaken. CRHWs were trained on overview and experiences of OHU; management of invasive species and rangelands; community awareness and monitoring; nursery management; practical visits. Follow up of piloting CRHWs system was undertaken by HEAL Project staff and partners.

Results

Assessment report on possibility of establishing CRHWs system was organized covering different topics.

Health Extension Program (HEP)/HEWs: The Ethiopian government established a 20-years Health Sector Development Programme in 1997. After implementing the first five-years plan, health sector performance improved but the ability to deliver essential services in rural settings was less successful (EFMOH 2008). The government introduced HEP, a primary care delivery strategy, to address the challenges and achieve WHO MDGs. HEP was launched at scale in 2003 with 17 health extension packages for rural regions, which were later adapted for towns and pastoral areas. The program focused on promotional and preventive measures based on training and awareness creation. Sustainability required institutionalized and integrated health program with developed human capacity, infrastructure, decentralized management and political commitment. HEWs are selected in a participatory way from community members using selection criteria and are given training for 1 year. Model families and non-paid community health voluntaries support HEWS. The system is recognized globally (Bowser *et al*., 2023).

CAHWs: Establishing and maintaining nationwide animal disease surveillance systems is a major challenge in many developing countries due to various reasons. Use of CAHWs selected in participatory way from community using selection criteria was found as the best option for preventive and primary curative purposes. It has demonstrated remarkable achievements. Its sustainability depends on: income generated from their livestock health services, connections with local drug suppliers, level of training and supervision by veterinary statutory bodies, institutional arrangements for legalization and promotion of the services delivered and entrepreneurial skills (OIE 2013).

Key lessons learnt from HEWs and CAHWs: the long journey with many ups and downs; the need to start with the HEAL project; sustainability; good preparations, engaging community and relevant actors from beginning for buy-in of the concept; use of multidisciplinary approaches; community access to services in times of need; awareness creation etc.

Organization of CRHWs system: The response of the KII indicated that CRHWs system needs to be established in Ethiopian rangelands as we have limited experienced professions in rangeland management resulting in the lack of adequate service delivery particularly at the community level. The rangelands are degrading rapidly, requiring faster action. As CAHWs (livestock) and HEWs (humans) are already collaborating in the OHUs, supporting them by including CRHWs is essential. It is suggested for CRHWs to undertake simple tasks within the preventive and promotional general umbrella: **rangeland health education and communication** (e.g., awareness raising, community mobilization, sharing information on invasive species/rangeland status); **Rangeland evaluation and monitoring c) rangeland management and rehabilitation** (e.g., involve in degraded area identification, suggest interventions with community and inform responsible body timely). The aim of the CRHW system is not to replace NRM services but to complement them. Their role in OHU will include: support HEAL project officers in planning, site selection, implementing, training, awareness creation etc. The respondents and review work indicated that CRHWs selection criteria can vary among different Regions of Ethiopia. However, the important are: a) be a kebele resident and know the area well, b) 25 years of age or older and own livestock, c) have basic reading and writing skills, d) have time, willing and committed to work and serve community, e) pro-development, f) trustworthy and respected by different actors, g) have good relationships with people at different levels, h) willing to learn and take action, i) have some training related to rangelands and NRM. They should be selected in a participatory way from the community based on selection criteria.

Institutionalizing CRHWs: The significance of institutionalization of CRHWs system was indicated in the study results. The participants suggested three options for making the CRHW system sustainable. First, there is no need to establish a separate structure. Instead, they can be under the kebele natural resource management administration office, or the livestock production and marketing office (embedded in the existing system). The second option is formal institutionalization by having a focal person from the agricultural or pastoral development office at the region, zone and district levels for follow-up, supervision and other issues. These government officers should help with training and regular follow-up. The third option is for CRHWs to operate within a local rangeland management institution, which must be adapted to each context, considering specific sociocultural, political, economic and environmental factors. Therefore, one-size-fits- all model does not work. Potential sources of income for CRHWs include: i) advising, guiding and getting involved in bush control ii) collecting forest products iii) seedling production or collecting seeds of native plants for rangeland improvement, iv) participating in rangeland monitoring and reporting, v) training other community members, vii) getting involved in apiculture, viii) playing role in identifying rangeland plants of medicinal and other economic value. Among these, the HEAL project focused on supporting nursery establishment in consultation with the administration and CRHWs. Budget is needed for different purposes (e.g,, training materials preparation, training, equipment), Sustaining factors of the CRHWs include i) individual and community commitment, ii) sources of income, iii) legal status, iv) supervision, v) equipment, vi) political commitment, vii) public-private partnership.

Opportunities (e.g., rehabilitating degraded rangelands to create favourable situation for livestock production including better control of invasive and noxious plants, livestock feed resources, increasing rangeland production and productivity) and challenges (e.g., ownership, resource limitations. ensuring regular monitoring, accountability and coordination, increased rangeland privatization) of the CRHWs system and its implementation were also explored and documented through the KII and literature review. Working at the community level, the HEAL project can operationalize/pilot the system by discussing with local bodies at kebele rangeland unit and district levels. Piloting may not require specific legislation and policy. However, there will be a need to discuss policy issues with concerned officials once the CRHW system will be ready to scale. Also piloting and evidence generation, there will be a need to develop national minimum standards and guidelines for designing the system which include understanding the context; community dialogue and selection, training CRHWs, monitoring and refresher training and development of national training curriculum.

Validating findings, selecting CRHWs and training: 27 people attended the participatory workshops in Moyale and Filtu which validated the findings of the assessment report, included additional selection criteria and income source, and agreed on the way forward. Twelve CRHWs (6 from Borana and 6 from Dawa and Liben zones) were selected and trained for six days. The implementation of CRHWs system is handled by HEAL project staff and partners at different levels.

Discussion

The study showed that there are no community-based rangeland health workers in Ethiopia. The positive response of all key informants on the CRHWs system, lessons drawn, and information gathered from the HEP/HEWs and CAHW implementation and the review results have paved the way to pilot CRHWs system. The HEAL project has provided the foundation for beginning the pilot phase as it is assessing the value of an integrated service delivery model among pastoralist communities. To date, the rangelands component of the HEAL project has focused on participatory rangeland management and, while this has laid a solid foundation for improved rangeland management in the community, it did not allow to fully integrate rangeland health into the community-based service delivery model proposed through the OHU. Accordingly, piloting a CRHW system could take the rangelands component a step closer to embedding rangelands health at the local level and pave the way for developing private sector rangeland service provision in Ethiopia. It is also worth looking into the possibility of linking with existing initiatives like the pastoral safety net program. The CRHWs could help rationalize the program and other resources at the community level by targeting these resources where restoration is feasible and offers tangible benefits to pastoralists.

The progress made so far have shown that it is possible to develop a system of CRHWs. The project is maintaining a comprehensive documentation during the pilot period which will lay the foundation for scaling up. The short-term plan should start with what is in hand and develop mid- and long-term plans so that the CRHWs stand on their own. Collaborative efforts among different actors is highly needed. Institutionalizing the system, supporting the CRHWs system to stand on its own (sustainability), equipping the CRHWs so that they generate their own income source are founding blocks for the system's success. It has also to be linked to the broader development of the pastoral and agro-pastoral communities whose livelihood depends on livestock production and utilization of different ecosystem services from the rangelands.

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Understanding conservation of Orans in India through the lens of institutional bricolage

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Key words: Orans; Sacred Groves; Rajasthan; Rangelands; Conservation

Abstract
'Orans' are centuries-old traditional grazing lands of Rajasthan, India, that are preserved and conserved because of spiritual beliefs and cultural values of the local communities. Due to religious sanctity, the villagers do not cut trees or poach animals in the Orans. However, they use them to graze their animals for which there are strict guidelines regarding the period of grazing and the type of animals that are allowed to graze. In the arid state of Rajasthan, Orans play a vital role in supporting the livelihoods of the local livestock-based communities. They provide not only grazing grounds but are also a source of water, fodder, firewood, wild fruits, medicinal herbs and other utilities. The management and conservation of Orans heavily depend on the active participation of local communities. Therefore, it is crucial to consider the local socio-cultural practices that these communities have been practising from generations to conserve Orans. While formal institutional mechanisms deployed by the government and forest departments are important, understanding the informal dynamics of local actors are equally vital. Hence, this paper finds that the effectiveness of institutions depends not only on their formal design but also on their alignment with existing local practices. This process is called Institutional Bricolage that involves creative recombination and adaption of institutional elements to fit local contexts. The paper analyses the concept of Institutional Bricolage in the context of Oran conservation and management practices that will seek to understand the interplay between informal and formal institutions in natural resource management, highlighting the need to blend formal institutional frameworks with informal local practices for effective conservation outcomes. This paper emphasizes the importance of recognizing local agency and indigenous knowledge systems in conservation practices of rangelands, advocating for context-sensitive approaches to conservation policy in India and beyond.

Introduction

The state of Rajasthan is situated in the northwestern part of India and is known for its arid climate and desert landscapes, where water scarcity, hostile weather conditions and increasing desertification pose serious challenges to its inhabitants. The scarcity of vital resources such as water and fertile land demands careful management practices, many of which are embedded in the socio-cultural customs of the local communities. The *Orans* or *Devbanis* are one such example of community-based sustainable resource management. Central to the Rajasthan's pastoralist lifestyle, *Orans* are the sacred groves or rangelands traditionally protected and managed by the local communities (Singh 2016). In Rajasthan, agriculture is particularly challenging due to extreme weather conditions, poor soil fertility and low rainfall, forcing many rural communities to rely on livestock as a viable source of livelihood. Animal husbandry not only provides a steady source of income[1] but is also the much-needed insurance against frequently occurring scarcity conditions in Rajasthan. Since ancient times, the communities of Rajasthan used to keep aside a certain patch of land as grazing grounds that also contain water bodies like ponds or waterfalls in order to support their livestock. These lands are called '*Gauchars*' (*Gau*- Cattle, *char*- to graze). To discourage cutting of trees and exploitation of the resources, some of the *gauchars* or grazing lands were dedicated to the local deities or supranatural powers who are believed to be responsible for the protection and well-being of these sacred places and organisms residing within them (Chaudhry, Bohra and Choudhary 2011). *Orans*, thus, serve as vital natural reserves, offering crucial grazing lands and water sources for the livestock. However, in recent years, the growing demand for livestock and the increasing human population, coupled with surging consumerism and urbanization, have disrupted traditional institutions. This breakdown has resulted in the loss of collective wisdom, ultimately causing significant land degradation and desertification in the region.

Methods

Sacred groves, being cultural and ecological entities, demand a methodology that captures their complex socio-cultural, spiritual, environmental and economic dimensions. Accordingly, this study employed a qualitative, interpretive and ethnographic approach to examine the conservation of sacred groves in Rajasthan, drawing on both primary and secondary data sources. This strategy allows for an in-depth understanding of the narratives, practices and values associated with the rangeland management. The fieldwork for this study was conducted across 6 sacred groves in the *Shekhawati* region and *Dhundar* region of Rajasthan in the districts of Jaipur, Alwar and Jhunjhunu. 25 semi-structured interviews and 3 focus group discussions were conducted for this study. These interviews included elderly villagers, temple priests and women, who are the custodians of oral traditions. Other ethnographic methods such as participant observation and transect walks were also employed to capture the lived realities of the local communities. In addition to engaging with community members, this study also incorporates insights from forest guards, local leaders and elected representatives who belong to or are directly involved with the communities stewarding these rangelands. Their dual affiliations—to the community and to formal governance systems—help illuminate the bricolage between the indigenous practices and state-led conservation efforts. Along with the primary data, the study also used secondary sources such as published scholarly articles, books and governmental reports on the *Orans* of Rajasthan.

Results

The lifeline of the rural communities in Rajasthan, the *Orans,* are facing severe exploitation and destruction. The ever-increasing growing population of livestock is putting immense pressure on the grazing lands. According to the 20th Livestock Census[2], the total livestock population in Rajasthan has grown to 56.8 million in 2019, a significant jump from 32.43 million in 1956. This substantial rise in the livestock population highlights the increased demand for resources and the added pressure acting as a challenge to sustainable management of the region. There has been also a rise in the spread of non-palatable species of the grasses and weeds in the *Orans* such as *Prosopis juliflora* and invasive tree species of *Accacia* due to their faster growth rates and grazing tolerance. Due to these invasive species, an accelerated destruction of the native vegetation in the Orans can be observed. This has a direct impact on the capacity of the *orans* and *devbanis* to support the livestock of the locals on a daily basis.

The traditional beliefs and religious sanctions that once acted as powerful social deterrents have been sidelined due to rapid urbanization leading to over-exploitation of these *Orans.* The younger generations as well as rural communities, influenced by consumer-driven values, no longer hold the same reverence for the *Oran* deities. In addition, State-led forest conservation interventions often pitch formal and informal governance practices against each other. The *Orans* do not fit neatly into a single category of land use pattern in government records

[1] The livestock are good source of milk, meat, manure and transportation.

[2] The Department of Animal Husbandry and Dairying (DAHD) conducts the Livestock Census every five years in collaboration with State Animal Husbandry Departments. The latest 20th Livestock Census was conducted in 2019.

leading to their multifaceted classification as pasturelands or fallow lands or culturable wastelands or as forests lands. This inconsistency in classification results in competing institutional mechanisms creating challenges for local communities to uphold their traditional and spiritual practices. This ambiguity leaves *Orans* vulnerable to illegal mining, encroachment and overexploitation, further threatening their ecological and cultural significance.

Discussion and Conclusion

The *Orans* have been able to survive since time immemorial due to the socio-cultural norms and traditions (Singh 2016) ensuring their safekeeping for the future generations. These sacred customs meant that *Orans* were not subjected to the same kinds of commercial exploitation as the other lands in the locality. Trees could not be cut down indiscriminately, lands could not be exploited, animals could not be hunted on these sacred grounds and the collection of resources such as wild fruits, fuelwood and medicinal herbs were strictly regulated by the local communities. This unwritten code of conduct was passed down through generations by community elders and priests. Historically, the traditional practices such as rotational grazing, periodic restrictions on certain grazing practices, controlled tree lopping and vigilant monitoring by watchmen (Jodha 1990) played a crucial role in safeguarding these pasturelands. However, these community-sanctioned measures have lost their relevance in the face of increasing environmental threats and socio-cultural changes.

A unique aspect of *Orans* lies in the integral role of priests in their conservation and management. Acting as guardians of these sacred forests, priests maintain the socio-ecological divinity that fosters biodiversity conservation. These informal practices and community gatherings associated with *Orans* serve as powerful symbols for fostering social cohesion. These practices are deeply ingrained in local culture and spirituality thus providing a framework for trust, reciprocity and collaboration, which are essential for managing the *Orans* of Rajasthan. These traditions not only reinforce a collective cultural identity but also create mechanisms for conflict prevention and resolution through storytelling and mythological narratives that emphasize respect for nature. Elinor Ostrom (1990) also underscores such values of community-based practices in her design principles.

The analysis of sacred grove governance depends not only on the formal forest governance rules and regulations but also on the informal rituals and taboos. The institutional bricolage (Cleaver 2017) offers a great analytical lens to comprehend the informal institutions and their interplay with formal ones. For instance, communities decide which trees to cut based not just on formal laws but also on traditional norms and their livelihood needs. This flexible approach shows that regulations are not always followed strictly but are interpreted in ways that make sense in real life. This shows that how communities actively negotiate, reshape and reinterpret rules, creating a mix of old and new practices.

Institutional bricolage helps us understand that there is no one-size-fits-all solution. People adapt, change and create systems that fit their needs, cultures, and challenges. Therefore, effective conservation of rangelands in India and globally requires to look beyond written laws and pay attention to cultural values, traditions and daily realities. By respecting local knowledge, blending formal laws with traditional practices and supporting alternative livelihoods, we can create flexible and culturally appropriate conservation strategies. Involving communities, especially women, in decision-making and adopting adaptive management practices ensures that regulations are practical and sustainable. By embracing this nuanced approach, we can achieve conservation goals that are not only ecologically effective but also socially equitable and resilient.

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Exploring how gender intersects resilience in the face of chronic uncertainty in the drylands

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Key words: pastoralism; drylands; resilience; climate crises; gender

Abstract

Resilience strategies in African pastoral systems face increasing scrutiny, particularly in the context of climate shocks. This article explores gender dynamics in the generation of resilience in a dryland socio-ecological system and amongst pastoralist communities in Moyale, Northern Kenya. The findings challenge existing assumptions of women's adaptive capacity and traditional gender roles, highlighting women's nuanced understanding of household needs and their ability to innovate during crises through strategies such as community savings groups, fodder production, and diversification. Men's resilience, traditionally linked to livestock mobility and herd management, is undermined by recurring droughts, with psychological stress emerging as a key concern. Youth face barriers in translating educational aspirations into sustainable livelihoods, emphasizing the need for inclusive resilience-building interventions. Together, these results demonstrate the need for a gender-sensitive approach to resilience that emphasizes local constructs of adaptive capacity and the need to support relational forms of resilience in ways that bridge social, ecological, and cultural systems.

Introduction

Pastoralism supports millions of livelihoods in Africa, contributing 40% to agricultural GDP (Glatzel et al., 2020). However, pastoral systems in African drylands, particularly in the Horn of Africa, face increasing vulnerability due to climate change (Godde et al., 2020). Repeated droughts, including the recent five consecutive rainfall failures in the Horn, have devastated water and forage availability, threatening the food security of 54 million people despite significant investments in resilience-building programs (GCA, 2024; WorldBank, 2022).

Gender plays a significant yet underexplored role in how resilience is constructed in these contexts. While men typically manage herding and mobility, women assume vital roles in domestic management and economic activities (Flintan, 2008; Hodgson, 1999). As a result, the current literature has identified that women's vulnerability is increased and that women have limited capacity to adapt to climate change (Grillos, 2018; Walker et al., 2022). As Semplici and Campbell (2023) highlight, framing pastoralists as inherently vulnerable leads to an oversight in which pastoralists are assumed as lacking adaptive capacity, without examining how they respond during crises and ultimately overlooking dynamic adaptation.This study explores how gender influences resilience strategies among pastoralist communities in Northern Kenya, emphasizing the importance of nuanced, gender-sensitive resilience-building approaches using a theoretical framework based on relational resilience (Reyers et al., 2022). By recognising the agency of pastoralists, this study aims to explore how gender influences local resilience strategies in pastoralist communities in the Horn of Africa, contributing to a more nuanced understanding of resilience that will inform gender-responsive policies and development programming.

Methods

This study took place in six villages in Moyale, Marsabit County, Kenya, representing varying degrees of market integration and development (Figure 1). Data collection, conducted from January to February 2024, included 39 semi-structured interviews and focus group discussions with pastoralists, government representatives, NGOs, and researchers (Table 1). A pairwise ranking exercise was used during focus groups to understand the relative importance of gender and other actors in resilience strategies.

Table 1: Characteristics and research activities at study locations. Focus group discussions (FGD), key informant interviews (KII).

Location	*Population Size*	*No. of FGD (women)*	*No. of KII (women)*	*No. of FGD (men)*	*No. of KII (men)*	*No. of FGD (youth)*
Sololo		0	2	0	0	0
Madoadi		1	1	1	3	1
Walda		1	3	1	3	1
Bori		1	1	1	1	0
Amballo		1	1	1	1	0
Adadi		1	3	1	3	1
Total		**5**	**11**	**5**	**11**	**3**

Transcriptions were thematically analysed using Dedoose software to extract insights into gendered resilience pathways. Focus was placed on strategies such as diversification, destocking, mobility, and fodder management, with special attention to the evolving roles of men and women during drought crises.

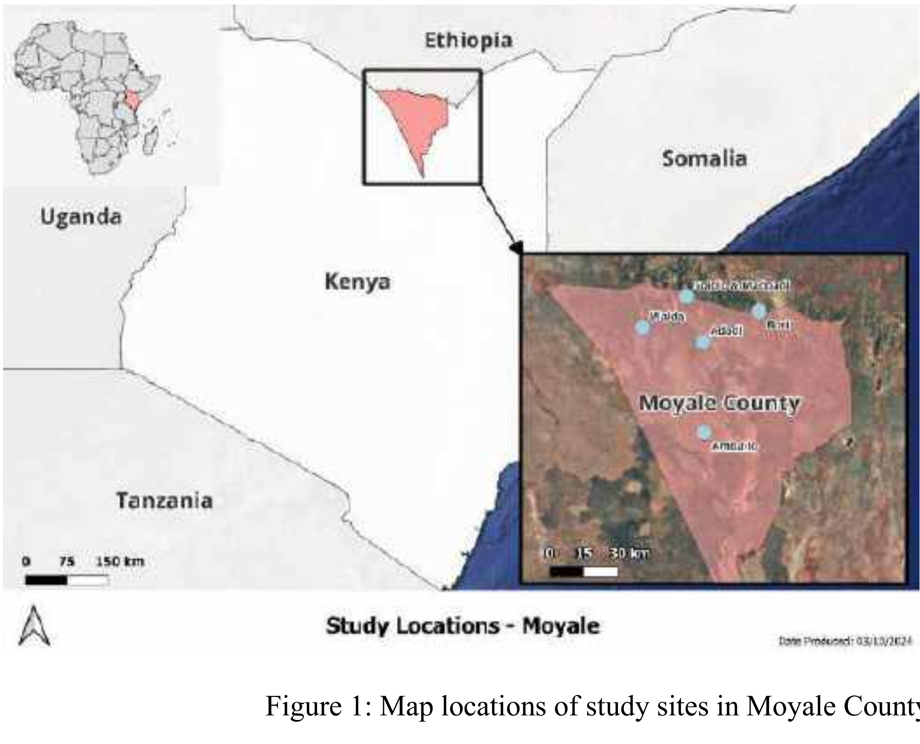

Figure 1: Map locations of study sites in Moyale County, Kenya.

Results

Resilience Pathways and Gender

Pastoralist resilience strategies during drought are multifaceted, with gender playing a central role in shaping both actions and outcomes. These strategies reflect the dynamic nature of pastoral adaptation and the evolving roles of men and women in responding to crises.

Small scale crop farming

Small scale crop farming has become an emerging resilience strategy for pastoralists, focusing on fodder cultivation or growing maize for livestock and human use. However, environmental challenges such as erratic rainfall and poor soil limit its viability. In some cases, poorly maintained infrastructure, like failed irrigation systems, exacerbates these difficulties. A participant from Madoadi noted, "Our land is fertile and has good soil, but the problem is that we don't have much education on it, and also the climate is not constant." Women often bear additional burdens in small scale crop farming, facing increased labour demands without sufficient training or support. Additionally, without external investments in education and infrastructure, crop farming often results in maladaptation.

Diversification

Both men and women have adopted diversification into non-livestock income streams, but women tend to drive this trend, especially during times of crisis. Women in locations like Walda, where infrastructure exists, have successfully engaged in camel milk trading, empowering them economically and enhancing their household resilience. Pastoral communities have also diversified their livestock to include a higher proportion of drought resilient species such as goats and camels to complement cattle.

While diversification can complement traditional livelihoods (McCabe, 2010), many pastoralists view it as a temporary survival strategy rather than a sustainable solution. One woman from Adadi reflected, "We didn't even know that we were rich. It was only after the animals started dying... that we realized how many cows we had." This sentiment underscores the cultural and economic centrality of livestock, highlighting the emotional toll of diversifying away from pastoralism.

Women's and Community Groups

Women-led community groups play a vital role in resilience by pooling resources, offering financial support, and fostering solidarity during crises. These groups engage in diverse activities, such as brick-making and fodder production, while also serving as emotional support networks.

The impact of these groups extends beyond economic resilience, promoting social cohesion and enabling members to navigate the psychological challenges of drought. Men also acknowledged the importance of these groups, with one participant stating, "After the loss of the livestock, we had no other things to depend on unless the women's groups sustained the family."

Mobility

Mobility remains a cornerstone of pastoral resilience, allowing herds to access grazing lands and water. Pastoralists expressed concern that areas they had traditionally relied on for pasture and water were also suffering from repeated failed rainy seasons. One man from a focus group discussion in Walda said, "When the drought comes, we used to run away with livestock to other parts but when there is drought everywhere, that is when we lose all our animals when it reaches that point, we call onto government for help". This research revealed the emergence of new mobility practices, such as using trucks to transport animals over greater distances. However, this option remains accessible only to a select few pastoralists with surplus income, often derived from educated family members working outside traditional pastoralism.

Decisions regarding livestock movement are typically made at the family or village level but are predominantly led by men, reflecting the entrenched tradition of male ownership of livestock (Flintan, 2008). During a focus group discussion with women in Madoadi, one woman expressed that, "All decisions are made by fathers. If there could be involvement of women and maybe children or a family member, we would have not lost all this livestock.” Fostering greater involvement of both men and women in mobility-related discussions and decision-making processes can provide valuable perspectives and contribute to more equitable outcomes.

Destocking
Destocking of the herd emerged as a crucial practice aimed at supporting remaining livestock and acquiring feedstuff for humans. This study found that decision-making surrounding destocking was predominantly led by men, reinforcing the prevailing sentiment from interviews that livestock ownership is traditionally associated with men. It was often not until later in the drought, when animal condition deteriorated and resources became scarce, that animals were sold, typically at a minimal ‘giveaway’ price. These findings highlight destocking as a gendered resilience strategy that necessitates more inclusive dialogues and reflective practices to enhance decision-making processes for better future outcomes.

Buying Fodder
Purchasing fodder is an emerging strategy, often funded through partial destocking or community savings. Many pastoralists bought fodder for the first time during the recent drought, underscoring their adaptability. However, challenges around pricing and quality remain significant. One participant described the fodder as “Poor, because it was just for business,” while another added, “We bought it because we didn’t have other options.”

Both men and women participate in fodder buying, reflecting evolving gender roles. Streamlining this practice through improved quality control and support for local fodder production could enhance its effectiveness as a resilience strategy.

Collecting Fodder
Collecting branches and twigs for livestock feed is predominantly a women-led activity. This physically demanding task often becomes a last-resort strategy during severe droughts, with women expressing frustration over men’s disengagement. One woman from Sololo noted, “Men sit idle, chewing mirra (khat), while we search for fodder.”

This dynamic highlights the gendered burden of resilience strategies, as women shoulder the dual responsibilities of livestock care and household management. Addressing these inequities through targeted support and training could alleviate the strain on women while enhancing overall resilience.

Cooking Human Food for Livestock
During extreme scarcity, women prepare human food such as maize or boiled feed for livestock, prioritizing herd survival over their own nutrition. This practice underscores women’s adaptability and commitment to maintaining livestock health. However, it also reflects the dire circumstances faced by pastoral families, emphasizing the need for timely interventions to prevent such drastic measures.

Humanitarian Aid
Humanitarian aid, particularly cash transfers, plays a pivotal role in supporting pastoralist households during crises. Women, who are often the recipients of these transfers, effectively manage the funds to meet immediate needs. The fact that women predominantly managed cash transfers reinforces their role as key actors in maintaining household resilience, underscoring their capacity to stretch limited resources in ways that ensure the family's immediate needs are met. One participant remarked, “The money helped us buy food and water for the children.”

However, delays in aid delivery often limit its impact. A pastoralist lamented, “If only they held our hand while we still had strength.” While essential for short-term survival, aid must be complemented by long-term strategies that reduce dependence and enhance local resilience.

Pairwise Ranking

Pairwise ranking exercises revealed that women are consistently viewed as the most critical actors during crises, followed by men, NGOs, youth, and the government. Women's central role in managing household resources, community groups, and resilience strategies underscores their importance in crisis response. A participant from Bori summarized, "Women are the ones who keep families alive when the animals are gone."

Discussion

While both men and women contribute to resilience-building in pastoralist communities, the roles they assume are shaped by deeply ingrained gender norms. Women often take the lead in household management, resource allocation, and community support, particularly during times of crisis. Participants from both gender groups acknowledged that women are central in efficiently managing available resources, including money, food, water, and livestock through fodder collection and the preparation of human food for animals. Their multifaceted role reflects broader literature that positions women not only as primary caretakers of their families but also as key contributors to the community's well-being during hardship (Flintan, 2011; Huyer et al., 2024).

These findings challenge the dominant narrative in some of the resilience literature, which portrays women in pastoral communities as the least resilient due to increased vulnerability and reduced adaptive capacity (Huyer et al., 2024). Contrary to this perspective, women emerge as key actors in sustaining lives during shocks, particularly through short-term household resilience strategies. This calls for a rethinking of gendered assumptions in resilience studies and underscores the importance of strengthening the pathways women use to support households, such as community savings groups, diversification activities, and water management practices. However, resilience-building programs must also address socio-cultural barriers that limit women's involvement in broader decision-making processes.

Rather than focusing on access to capital assets and income, such a perspective on resilience emphasizes the social, relational roles that women play in supporting households, often as part of collective efforts, both with men but also particularly other women. These efforts align with the concept of relational resilience, emphasizing the dynamic interconnections between social, ecological, and household systems. Women's expertise in navigating uncertainties and complex socio-ecological systems positions them as pivotal actors in both immediate and long-term responses to shocks. The capacity of women, rather than their associated capital, and their ability to draw on relational networks therefore emerged during this study as important factors for ensuring resilience through drought, across the activities. These findings align with wider perspectives on resilience theory explored by Reyers et al. (2022) and the highlighting of relational resilience as central in pastoral systems (Konaka et al., 2024; West et al., 2024).

As droughts intensify in the context of climate change, gendered roles become more fluid. Women increasingly take on additional responsibilities, while men face new psychological and emotional challenges. Studies indicate that men's traditional roles in pastoralist communities, particularly in livestock herding and mobility, are increasingly undermined by climate-related shocks (Hanigan & Chaston, 2022). This disruption often leads to heightened psychological stress, with some men turning to distractions like mirra (khat), contributing to disengagement as livestock losses mount (McPeak & Little, 2019). This study echoed these findings with substance use reported among men highlighting the need for mental health interventions that are culturally sensitive and embedded within existing community structures. Addressing men's mental health is crucial not only for their well-being but also for maintaining their active role in long-term resilience strategies, particularly in adapting livestock management to changing conditions through mobility and livestock care.

Meanwhile in terms of external support through 'resilience' programs, even though overall they were ranked low, some NGOs were acknowledged for their life-saving interventions, even though pastoralists expressed frustration over the delayed arrival of aid, a critique echoed in other studies that document the lag in humanitarian responses in pastoral areas (Fitzpatrick, 2024). The government was ranked as the least essential actor, often seen as offering minimal and delayed support, reinforcing findings on the lack of timely state intervention in pastoral regions.

Furthermore, the shifting dynamics observed during the depths of drought suggest a broader evolution in gender roles (Karmebäck et al., 2015). As men become increasingly dependent on women for household survival during crises, this dependence has the potential to reshape gender relations beyond the immediate crisis period. There is a need for more longitudinal research that tracks how gendered resilience strategies evolve over time in response to recurring shocks (Bryan et al., 2023; Juran & Trivedi, 2015). While much of the existing research focuses on short-term responses to crises such as drought, little is known about how men's and women's roles in resilience change across multiple cycles of shock and recovery. This could offer insights into the sustainability of certain strategies and whether they are becoming more or less gender-inclusive over time.

To foster holistic, gender-sensitive resilience, interventions must address socio-cultural barriers limiting women's involvement in decision-making while equipping men with the mental health and adaptive capacity-building support needed for sustainable livestock management. Aligning with relational resilience, which emphasizes context-sensitive, adaptive strategies rooted in local knowledge, such efforts can better navigate the uncertainty characteristic of pastoralist systems.

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Unleashing multifunctionality: How policy support and good governance are key to sustainable land management.

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Keywords: Silvopastoralism, dryland forests, policy reform, participatory processes, sustainable land management

Abstract

This paper examines how policy and legal frameworks in Morocco and Lebanon are evolving to promote sustainable silvopastoralism in dryland forests. In Morocco, a participatory approach led to the development of a national silvopastoral strategy in 2016, building on earlier initiatives that offered financial incentives to communities for protecting reforestation sites. This approach has resulted in improved forest restoration, better livestock management, and socioeconomic benefits for local communities. Lebanon, facing challenges posed by its outdated Forestry Code, initiated a comprehensive review process in 2015 with support from the Food and Agriculture Organization of the United Nations (FAO). Alongside the development of a national agricultural strategy and rangeland management guidelines, this process aims to modernize forest and rangeland governance, promote community engagement, and ensure the sustainable use of natural resources. Both case studies highlight the importance of adaptive policy frameworks, stakeholder collaboration, and community engagement in achieving sustainable forest and rangeland management in dryland ecosystems.

Introduction

Rangelands play a crucial role in rural development by producing goods and ecosystem services, including supporting, provisioning, regulating, and cultural services. In several middle eastern countries, dryland forests and silvopastoral systems are vital for the livelihoods of rural communities, significantly contributing to national livestock production. However, forest and rangeland policies often consider pastoralism and pastoralist communities as a driver of degradation, favouring afforestation and reforestation policies that marginalize pastoralists instead of considering silvopastoralism as a true asset for enhanced ecosystem management. This paper examines how an enabling environment, brought on through enhanced policies and legal instruments, is helping to restore and sustain the pastoral areas in Morocco and Lebanon.

Towards enabling policies

In Morocco, customary laws permit people living near forests to graze their livestock within forest domains, making silvopastoralism an integral part of the ecosystem. However, socioeconomic changes and environmental factors have led to overgrazing, threatening the sustainability of these ecosystems (Moukrim et al., 2019). To address these challenges, the Forestry Department developed a national silvopastoral strategy in 2016 aimed at restoring and sustainably managing forest resources. The strategy emerged as a response to the pressing issue of overgrazing in dryland forests, which contributes to vegetation loss, land degradation, and soil erosion. The strategy, developed through a participatory approach, represents a legal instrument to achieve sustainable forest management by addressing ecological, social, and economic factors. The strategy focuses on long-term restoration and sustainable management of silvopastoral resources through good governance, ensuring socioeconomic well-being of the population, biodiversity conservation, and climate change mitigation. The development process involved five key phases: 1) ***Diagnosis*:** A silvopastoral diagnosis of existing conditions and challenges was conducted; 2) ***Capacity building:*** Strategic planning capacity was built among stakeholders to ensure institutional anchoring; 3) ***Interactive workshops:*** Workshops with partners and civil society facilitated strategy formulation; 4) ***Sharing workshop results:*** Results from workshops were shared with managers to ensure a uniform understanding of the strategy's direction; and, 5) ***Formulation and restitution:*** The strategy was formulated and presented in a simplified format to ensure visibility and readability (FAO, 2022).

This strategy builds on Morocco's previous policies to support pastoralists. In 2002, the government initiated a compensation programme for forest areas closed to grazing. This sought to facilitate long-lasting and viable solutions, reduce the heavy grazing pressure on forest ecosystems, and support reforestation initiatives. Financial incentives were offered to forest users organized into grazing associations, provided they adhered to grazing restrictions in designated reforestation sites. These communities were made responsible for protecting their lands and organizing grazing schedules to prevent overgrazing and allow the land to recover (FAO, 2022).

In Lebanon, the Forestry Code of 1949 has been the cornerstone of forest management in the country. It grants the Ministry of Agriculture (MoA) authority over the use, protection, and management of forest resources. However, the 1949 Forestry Code faced increased fragmentation, lack of clarity on rangeland management and insufficient community engagement. Recognizing these limitations, the Lebanese government, with support from FAO, undertook efforts to enhance forest and rangeland management policies. Since 2015, the MoA and FAO have collaborated ***to review and amend the Forestry Code***. The review process was divided into three phases: 1) Detailed review of the existing forest code to identify its strengths and weaknesses; 2) Consultations with a wide range of stakeholders, including government agencies, NGOs, and the private sector to gather feedback on the proposed revisions to the forestry code; and, 3) Drafting of the revised forestry code, integrating the feedback from the consultations. Regarding rangeland and silvopastoralism, the revised law aimed to address the specific challenges of rangeland management, regulate grazing practices, promote sustainable livestock production, and minimize conflicts between pastoralists and other stakeholders (FAO, 2024). In addition to the review of the forestry code, the Ministry of Agriculture developed the ***Agricultural Strategy*** (2020 - 2025), which emphasizes the importance of community engagement and sustainable management of rangelands, within and outside forests. This strategy aims to improve food security and the livelihoods of pastoral communities, promote climate change adaptation, and ensure the sustainable use of natural resources (MoA, 2020). Furthermore, in 2018-2019, the UNDP, through its project "Sustainable Management of the Qaroun Watershed", developed ***National Guidelines for the Management of Rangelands*** within and outside of forests.

Preliminary **positive changes**

The Moroccan Forest Department realized the importance of piloting initiatives to ensure the effective implementation of the strategy and evaluate its effectiveness. This led to the development of a regional silvopastoral strategy and a territorialized action plan, involving communities and stakeholders to ensure adaptation to local contexts and climate change considerations. The regional plans aimed to enhance silvopastoral ecosystems, improve the organization of pastoralists, support socioeconomic development of areas, improve the governance of resources, and promote holistic research (FAO, 2022).

The number of grazing associations and their members participating in the incentives programme has steadily increased. By 2019, more than 175 beneficiary associations were managing over 101 000 hectares of dryland forests. This growth in grazing associations has been directly linked to improved reforestation success rates and a significant reduction in grazing offences. A fundamental aspect of the programme's success is its participatory approach. Stakeholders embraced community involvement in forest resource management, and local communities agreed that this mechanism had improved collaboration with the forest administration. The policy changes, co-created with local communities and pastoralist groups, have resulted in better livestock management, effective forest restoration, enhanced land and forest management, and economic and environmental benefits for all involved.

Despite the challenging economic and security conditions Lebanon has faced in recent years, the country successfully completed the revision of its Forestry Code and submitted the revised law for official endorsement by the Council of Ministers. This revised law is a major national milestone that will provide a solid foundation for the sustainable management of Lebanon's forests and rangelands while improving the livelihoods of the people that depend on them (FAO, personal communication). The Agricultural Strategy, which integrates rangeland priorities, has increased national interest in rangeland management and encouraged more local actors and development agencies to integrate rangeland management within their strategies. Additionally, the National Guidelines for Rangeland Management were applied in a pioneering project implemented by FAO, in collaboration with the MoA, to prepare a comprehensive management plan for the Tannourine community in North Lebanon, balancing environmental conservation with social needs.

Discussion

Policy reform is essential for advancing rangeland management and recognizing pastoralist communities' rights to access and benefit from range resources. Policy bottlenecks have been identified as significant barriers to effective rangeland management in various parts of the world. Misunderstanding of pastoralist communities has resulted in policies that harm rather than help these communities. This outdated view creates tension, marginalization, and instability within pastoral communities (Nori and Scoones, 2023). The process Morocco followed to update its policy framework reflects the importance of formulating adaptive, locally contextualized strategies that incorporate the latest scientific advancements (Dong et al., 2016). Moreover, financial incentives, when implemented correctly, can significantly increase the adoption of sustainable practices. Evidence suggests that these incentives are a more effective alternative to state subsidies for fodder purchases and barley cultivation (Louhaichi et al., 2016).

Conclusion

Effective management of silvopastoral systems is essential for preserving the ecological integrity and socioeconomic well-being of Morocco and Lebanon. Ongoing efforts to enhance policies and legal frameworks highlight the importance of a shared vision and collaborative effort among stakeholders. Further, they provide a crucial opportunity to address existing challenges and promote sustainable forest and rangeland management practices. Successful implementation depends on fostering community engagement and strengthening the capacity of stakeholders. Continuous monitoring, evaluation, and adaptive management will be crucial to ensure an enabling framework for the sustainable management of Morocco and Lebanon's valuable dryland forests and rangeland ecosystems.

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Bridging gender gaps in rangeland resource and conflict mapping: the role of participatory GIS, a case study in Kenya

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Key words: Participatory GIS (PGIS); Gender Inclusion; Rangeland; Resource Mapping

Abstract

This study examines the role of Participatory Geographic Information Systems (PGIS) in resource mapping, policy formulation, and conflict resolution in Isiolo County, Kenya. PGIS integrates Traditional Ecological Knowledge (TEK) with modern mapping to engage local communities and enhance mapping accuracy beyond conventional methods. The approach emphasizes gender inclusion, as men and women contribute distinct yet complementary knowledge. Men typically identify broader geographic features and economic stability resources, while women provide insights into water sources and household-level needs, addressing issues such as water access and food security. Gender-specific maps underscore the value of including women in resource management, fostering strategies that reflect the needs of all community members and enhancing decision-making equity. PGIS also helps address regional conflicts over rangeland resources by mapping contested areas and facilitating dialogue among groups like the Samburu and Turkana communities. Through Focus Group Discussions (FGDs) and Key Informant Interviews (KIIs), the study captures a wide range of local perspectives on environmental challenges, climate impacts, and security risks. This inclusive approach supports culturally relevant and scientifically grounded resource governance, which is essential for building resilience in pastoralist communities. Overall, the findings highlight PGIS as a valuable tool for sustainable rangeland management, aligning with broader frameworks for climate resilience and conflict management. By promoting community-led mapping and incorporating diverse perspectives, PGIS enables comprehensive solutions to complex environmental and socio-economic challenges, advancing effective policy outcomes in Kenya's rangelands.

Introduction

Rangelands, often arid or semi-arid landscapes, are essential for millions of pastoralists and agro-pastoralists who rely on grazing lands, water sources, and vegetation for their livelihoods. However, these resources are highly variable and vulnerable to environmental pressures. Participatory Geographic Information Systems (PGIS) is a valuable tool in Africa for managing these rangelands (Cho and Mutanga 2021). PGIS combines traditional ecological knowledge with modern mapping technologies, allowing local communities to contribute their understanding of the landscape to create accurate, context-specific maps that often surpass what remote sensing alone can achieve (McCall and Dunn 2012). Incorporating gender balance in Participatory GIS (PGIS) is essential because men and women bring distinct knowledge and experiences regarding natural resources. Including both perspectives ensures comprehensive, accurate resource mapping and supports equitable decision-making (Bullock et al. 2022). Actively involving women in PGIS recognizes their specific needs, like water accessibility, fostering solutions that benefit all community members (Boongaling et al. 2023). This inclusivity also boosts community buy-in, as both genders see their input reflected in management plans, creating shared ownership crucial for sustainable resource initiatives.

Our study examines community perceptions on land use, natural and market resources, land management challenges, and climate-related risks, recognizing the often-gendered nature of these views. We used PGIS, focus group discussions, and key informant interviews to capture gender-specific local knowledge for more accurate rangeland mapping. Key objectives include integrating traditional ecological knowledge into PGIS, engaging diverse community members—especially women and marginalized groups—to ensure comprehensive resource management, and using PGIS to map conflict zones, promoting dialogue and cooperation to resolve disputes.

Methods

We conducted a Participatory GIS (PGIS) workshop in Isiolo County, Kenya, to gather local insights on rangeland resource management in May 2024. Participants were divided into three groups—men, women, and a mixed group (both men and women). Each group was supported by an enumerator trained in map reading and effective questioning. The male and female groups were facilitated by male and female enumerators, respectively, to ensure comfortable and open discussions. Each group received a paper map created from Google Earth images (scale 1:22,000) of western Isiolo, consisting of seven joined A1-sized sheets (Corbett 2009). Participants mapped natural and market resources, livestock migration routes, water sources, overgrazed and underutilized areas, and conflict zones (Figure 1).

Figure 1. Different groups at doing a mapping exercise. The right panel shows the map after exercise was conducted

In addition to mapping, we held focus group discussions (FGDs) with all three groups. These discussions aimed to deepen our understanding of the participants' perspectives on local geography, resource utilization, environmental and land management challenges, service access, climate impacts, conflict zones, and security risks. To further validate and expand on the FGDs and mapping results, we conducted key informant interviews (KIIs) with local experts.

Our data analysis involved multiple steps: initially, participants identified and marked familiar features on the map. FGD transcripts were organized and coded based on recurring themes, including land use, resource ownership, climate stressors, and conflict dynamics. Using Nvivo software, we performed thematic analysis to explore patterns across the groups, paying particular attention to gender-based differences in perceptions. This comparative approach helped reveal how men, women, and mixed groups experienced and prioritized rangeland issues differently, enriching our overall understanding of resource management challenges in Isiolo County.

Results

Gendered Perspectives on Resource Mapping

Incorporating gendered perspectives in Participatory GIS (PGIS) exercises has highlighted the distinct yet complementary contributions of men and women to resource mapping in pastoralist communities. The differences in how men and women valued and utilized rangelands were evident in their contributions. Men, often engaged in broader community-level resource management, were quick to map livestock routes, conflict-prone areas, and critical grazing lands, emphasizing practices that sustain herds and support economic stability. Women, initially hesitant, contributed detailed insights into household-level resource needs once engaged. They mapped essential water sources and seasonal rivers, underscoring the critical impact of water scarcity on daily routines and food security. In the mixed group, these perspectives merged, creating a holistic view of rangeland resources (Figure 2). This integration showcased the value of both men's ecological knowledge and women's focus on resource availability for household and livestock needs, emphasizing that inclusive mapping fosters a comprehensive understanding of resource use and challenges.

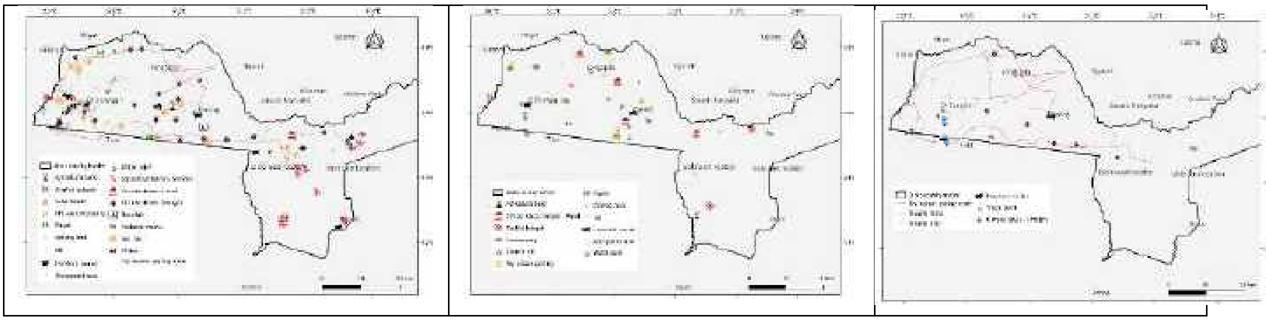

Figure 2. Features marked by men, mixed (both men and women) and women group

Gendered Roles in Environmental Resilience and Conflict Management

The FGDs provided deeper insights on how gendered perspectives shape responses to land challenges, climate stressors, resource conflicts, and climate-related security risks (Figure 3). Men focus on grazing boundaries, livestock disease management, and constructing gabions to prevent soil erosion, while women manage household water resources, build soil conservation structures, and plant grass to protect soil. Climate change exacerbates these challenges, with men noting issues like livestock diseases and resource loss, and women facing heightened burdens in household care and food security due to water scarcity. Conflicts over grazing lands and water points also reveal gendered impacts, with men often involved in cattle rustling disputes and women facing increased vulnerability when managing household survival after conflict. Community-driven solutions, like peace committees and local agreements, demonstrate the need for inclusive, culturally grounded strategies that integrate both men's and women's knowledge for effective resource management and conflict resolution.

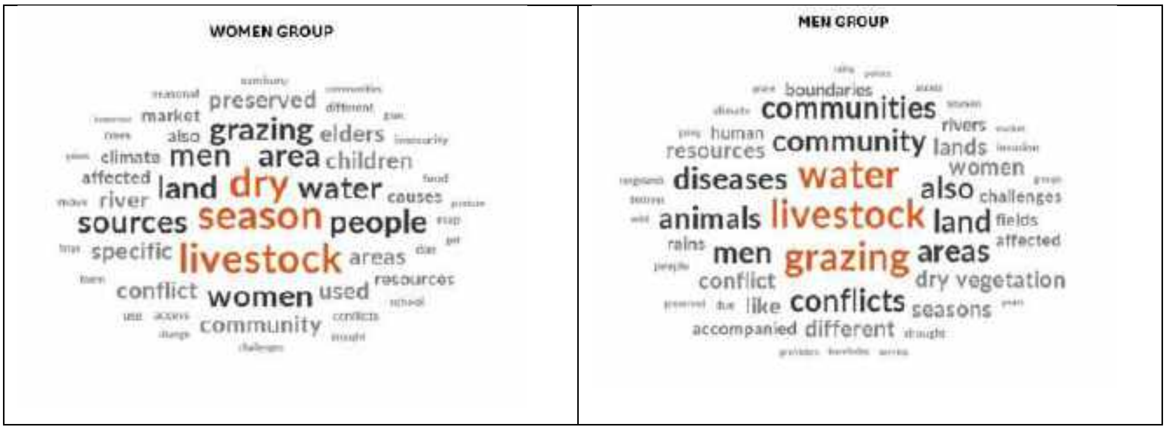

Figure 3. Comparative word clouds highlighting key concerns of women and men groups in Isiolo county, Kenya on resource management and environmental challenges.

Discussion and Conclusions

Our study demonstrates the effectiveness of Participatory GIS (PGIS) for resource management and policy formulation by promoting inclusive decision-making. In our study, we prioritized the inclusion of diverse community members, particularly women and marginalized groups, to capture a wide range of knowledge and experiences related to resource management. The findings revealed that while women provided valuable insights on water points and grazing lands, they lacked confidence in addressing topics like agrovet locations and climatic stress points, often highlighted by men. This reflects women's historical exclusion from resource management discussions, which has limited their exposure and capacity to communicate on these platforms. Gender-specific maps created in our study underscore the unique insights that women bring, especially in areas like water access and household resource use, making them essential for comprehensive management plans. Comparing responses from men, women, and mixed groups provided a deeper understanding of local geography, resource use, and environmental challenges. In conclusion, our research underscores the importance of PGIS, community engagement, and gender inclusion in managing Isiolo's resources. Furthermore, PGIS fosters greater community engagement in policy development, ensuring that policies are grounded in local realities and supported by the people they impact. This engagement helps build trust (McCall 2021).

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Pastoralists training and peer-learning

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Empowering pastoral landowners through soil understanding and land management strategy

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Key words: participatory research; soils; pastoralism

Abstract
Rangeland soils in Australia are diverse and integral to the country's vast arid and semi-arid landscapes, covering approximately 75% of the continent (DAFF 2024). These soils are typically shallow, often but not always nutrient-poor, and have low organic matter due to the region's low rainfall, high evaporation rates, and sparse vegetation. Rangeland soils are commonly prone to erosion and salinity, especially when vegetation cover is disturbed. Despite their limitations, these soils support unique ecosystems and are used for extensive grazing, playing a critical role in Australia's agricultural and ecological systems. Sustainable management practices are essential to maintain their productivity and prevent degradation. Education, training, and support for pastoral land managers in the soil sciences is pivotal to protecting and enhancing rangelands systems, especially given the frequency and intensity of rainfall events that are predicted with future climatic variability. Shifting the focus of rangelands management back to the fundamentals of understanding soils from a whole of landscape perspective and adopting a "from the ground up" approach to pastoral productivity is re-empowering a new generation of pastoral land managers with knowledge and confidence to adopt regenerative land management tools.

Introduction
The South Australian Arid Lands (SAAL) Landscape Board region covers over **400,000 square kilometres**, making up more than half of South Australia (SAAL 2024). Characterized by expansive plains, low-lying scrublands, and distinctive ecosystems adapted to harsh conditions, including hot dry summers and cold winters, this vast area includes some of the driest climate zones and most ecologically significant landscapes in the state. Despite the challenging environment, the southern rangelands are rich in biodiversity and offer opportunity for productive grazing systems.

Comprehensive soil testing across rangelands regions can be expensive and, outside of crop production systems in more reliable rainfall regions, have largely been an uncommon practice. There are very little agronomic inputs or interventions that can be administered to rangelands soils to alter soil chemistry or initiate soil structural change in a cost-effective manner, and for this reason it is uncommon for intensive testing or review of soils to have been undertaken. However, rangeland managers can learn and derive value from agronomic and environmental soil testing practices and other areas of formal soil science. This paper highlights the importance of understanding soil fundamentals to make more informed and effective land management decisions through exploration of datasets and techniques employed to engage pastoral land managers in the process of understanding rangelands soils.

Methods

The project has involved the design, implementation and delivery of extension programs focussing on collecting and analysing soil data from southern rangelands regions of Australia. This involved collaborating with land owners, pastoral station managers, Government and non-government organisations and experts aligned with advising or supporting the implementation of on-ground soils focussed trials or training opportunities in the SA Arid Lands region. The program also reviewed data that was collected from complementary field trials and soil sampling work funded outside of the original projects funded scope.

Soil Sampling

This project enabled the construction of a contemporary soils data set from the SA rangelands region and a total of 200 samples were analysed and reviewed with 175 samples having comprehensive laboratory analysis conducted (SAAL 2024). Soil testing parameters also included measuring soil temperature, biological activity and infiltration rates in the field with land managers. Laboratory results were independently analysed to consider:

- Typical ranges of Soil Organic Carbon across the SA pastoral zone (and causes of outliers)
- Characteristics of southern rangeland soils (chemical & physical traits) that influence the ability to manage regeneration of degraded grazing land
- The potential of different soil types to regenerate, and where to focus management efforts to gain the best outcomes
- Influence of soil health on pasture growth and livestock production parameters

Demonstration sites

In addition to testing soil samples from a range of land systems and rainfall zones, sites of specific interest to pastoral land managers were also tested. Results were used to show case the influence of land management techniques on soil health at demonstration sites on commercial-scale pastoral and rangeland properties, enabling the construction of a soils data set from a total of 21 pastoral leases across the SA Arid lands region. The data has been showcased at field days, demonstration sites, in project communications and on social media channels.

Previous research has shown that engaging land manager participation in scientific research is integral to raising awareness, building knowledge and leading to practice change (Pino et al 2022). At nearly all sites, data was collected with and alongside pastoral land managers. Where possible, qualified soil scientists were engaged to attend field visits. Collaboration with soil scientists and extension personnel with backgrounds in intensive agriculture and broadacre cropping allowed for the application of a broad scope of skills, technologies and backgrounds outside of the normal scope of rangelands ecology. The cross-sector collaboration proved invaluable to further investigating data sets and improving understanding of soil chemical processes and plant growth responses when analysing laboratory data and visiting sites to consider soil property constraints by bringing a different lens to the approach.

Where possible, samples were taken at paired sites, using fence line or track boundaries where areas with identical soil type and rainfall could be compared. Comparisons of soil sample sets at sites where rehabilitation techniques (including water slowing techniques, brush packing to increase rainfall infiltration or differences in grazing management) were undertaken to measure the range and differences of soil properties caused by management inputs or techniques.

Extension activities and land manager engagement

A range of extension tools and facilitation techniques were employed to engage land managers in understanding local rangelands soils through a variety of workshops and field day events. All events were designed to provide as much practical, "hands-on" learning as possible. Design and delivery of field trips, tours and training days took participant experience and demographic background into account. Adult learning styles were considered carefully during event design, with special attention given to constructing activities and content delivery to focus on kinaesthetic, interpersonal learning types using varied instructional methods (Burns, 1995).

Out-of-classroom demonstrations were employed as much as possible, encouraging the group to collect data and measure soil properties in the paddock. These soil properties included measurement of pH, salinity, soil texture and colour, water infiltration rates and soil temperature. To create engaging dialogue, a fundamental soil property principle was described (for example, the influence of soil organic matter on soil structure) then participants were asked to estimate the measure or impact of an application of management inputs to the concept and collect data in teams. By engaging small groups to apply the experiment or collect data, a competitive element was added to increase engagement from the group. This form of engagement works well with pastoral audiences. Retention of knowledge and learnings about soil properties was enhanced by paying special attention to participants response and engagement and allowing flexibility to change demonstration approaches if needed.

Soil biological indicator trends were monitored using the 'Soil Your Undies' technique (DeBruyn 2018). Cotton underpants were buried at demonstration sites up to two months in advance of field days at the site. Participants were asked to uncover the buried material and share observations with the group. Cotton underpants were consistently more degraded in healthier soil patches (aligned with higher Organic Carbon (OC) and perennial plant cover) at all paired trial sites. As soil biology is expensive and difficult to measure with laboratory sampling methods, this form of experiment was a powerful and cost-effective tool, using a novel approach to educate land managers, integrating visual interactive assessment, humour and science.

Results

Numerous soil parameters were measured from laboratory test sets (SAAL 2024), for the purposes of this paper, data analysis will focus on a sub-set of parameters of interest to pastoral land managers.

Soil Organic Carbon

Organic Carbon (OC) is influenced by climate, soil type and management. The SAAL region has challenges around all three of these factors. The OC levels (Walkley and Black) from soils tested ranged from 0.25% to 1.5% with some outliers up at 2 to 2.5% OC. The average OC% was 0.58% and half of the samples were below 0.45% OC. The level of detection for OC% as a Walkley & Black analysis is 0.25%.

Building soil carbon in rangelands soils is complex and largely dependent on climatic variables and soil types, however data collected from paired treatment sites across the project footprint suggest that soil conservation practices and rest-based grazing management can have a significant impact on soil carbon stores at scale.

Soil Salinity

Salt content of the top 10cm of soil profiles across the pastoral soils data set, measured as Electrical Conductivity ECe, ranged from 0.15 to 32dS/m (with an outlier in salt lake country reaching 55dS/m). All areas in the southern rangelands need to be managed to address the salt accumulation potential at the soil surface, which can lead to scalding, plant species decline and reduced pasture growth. The data sets at paired sites consistently demonstrated that improving soil water infiltration, and maintaining soil cover reduces salt accumulation in topsoils, which is critical for seed germination and seedling establishment.

Soil water infiltration and surface temperature

Opportunistic testing of soil surface temperatures along transects with different vegetation cover parameters were particularly impactful in group training exercises during paddock walks. Using a digital infrared thermometer, participants were asked to monitor and record soil surface temperatures with and without perennial plant cover. The presence of large perennial shrubs and ground cover influenced soil surface temperatures by up to 32 degrees Celsius – being the difference between extremes in soil surface temperature recorded across a short gradient. Participatory data collection in 'real-time' enabled strengthened learning outcomes. The same approach was made with testing differences in simulated rainfall infiltration experiments (NQ Dry Tropics 2019). Differences in soil water infiltration times ranged significantly according to soil type, with the most significant differences being measured in paired treatments sites that had undergone mechanical intervention, such as deep ripping.

Project participation

In total, 324 individuals participated in one or more soils focussed field days over the two-year life span of the funded project. This included on-ground field days, training days, a virtual field day and a week-long bus tour into western New South Wales. Of note was the attendance (not captured in attendance data) of more than 55 children to the events. Designing and facilitating inclusive events (families encouraged to attend events) is important in a region where childcare is limited, and all family members are involved with the day-to-day activities of a pastoral business.

The outcomes of a week-long facilitated inter-regional tour with twenty pastoral participants, continues to be monitored. All participants engaged in the learnings have committed to undertaking practice change since returning to their home properties. Participants on the tour alone are collectively responsible for managing 1.8 million hectares of pastoral and grazing lands in South Australia. Follow-up interviews with participants have recorded changes which include transition to changing livestock enterprise make-up, installation of major soil conservation works, successful enrolment in post-graduate study in soil biology and the acquisition of grant funds to undertake large-scale land rehabilitation works.

Discussion

South Australia’s environmental trend and report card published in 2023 states that soil erosion risk in the southern pastoral region of South Australia has been worsening over the last five years (DEW 2023). The report illustrates the impact of dry conditions on soil health and erosion risk, and further strengthens the importance of understanding the fundamental of soil properties through case studies, training and well-designed soil extension programs to support land managers with regard to managing soil health.

In the southern rangelands, especially in pastoral areas where the land area under management is vast, it is often considered that the soil “is what it is” and focus is given to the landscape from a vegetation dominance perspective. Soil analysis within the pastoral industry is generally limited and land managers often lack the context of what the soil data means relative to other areas of the landscape. Supporting pastoralists to adopt strategic soil sampling regimes, and appropriate analysis to target an improved understanding of the soil properties that are driving high and low performing production zones is a critical step forward.

Water and where it goes, defines what grows; Land managers adopting a strong understanding of the soils influence on landscape hydrology and water movement within the soil profile are recognising they have impact and control to redefine soil management in the rangelands, for future productivity and environmental gains.

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Northern Australian Indigenous producer group progress, learnings and contributions

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Key words: Indigenous; Two Way; Engagement; Empowerment; Participation

Abstract

This paper tells a story of engagement, respect, learning and hope. Indigenous involvement with the northern cattle industry has been a foundation element since the industry began to operate on indigenous land, over 150 years ago. That involvement has seen many changes and this project represents a change towards improved indigenous engagement with research and extension, with industry movement towards sustainability and with a two-way approach to developing ways to live in this landscape while meeting environmental, social, cultural and financial aspirations. Engagement with elders, time on country, time for yarning combined with a joint exploration of the collection, analysis and use of data, along with listening to experience both in livestock and land management and care have combined to present pathways and tracks to follow.

Indigenous businesses in this context are largely community owned and operate on community held land. Aspirations for the businesses and for the land differ from the conventional Australian cattle enterprise either family run or large corporate agribusinesses. Employment, caring for country, social and cultural access are important drivers for indigenous land owners and business operators. Profit, efficiency, and asset accumulation are some of the major drivers for non-indigenous cattle enterprise operators. All operators however, have in common the requirement and the desire to care for the natural resource, the livestock and the people and to be productive and profitable. The potential has always existed to work together to create and develop appropriate land management and care approaches.

This project is taking important steps towards integrating indigenous and non-indigenous aspirations and providing learnings for the Australian cattle industry as a whole.

Introduction

Indigenous communities and corporations throughout northern Australia own over 5 million hectares, run over 300,000 head of cattle and employ more that 200 people in the cattle industry. The total footprint of the Indigenous Agricultural sector is estimated at 8.1 million hectares and includes land in every state and the Northern Territory (Barnett 2022). The northern indigenous cattle holdings are on par with the large Agribusiness corporations which have been involved in the Australian cattle industry for over 100 years. Indigenous people have been involved in the Northern Pastoral Industry from its beginning in the mid nineteenth century (Duncan-Kemp 1934). This involvement, from the start has engaged men and women and each are recognised as superb stock handlers and managers. (Simone 2016). However, for much of the last 100 years indigenous pastoral workers and businesses have not been engaged with industry research and extension in any meaningful way, nor have indigenous cattle and land owners and managers been involved in development of industry level strategy, policy or direction (Barnett 2022). Research and extension services, originally provided by state governments, now largely provided by industry bodies, universities and private consultants have been readily available and accessible to non-indigenous producers and have shaped many changes throughout the industry. The lack of engagement of indigenous producers and industry participants is apparent at any cattleman's meeting or workshop throughout northern Australia and at any interaction between industry and government. The level of indigenous employment has significantly declined over the past 50 years (Josif 2009). This results in a two-way loss. Indigenous pastoral workers and managers miss opportunities for employment and to engage with developments in research, technology and management and the industry does not have the opportunity to benefit from indigenous knowledge and experience in land management. Indigenous knowledge has a crucial role to play as the industry develops appropriate responses to the challenges it is facing. Engagement with research and extension and with the broader industry by indigenous cattlemen and women, communities and corporations will be crucial for the industry and for indigenous participants.

The Australian cattle industry faces a period of significant change as resource degradation becomes apparent, the impacts of climate change begin to have an effect and the wider world places more responsibility on land managers to ensure practices are sustainable and now, regenerative. The northern beef industry also faces considerable issues of low productivity and low profitability (McCosker 2010, McGowan 2017). Industry research in 2020 concluded that "poor adoption of production technologies or practice change on farm has been a long standing industry issue" (Fitzpatrick 2020 p. 6.). The Northern Beef Breeding Project was initiated with the aim of addressing the issues of productivity and practice change. The project aims to use peer to peer learning techniques to "engage northern beef producers in the use of objective data to inform business decisions and provide a direct conduit for research and development outcomes to changes in business practice" (Fitzpatrick 2020 p. 3.). This project has taken important steps to encourage, enable and facilitate indigenous participation and two-way learning.

The indigenous component of the Northern Beef Breeding Business project is a joint venture initiative with support from Meat and Livestock Australia (MLA), Indigenous Land and Sea Corporation (ILSC) and Animal Health Australia (AHA) under the Northern Breeding Business (NB2) project framework.

Methods

The project is currently working with twelve indigenous businesses. These businesses manage over 4 million hectares, run around 150,000 head and employ 70 indigenous people.

The project was initiated through personal contact and on property visits with indigenous communities and corporations managing land and operating cattle enterprises. Engagement with elders has been an important aspect of the project from the beginning and has been crucial to ongoing engagement. Most of the indigenous enterprises involved in the project are managed by community owned indigenous corporations. These corporations each have a board of community members which is responsible for strategic decision making. Group membership is diverse and includes board members, station managers, station staff and agricultural advisors.

The NB2 project places emphasis on facilitator training and on building trust within each group. All project facilitators have access to a mentor and the other project facilitators to discuss group progress, to learn from each other and to exchange ideas and experience. The indigenous component of the project utilises facilitation, communication and training processes tailored to suit indigenous property managers, communities and pastoral workers. The process is based around "on country" residential style workshops, peer to peer learning and exchange, specialist input, individual property work and ongoing mentoring. There is a strong focus on member participation, ownership and engagement. The focus is set by group members and the process follows directions established through participatory group input. Four to five workshops are conducted each year. These workshops are based on land operated by group members and involve land and livestock-based activities as well as meeting room sessions. Participants are accommodated together and share meals and informal time, so there is time for stories and yarning, getting to know each other and exchanging ideas and knowledge.

The broader project aims of engaging beef producers with objective data and using this to change business practice are met through engagement with specialist input and communicated through shared group experience. Meetings allow for one on one information exchange as well as group interaction. Group members are at varying levels of management intensification and are engaged with different aspects of land management. There are opportunities for all group members to learn from and benefit through contact with all other group members.

Indigenous group activities are integrated with the broader NB2 project which exposes participants to other aspects of the cattle industry and people from a range of backgrounds. These contacts enable the building of a range of networks across the spectrum of the cattle industry and facilitate a two-way cross fertilisation of ideas, experience and knowledge across groups and across the industry.

Results

Engagement with the process, with other group members and with industry personnel is a highlight of the group activities. Indigenous pastoral workers, land owners and managers have demonstrated a hunger for information and for engagement with the wider cattle industry. Group members have been operating businesses for some time and have been aware of other indigenous cattle enterprises but often have not made contact or worked together and have largely not engaged with the broader industry. These meetings and workshops have provided welcome opportunities for people separated by large distances to meet, yarn and share experiences, knowledge and information.

The project has been operating for four years and members have attended at least four meetings/workshops each year. Awareness of the importance of data, of collecting good data, collating and analysing the data and using the results for development of strategic management interventions has grown. Members are now ready to use data management templates developed by the project throughout their businesses. Opportunities to learn about research and technological developments have been embraced by group members as has the opportunity to meet with and discuss common issues with non-indigenous industry members.

Group meetings and workshops are designed to encourage a cross flow of information, experience and knowledge and this is leading to practice change. A number of strategic and operational management interventions have been implemented by group members. These include improving reproductive efficiency, changing turnoff strategies, infrastructure improvements and an increased focus on supplementation.

An important aspect of the project is the use of mentoring both formal and informal. Group membership is highly diverse in terms of expertise, experience, knowledge and aspirations. The businesses range from large scale beef breeding enterprises to smaller beef businesses, enterprises with a focus on managing for environmental outcomes such as carbon sequestration and savannah burning, cultural tourism and indigenous ranger programmes. The open, participatory nature of meetings means that all members are able to contribute to discussions and there is always something to learn.

Elder members of the group have gravitated towards mentoring roles and this is actively facilitated. In addition to the group workshops and meetings group members conduct property visits, knowledge exchange and management support covering a variety of topics. The group has a natural focus on bringing all members along and the structure of the project enables this.

The broader NB2 project has developed a number of tools to enable and facilitate data collection, analysis and management. Specialists are invited to group meetings and regularly conduct training sessions focussed on data management, reproductive efficiency, pasture and grazing management and business management. The degree of literacy on these topics has improved markedly through the life of the project.

As the project progresses group members aim to broaden the focus to incorporate broader aspects of land management and include multi-functional approaches such as land management for environmental, cultural and social outcomes. This will open opportunities for two-way information flow and co-design and will provide opportunities for employment, training and income diversification.

Discussion

The project has built significant social capital within the group and with industry members engaged with the group. A combination of time spent on country, formal and informal time spent together and a generosity of spirit on behalf of land owners and custodians has enabled the development of group cohesion and trust. To provide an example of co-design, the principles of operation of this group, a group of indigenous cattlemen and women, have been developed by the group. This, in turn, has facilitated an open approach to the application of knowledge, research results and advice and is enabling practice change. The building of trust and group cohesion has been a crucial first step and this takes time, yarning, shared meals, sharing and respect.

Indigenous pastoral workers, land owners and managers have much in common with their non-indigenous counterparts but also have significant differences. Indigenous landowners and business operators have different aims and aspirations to non-indigenous landowners and business operators and operate under a different land tenure/land ownership framework (Barnett 2022).

The beef cattle industry in Australia, like many primary industries is continually facing pressure on costs and the industry, particularly the non-indigenous sector is focussed on using technology to reduce labour and resource use costs. Two of the most important aims of indigenous communities engaged with the cattle industry are employment and training. Improved engagement of indigenous pastoral workers, land owners and managers with the broader industry and participation in industry events and activities may deliver positive outcomes in terms of stable employment and staffing levels and opportunities for indigenous and non-indigenous industry participants. For this to become reality indigenous and non-indigenous industry members must continue to engage in dialogue and create frameworks for meaningful discussion.

Group members are also considering other, innovative aspects of land management which may provide opportunities for employment, training, income diversification and engagement with non-indigenous land managers. These include landscape management for environmental outcomes such as carbon sequestration, biodiversity conservation and regeneration and will come into focus as the group continues to grow. In many cases these enterprises and activities will be more important than the operation of a cattle enterprise on the land. These aspects of land management and enterprise operation will also benefit from two-way discussion, listening and learning and may involve increased engagement with the emerging environmental management sector and potentially provide direction for the broader cattle and land management industries.

Many people involved in land management in Australia, indigenous and non-indigenous have seen a future where indigenous and non-indigenous, scientific and experiential, community driven and corporate ways of managing land are combined to create land management approaches that are multi-functional and appropriate for this landscape and will care for the country and the people into the long term (Massey 2017). There are those also, who say that this possibility provides real cause for optimism for the future of the planet (Tacey 1995). “If we are to make changes of this kind, we need to talk with the whole country about it” (Gammage 2021 p. 183.).

For these dreams to become reality there is a requirement for dialogue, for sharing, listening and the creation of opportunities to move forward together.

This project with the support of MLA, ILSC and AHA has taken steps towards developing a framework for working together for the long-term benefit of indigenous cattlemen and communities and for the broader Australian cattle industry.

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The Northern Territory Rangeland Management Course: growing the next generation of land managers

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Key words: Extension; Pastoral Industry; Rangeland Education; Cattle Station

Abstract

Productive rangelands are vital to the Northern Territory (NT) pastoral industry but require careful management of grazing pressure to prevent rangeland deterioration. This is generally the responsibility of station managers, who often began their careers as station hands. However, despite it being a large component of a pastoral business, rangeland management is not often included in station hand training.

The NT Rangeland Management Course (RMC) aims to bridge knowledge and awareness gaps in grazing land management within the NT pastoral industry. The RMC is a free, one-day, on-station workshop, designed using hands-on, interactive learning for NT cattle station staff new to the region/industry. It is a series of classroom and paddock presentations and activities, covering topics including pasture composition and dynamics, land condition, carrying capacity, weeds and poisonous plants, cattle nutrition and using fire as a management tool.

In 2021, the RMC was upgraded and expanded. Between 2022 and 2024, the course was attended by 219 staff from 25 cattle stations, representing over seven and a half million hectares of pastoral land. The feedback received from the NT RMC participants during this period indicated increased interest in the topics covered, and suggested the course structure and delivery is effective in providing a practical introduction to rangeland management that is relevant to their station duties. The annual recruitment of new station hands and high turnover of staff in land management service delivery agencies means there will be an ongoing need and demand for the RMC in the future.

Background

Productive rangelands are vital to the Northern Territory (NT) pastoral industry. They provide low input, low-cost pasture allowing cattle producers to run large numbers of cattle (over large areas) where it is not always feasible to grow or buy in other livestock feed due to climate and remoteness. However, Australian rangeland pastures have evolved with very little grazing pressure. This is especially the case in the NT where, prior to infrastructure development, the landscape had limited water available for native grazing animals (e.g. macropods) for much of the year (James *et al.* 1999). The introduction of livestock (predominately beef cattle) has led to higher, more continuous and more selective grazing pressure, which has led to the loss of palatable pasture species, reduced ground cover and contributed to decline in land condition. This directly impacts pastoral businesses by reducing the productive capacity of the landscape.

Matching grazing pressure (i.e. stocking rates) to the safe carrying capacity of the country is a key practice station managers can implement to prevent deterioration of pasture and land condition or help mitigate the effects of historic overgrazing (O'Reagain *et al.* 2014). Doing so requires knowledge of pasture species, pasture yield, land condition monitoring, cattle numbers and feed intake, cattle nutrition, and strategies or tools available to assist in calculating and achieving sustainable stocking rates. However, the career progression into a station management role often begins as a station hand and does not usually involve exposure to or training in grazing land management until the person is in the decision-making role. Ideally, future station managers would start building their understanding of NT rangelands and maintaining long-term productivity well before they are required to make decisions, but it is uncommon for station hands to be aware of, trained or involved in the rangeland management side of pastoral businesses.

The Northern Territory Rangeland Management Course (RMC) is a workshop originally developed and delivered by the Northern Territory Department of Agriculture and Fisheries (NT DAF). Its' purpose is to provide pastoral businesses access to relevant, entry-level rangeland management education for early-career station hands. The RMC provides station staff, who have often come to the property as school-leavers from interstate, with an introduction to the unique environment and production system they work in, an awareness of the impact grazing can have on rangeland pastures (and in turn, cattle production), and an understanding of what grazing management strategies they are unknowingly assisting with in their day-to-day roles on their properties.

While the RMC has been delivered on stations since the early 2000s, this paper assesses RMCs run throughout 2022, 2023 and 2024, looking at the course structure, feedback received, the suitability of the course to the target audience and potentially other industries or regions.

Method

Prior to 2021, the RMC had been a relatively small and home-grown product, funded by the Northern Territory Government for almost 20 years. It was initially designed for stations in the Barkly region (Central-east NT) and then adapted for the Victoria River District (VRD) (North-west NT). In late 2021, the Australian Government, through the Northern Hub, funded the Next Generation Land Managers project which funded all RMC activities from 2022 to 2024, including upgrading the content and delivery of more courses.

The existing course content (PowerPoint presentations, accompanying activities and a printed workbook) was updated throughout 2022, both to incorporate new research findings and create more modern and visually appealing materials for the target audience (station staff, generally 17 – 25 years of age). A new version of the RMC with content relevant to the arid region was created for Central Australian stations, so that three regionalised versions of the course were available: Barkly Region, Big Rivers Region (replacing VRD) and Central Australian RMC. A modernised look was developed and applied across the suite of materials. Branded merchandise was introduced to use as course materials and prizes for participants (pens, notebooks, caps).

The general structure of the RMC was not altered much from the existing course. From 2022 to 2024, the RMC was offered free of charge to stations across the NT though public advertising and existing connections between NT DAF and station managers. It was delivered on-station by NT DAF extension and rangeland research staff who travelled to each station with all materials and equipment required. Stations were requested to have 8 to 20 participants in the course, which could include staff from neighbouring properties, and was not limited to staff in station hand roles. Each course was flexible according to what suited each station and would generally begin after breakfast (e.g. 7am) and finish mid-afternoon. Participants were welcomed with an icebreaker activity upon arrival and provided with resources/materials (workbook, notebook, pen, textbooks/guidebooks, optional resources). Throughout each course, NT DAF staff facilitated a series of PowerPoint presentations, group discussions tailored to the station, and both indoor and outdoor interactive practical activities. Topics covered in the series of modules included: climate variability, pasture dynamics, species identification and pastoral value ("3P" concept), land condition and monitoring (ABCD framework), forage budgets and carrying capacity, cattle nutrition, weeds and poisonous plants, using fire as a management tool, resources and tools available, and how these things can be applied on NT cattle stations.

Prizes were awarded to participants who were the most engaged at each course, and feedback forms were completed by each participant. Where the station manager couldn't participate in the course, the deliverers liaised with them afterward to discuss what their staff had learnt, offer to work with them further, and gauge interest in them hosting another course the following year for new staff.

Results

Between 2022 and 2024, NT DAF delivered 20 Rangeland Management Courses. The 219 participants were from 25 different cattle properties (11% of all pastoral leases), representing 75,837km^2 of grazed land, and 13% of the total pastoral lease area in the NT. This included two Western Australian properties (east Kimberley region). Most participants were early-career station staff (~77%); with some station management staff (~7%), and service providers, agricultural business representatives, and research staff (~16%) also attending.

The average feedback score out of 5 for whether participants would usually have attended a course like this, and their prior knowledge on the topics covered were 3.6 and 2.6 respectively (Fig. 1, orange colour group). For questions on the presentation, delivery, structure and incluson of activities, the average score was between 4.6 – 4.9/5, except for "should there have been more time spent on activities/in the paddock?", which received 3.1/5 (Fig. 1, blue colour group). All questions on whether participants will use learnings from the course in future and increased interest in the topics scored 4 – 4.5/5 (Fig. 1, green coulour group). The average overall value score was 4.6/5 (Fig. 1).

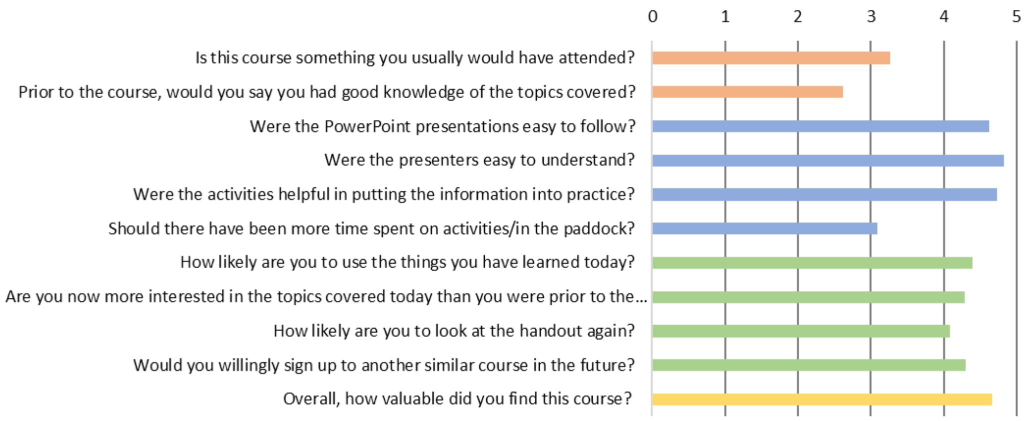

Fig. 1: Feedback from RMC participants from 2022,2023 & 2024, for questions which asked for a 0-5 rating (0 being very unlikely or very low, and 5 being definitely or very high)

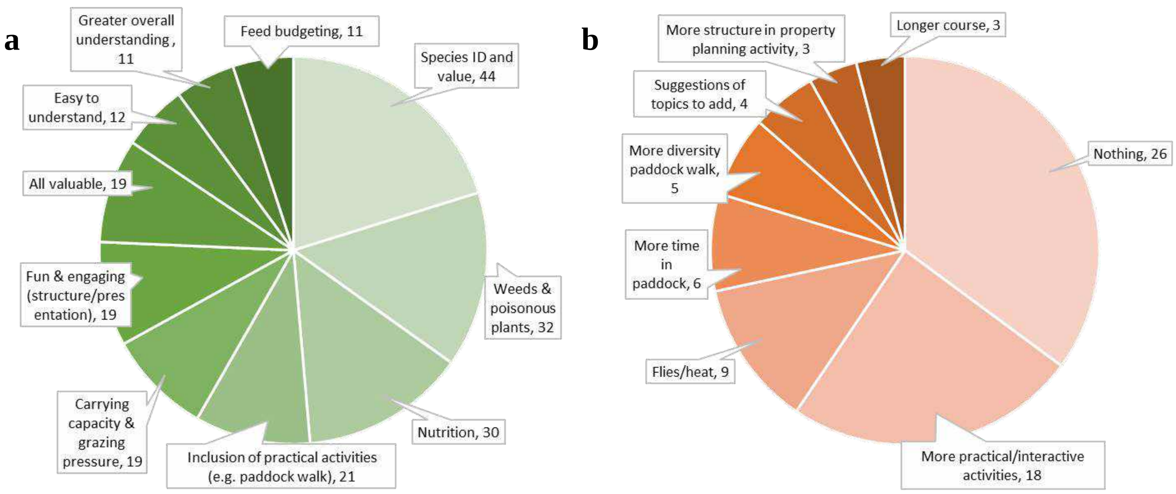

Fig. 2: RMC participant feedback from for the questions a) "Any standout things that were useful, interesting or surprising?" and b) "What wasn't so great, what should we change before we run the next course, or any other comments?". Answers are grouped as themes and ranked by occurrence (out of 219 participants)

When asked for standout/interesting/surprising things from the course, the most common themes in feedback included: species ID and value (44), weeds and poisonous plants (32), nutrition (30) and the inclusion of practical activities (21) (Fig. 2a). The most frequent feedback themes on what could have been done better included: nothing (26) and more practical/interactive activities (18) (Fig. 2b).

Discussion

Many stations offer training for first-year station hands, such as cattle handling, horsemanship schools and other skills required in day-to-day work, but there are few stations with staff inductions that include training on rangelands or pastures. There is other grazing land management training available to station staff for a fee. However, it is at a higher level than first- or second-year station staff need to know. In 2022, 2023 and 2024, 25 cattle stations/properties opted to host or send staff to an RMC, indicating that there are a large number of pastoral properties interested in providing this training for early-career staff. In addition, the RMC was free and could be run on their stations with content tailored to them, which, may have reduced barriers that prevented stations seeking similar training before. Having 25 pastoral properties involved in RMCs also facilitated connections between DAF staff and 25 station managers, which is valuable in that the remoteness of stations can be a barrier to forming industry-government relationships, and for the significant amount of pastoral land in the hands of these 25 managers.

The way the RMC was structured and delivered rated highly in the feedback received. The target audience are often kinesthetic and/or visual learners and not usually the type of people that enjoy textbooks and lectures. It is also not uncommon for literacy and numeracy to be a barrier for some station staff, particularly those that found classroom learning difficult in school. To ensure the RMC catered to this kind of audience, multiple visual, verbal and interactive components were incorporated. These included activities that involved group discussions so that participants could share knowledge/experiences, hands on activities that simulated putting theory into practice (e.g. using property maps to calculate carrying capacity), and a visit to the paddock to relate what they had learnt inside to how it looks on their property. The paddock visits included participants collecting and identifying pasture species, scoring the land condition as a group, discussing soil types and biocrusts, estimating yield, and pasture cuts to estimate yield. High feedback scores for course structure and inclusion of activities, particularly the time spent in the paddock, indicate that this approach was engaging and effective for this audience. Additionally, some feedback suggested the RMC could include even more interactive activities.

Many participants indicated they had limited prior knowledge of rangelands, northern pastures or the northern beef industry, both through written and verbal feedback. Most station staff in the NT have come from a variety of different agricultural and non-agricultural backgrounds, in vastly different areas and climates (pers. obs.).

Hence, the RMC content was designed to be understood by someone with no previous knowledge of the region and no science or agricultural background. Presenters used plain English, or slang terminology where possible to describe technical concepts and processes, rather than using scientific language that participants may not be familiar with. The deliverers were also flexible in the way each topic was presented, spending more time on things that were highly relevant or of interest to participants, and adapting presentation styles to the people in the room based on where they were from or what previous livestock/pasture experience they had. The average rating for how easy presenters were to understand was 4.8/5, so the level of language used to describe scientific processes that can be quite complicated was effective. The rating for if participants were more interested in the topics covered after the course was 4.3/5, and while this is not directly a measure of knowledge increase, it indicated that participants were much more aware of what was covered, and therefore more inclined to seek further information in future.

Delivering the RMC was also a valuable opportunity for new DAF staff to learn about rangeland management, enhance their public speaking and facilitation skills, expand their networks, and engage directly with producers. From 2022 to 2024, six DAF staff delivered their first RMC and worked with producers they had not met before. This, along with the positive feedback received from station managers and course participants has led to support from multiple organisations for the course to continue, and there has been interest to expand the course into other states. The RMC could also be used as a model to provide education to on-ground staff in other rangeland-based industries, offering an introduction to best practice land management and the "why" behind management strategies, and encouraging staff to seek a deeper understanding of the environment they work in. The annual recruitment of new station hands and high turnover of staff in land management service delivery agencies means there will be an ongoing need and demand for the RMC in the future.

Acknowledgements

From 2021 to 2024, the NT RMC was funded by the Australian Government through the Northern Hub project: Next Generation Land Managers. The authors would like to acknowledge all NT DAF employees who have assisted with upgrading and delivering the RMC. The authors would also like to acknowledge the contribution of the creator of the original RMC, Chris Materne.

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Developing next generation beef leaders to impact and influence within the rangelands

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Key words: Capacity building; Advancing Beef Leaders; Impact; Influence

Abstract

The Australian northern beef industry faces significant challenges in environmental stewardship, economic sustainability, and human resilience. The next generation of industry leaders must understand, develop, advocate for, and implement solutions to these issues. To support this process, Advancing Beef Leaders (ABL) was launched in 2020, as a joint initiative led by the Queensland Department of Primary Industries (DPI), and supported by private sector collaborators. A capacity building program, ABL aims to develop groups of emerging producer and community leaders who are skilled and enthused to pursue positive change in their industry, regions, and personal businesses. The focus of the program is to overlay relevant beef industry technical content with appropriate personal development, governance, and communication skills; encouraging participants to build stronger peer and mentor networks and spark the confidence needed to influence effectively in their businesses, community, and industry. By mid-2023, from 53 past participants there were 22 appointments to community and industry committees within two years of finishing their ABL programs. Also from the 53 participants were 45 examples of leadership progress such as applying for a higher-level leadership program, progressing careers, and getting directly involved as a co-operator in industry RD&E. Graduates have reported applying ABL learnings to their beef businesses, including adoption of on-property improved practices, better financial literacy, focus on drought resilience and business planning, earlier attention to family succession, and improved communications. Recently, another 22 new participants were selected for the 2024/2025 cohort. Advancing Beef Leaders has proved to be a program that opens pathways to leadership, enhances industry impact and adoption, and develops influence for graduates. With a growing interest from across Australia, the ABL program is excited to begin expansion nationally.

Introduction

Australian family beef businesses face a complex mix of biophysical, productivity, financial and family (people) challenges (Rolfe et. al. 2016). Better business management involves balancing these facets for long term success. Equally, the broader beef industry faces similar challenges at a larger scale beyond the farm gate. As these challenges grow, so does the need for technical and economic training. Agriculturalists the world over, regardless of the size of the enterprise, are motivated by the need for knowledge (Larard, 2022). In response to this, Governments and Natural Resource Management groups are investing significant resources to restore landscape health and productivity. Fundamental community expectations also include the beef industry achieving broader environmental outcomes such as reducing industry greenhouse gas emissions

(Rolfe et. al. 2016). Due to these social licence and economic pressures, it is no longer enough for family beef businesses to only be good at the basics of beef production. Appropriate resource management, savvy cattle marketing decisions, and managing the business's finances are management skills currently required to succeed in a multimillion-dollar beef business. Australia's beef producers need to move from thinking they are 'just' cattleman, to learning the market-centric approaches required of significant commodity suppliers (Larard, 2022).

Currently there are several leadership programs, scholarships and bursaries available to people in Australian agriculture. These include but are not limited to: The Nuffield Scholarship, Australian Rural Leadership Program, Rising Champions and the Zanda McDonald Award. All provide training for participants in increasing practical skills, industry knowledge, management skills and techniques through tailored mentoring programs, where graduates are well documented to progress on to significant industry roles or build family or corporate businesses. The Queensland Department of Primary Industries (DPI) identified an opportunity to develop a leadership program specifically for the northern beef industry, with a focus on family businesses as well as placing ABL as a pathways program for higher-level leadership programs.

In 2020 Advancing Beef Leaders (ABL) was launched with a small pilot group of beef producers and industry professionals in the Charters Towers district of North Queensland. The program aims to develop groups of emerging leaders who are skilled and motivated to pursue positive change in their industry, communities, and personal businesses. The program has now been delivered to seven peer cohort groups and this paper outlines the design of the program and its impact in the Queensland beef industry.

Methods

Participant selection

Participants for each cohort are selected by a rigorous and transparent selection process including a written application and interview with a selection panel. Selection criteria include qualities that indicate focus and passion for the beef industry, willingness to address industry challenges by being involved in community and industry leadership roles, and ability to work within a group. Peer groups are put together with eight beef producers, two agribusiness personnel, and one extension officer.
Each cohort of participants is facilitated and coordinated by an experienced industry professional facilitator and a DPI extension officer.

Program components

The ABL program is delivered over 12-months mostly through online meetings for 2 hours once a week for about 22 weeks of the year. The online sessions deliver content from six training modules: Understanding self and others; Governance; Business planning and financial fundamentals; Industry technical foundations; Industry spheres of influence; and Communication skills. Each module is presented by a mix of experts and other beef producers who practice the skills in their business.

There are three face-to-face meetings throughout the year including an introduction to the first module (Understanding self and others), a two-day supply chain tour and the final two-day communications module and graduation event.

In the second half of the year, participants work in a smaller group on an action learning project. Projects are designed by the group to deliver something that will benefit their community or the broader beef industry. The learning objectives of the group project include: understanding the importance of good group governance and function, application of program learnings from all modules, and learning how to collaborate with all relevant stakeholders and contribute appropriately to a community or industry topic of interest.

Participants are paired with a mentor of their choosing that they believe will help them address their goals and skill development targets. Mentor and mentee pairs meet regularly throughout the year in a private capacity.

Alumni

Graduates of ABL join the alumni network that fosters continuous improvement and peer learning through scheduled activities, training opportunities and other program events. Alumni are encouraged to take opportunities to become ABL mentors, guest speakers or hosts of activities for face-to-face events. In 2024 The Connection Table was launched for alumni as a “What next” platform providing leadership pathways to amplify their impact beyond completing the program.

Governance

ABL continues to be developed and delivered under a collaborative private and public sector partnership model. Each regional cohort is delivered by a private sector lead facilitator and a DAF coordinator. Each participating staff member receives substantial skills development, as well as significantly enhancing their industry networks. DPI co-ordinators are also able substitutes for the lead facilitators and program manager when required, giving them the opportunity to hone valuable facilitation and project management skills fostering professional development. There are also opportunities for all alumni to further their skills by going on to be mentors of future participants of the program, as well as be involved in program committees, planning and delivery. This structure of re-engaging alumni to lead within the program ensures the foundational values and culture remain as the program continues to expand.

Results

Since 2020, 53 participants have graduated from 7 cohorts. 22 graduates (41.5%) have been appointed to community and industry committees within two years of finishing their ABL programs. There are 45 examples of leadership progress such as applying for a higher-level leadership program, career progression, and becoming directly involved as a co-operator in industry RD&E. Graduates have reported applying ABL learnings to their beef businesses, including adopting improved practices on-property such as better financial literacy, focusing on drought resilience and business planning, earlier attention to family succession, and improved communication. The current 53 alumni remain connected to the program through social media platforms, attending a biannual forum and most recently, through partnering with The Connection Table.

During the 2024/2025 mid-point reflection step, the current 22 participants have already recognised improved confidence in their approach to new opportunities for personal and professional growth as well as gratitude for a new level of awareness and understanding of the beef industry supply chain.

Monitoring & evaluation (M&E) of past ABL cohorts recorded a consistently excellent participant satisfaction rating >85% for all online learning modules, and >90% rating for in-person events. The mid-point reflections of the first three modules of the 2024-2025 program has similarly documented exceptional results. Participants answer four questions using a rating between 1 and 7. The averages of the results of these questions are expressed as percentages in *Table 1*. ABL modules are designed as ‘tasters’, including skills and knowledge important to leadership and beef industry professional development. This program, Modules 1-3 have shown significant before-after knowledge improvement, are averaging >90% score for the value of the information to the individual’s business, and average >85% for the likelihood of making change/s.

Table 2. ABL participant feedback scores, modules 1-3 (2024/2025).

	How would you rate your knowledge and understanding BEFORE this module?	How would you rate your knowledge and understanding AFTER this module?	How valuable was the information you have been provided in the module in assisting you to conduct your business?	How likely are you to make this change/changes?
Module 1 Understanding Self and Others	47%	80%	97%	92%
Module 2 Governance	40%	77%	88%	84%
Module 3 Financial fundamentals	53%	79%	89%	82%
Average	**47%**	**79%**	**91%**	**86%**

Discussion

ABL has been developed as a tailored leadership program that overlays relevant technical skills with self-development that fosters attitudinal change and enables participants to build stronger networks and develop the confidence to contribute and influence. This is demonstrated through the large number of participants who have moved from the program into community and industry roles. The program builds capacity to create awareness of the significant challenges the beef industry faces throughout the supply chain that are specific to environmental stewardship, economic sustainability, and human resilience and participants reporting leadership progress are better placed to help address these challenges.There have been numerous occasions where participants have acknowledged that the skills and confidence developed through ABL have allowed for improved communication and conversations on property, which has resulted in better relationships and positive impacts on succession within family businesses.

Nettle et al (2022) reports that extension strategies that most facilitate practice change are peer-to-peer groups and one-on-one advice and they are most impactful when stacked together. This is consistent with the results ABL has achieved in participants adopting new practices that include better financial literacy, focusing on drought resilience and business planning, earlier attention to family succession, and improved communication. ABL participants were selected based on application criteria that also considered their likelihood to contribute to group culture such that learning from other group members was possible. Group engagement through face-to-face events was critical in building relationships necessary for successful online engagement. Creating groups with a balance of beef producers, industry professionals and service providers meant a range of personalities, technical skills and industry experience needed to be navigated with skills learned in the program. One-on-one advice was provided by mentors with whom participants met with on a regular basis.

The ABL Alumni recognise the program as being pivotal in their personal and professional development, often referring to the program as "life changing". The alumni have developed a sense of ownership of the program with a culture of support for each other, further increasing the cohesiveness of Alumni peer to peer learning and relationships. They have continued to expand their networks and the recent launch of The Connection Table has enabled further pathways to leadership development (The Connection Table, 2023). ABL fits comfortably into the landscape of agricultural leadership programs as a first steps program. ABL provides a pathway to more advanced or specific programs such as The Nuffield Scholarship, Australian Rural Leadership Program, Rising Champions and the Zanda McDonald Award.

ABL has positioned itself as a critical change agent, increasing the capacity of individuals for meaningful contribution and addressing challenges across all beef industry sectors. The successful delivery model of topical modules, mentoring partnerships, and group action learning projects facilitated by trained extension and adult learning practitioners, has proven ABL to be a leadership development program unique amongst the beef industry.

The ABL program has built a respected reputation within the beef industry due also to the high calibre of ABL alumni . As a result, the ABL program is now in demand across other states and territories of Australia. There is much to gain for the beef industry in Australia through slowly expanding the footprint of the ABL program beyond Queensland. Improving the knowledge and capacity of the next generation of beef leaders will only benefit the beef industry further.

As of 2025/2026, ABL will endeavour to meet interstate demand for the program and begin to expand across the Northern Australia and New South Wales.

Acknowledgements
The ABL program gratefully acknowledge the funding provided by Australian Government's Future Drought Fund and the Queensland Government's Drought and Climate Adaptation and Reef Water Quality Programs. Thank you to Alison Larard for the passion and commitment to the program development as well as to supportive DPI colleagues Joe Rolfe (deceased), Bernie English, Tim Emery, Kylie Hopkins and Emma Knight who have contributed to the growth of the program. Thank you to the key facilitators Ben Reeve and Amanda Roughan for their group facilitation to date. Thank you to the various professionals who deliver the program milestones, and to the industry leaders who have volunteered their time as mentors. Most importantly thank you to the ever-growing Advancing Beef Leaders Alumni who continue to have positive influence by showcasing impactful leadership across all industry tiers.

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Grazing Fundamentals EDGE: partnerships, collaboration and co-design in practice

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Key words: Grazing management; land management; peer-to-peer learning.

Abstract

Across the Australian southern rangelands, 54% of the total land area is utilised for extensive livestock production (Hacker and McDonald 2021). With such a significant influence over land management, it is critical that pastoralists are supported to implement land and livestock management practices that ensure ongoing sustainability of both landscapes and businesses. The Grazing Fundamentals (Southern Rangelands) EDGE course is a capacity building workshop that builds foundational knowledge and skills in the areas of land management, grazing management and livestock production. It has been developed to suit a range of learning styles with the inclusion of presented information, classroom-based activities and hands-on exercises. Using varied teaching and group facilitation methods, the workshop encourages attendees to share their knowledge and observations, supporting peer-to-peer learning.

The initial delivery of this workshop in South Australia was highly successful, engaging 146 workshop participants who manage a total of 22 million ha and reported an overall satisfaction score for the workshop of 9.4/10. 92% of participants indicated an intention to change management practices as a result of attending the workshop, with the most common area of change being to begin assessing land condition. The collaborative nature of the project is a key factor that determined the workshops success. In instigating the project, partnerships were formed with relevant industry stakeholders to effectively leverage the varying resources and skillsets of partner organisations. This allowed consensus to be formed on technical concepts to standardise terminology and messaging between northern and southern rangeland systems. Content was co-designed and delivered by project partners, ensuring relevance and appeal to the target audience.

Introduction

The Australian southern rangelands are described by Hacker et al (2019a) as lying outside of adjacent mixed farming zones with annual rainfall mostly within the 250mm isohyet and rainfall patterns being either winter dominant or aseasonal. While definitions of the southern rangelands vary (Foran et al. 2019), this definition was deemed most relevant as it aligns with the production area this extension product targets.

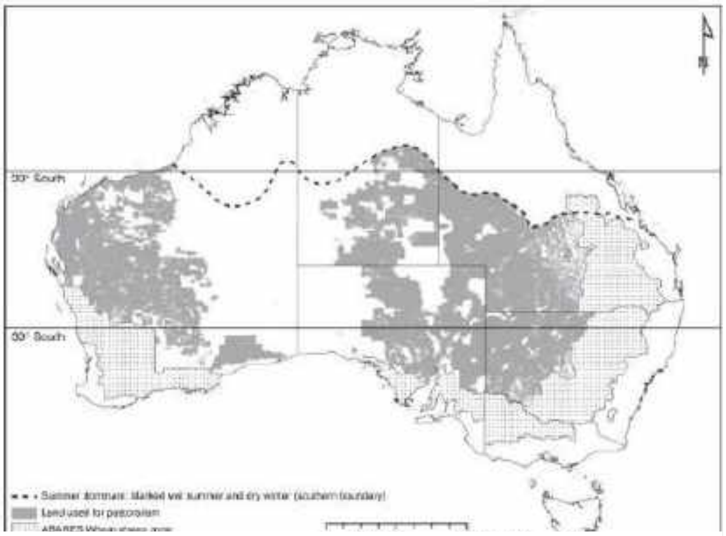

Figure 1. Approximate boundaries of the southern rangelands
(Hacker et al. 2019a).

As is shown in Figure 1, the southern rangelands makes up a significant portion of the Australian land mass. Within the southern rangelands 54% of the total land area is utilised for extensive livestock production (Hacker and McDonald 2021). With such a significant influence over land management, it is critical that pastoralists are supported to implement land and livestock management practices that ensure ongoing sustainability of both landscapes and businesses.

Decades of primarily public investment in research and development has led to a valuable knowledge base being available for best practice grazing management, land management, and livestock production principles within the Australian rangelands context. However, collation of this literature into producer facing resources such as technical guides and capacity building workshops has largely been limited to northern rangelands systems and the southern rangelands of New South Wales. These existing products include Grazing Fundamentals (Northern) EDGE, Grazing Land Management EDGE and Tactical Grazing Management. The southern rangelands are unique to Australia's northern rangelands as they incorporate a variety of chenopod dominated land systems, have a diversity of both C3 and C4 plant species and are utilised for grazing of sheep, cattle and goats. For this reason, it is important that resources be designed specifically for the region.

This extension resource gap had been identified by various southern rangeland practitioners. Through the Australian Governments Future Drought Fund, the South Australia Arid Lands Landscape Board (SAAL) delivered the 'From the Ground Up' project, a multi-year demonstration type project designed to build drought resilience. Within this project, SAAL partnered with Meat & Livestock Australia (MLA) to develop and deliver a one-day training course that covered the foundations of animal nutrition, land management and grazing management, specifically for the southern rangelands.

This course is known as Grazing Fundamentals (southern rangelands) EDGE. Course objectives are to build actionable technical knowledge and skills with pastoralists to increase the environmental and economic sustainability of pastoral businesses.

Methods

In delivering this project, MLA engaged six technical experts to contribute under the structure of a project Working Group. This group was involved in developing the course outline, content and extension design, delivering the course and providing strategic and tactical advice on project delivery. This level of collaboration bought together a diverse range of skills, knowledge and experience across research, development and adoption within the Australian pastoral industry.

The course was designed to cover three core modules of nutritional requirements for animal production, grazing land ecosystems and grazing management. A focus was also placed on teaching methods to ensure it incorporated practical activities, supported peer-to-peer learning and appealed to varying learning styles.

Course development

The approach of the project team was to use existing industry resources as a foundation for the course to reduce the need for starting a literature review from scratch. Content updates and/or gaps were identified, and literature was subsequently identified, collated and reviewed to inform the development of new material. Sections that required specific content development for the southern rangelands were climate, the management of shrublands and grazing management. Initially, a participant/deliverer technical manual was completed, which then guided the development of workshop slides and activities.

A significant aspect of the course development process was the delivery of a pilot workshop to SAAL staff and stakeholders with a knowledge of the region and target audience. Feedback from this group, combined with reflections from the working group strongly informed the final product. A key outcome from this was better defining the target audience and intended learning outcomes. The audience was defined as younger industry participants or those with less experience and exposure to scientific rangeland management concepts. The learning outcomes were sharpened to focus on key principles of rangeland management and how they may be implemented on-ground.

Course content was developed to suit diverse learning styles, using a mix of presented information, classroom-based activities and hands-on exercises. A focus was placed on deliverers utilising a range of presentation and facilitation methods to encourage participants to share their experiences, ask questions and learn from each other, through a supported peer-to-peer learning process.

Course delivery

Course delivery occurred as two distinct series in August and October 2023. These times and locations were guided by SAAL staff with local knowledge of participant availability and competing events.

Courses were co-delivered by two working group members, with a third working group member also co-delivering three courses under a trainee model. Alternating delivery of the workshop sections between deliverers allowed all to become comfortable with all course material, facilitating future commercial delivery.

Course review

Courses were reviewed primarily by a formal participant evaluation form. Course deliverers, SAAL representatives and Working Group members present at each workshop also provided feedback. To review and update the course in response to evaluation forms and peer observations, two different processes were followed.

In the first instance, debriefs were held following each workshop to share feedback and review evaluation forms. Wherever possible, changes and updates were made at this time to present the best product for the next workshop.

Where identified updates required more significant changes or research, these were addressed at the end of each workshop series. The primary changes made to the course were the way in which practical activities and the case study property were presented.

Results

Eleven workshops were delivered to 146 participants, at an average of over 13 people per workshop. These participants represented 66 pastoral businesses and a total management influence of over 22 million hectares, 150,000 head of cattle and 370,000 head of sheep.

The overall value and satisfaction scores for the workshops were 9.1/10 and 9.4/10 respectively. Value scores broken down by module (Nutrition, Grazing ecosystems, Gazing management) show a ratings difference of only 0.1/10 between each module.

Overall intention to implement change as a result of attending the workshop was measured at 92% of participants. Further insight to this figure is provided in Table 1, where the most common intended change to implement, at 64% of participants, was to assess land condition of paddocks.

Table 1. Summary of intended practice change

Will you make any changes?	**Yes %**	**No %**	**Maybe %**	**Already doing it %**	**Not applicable %**
Review livestock nutritional requirements	51	0	19	22	8
Review stock numbers and feed supply around key decision dates	48	0	6	37	8
Assess the land condition of your paddocks	64	0	4	28	5
Work out safe utilisation levels and/or carrying capacity	54	0	16	23	7
Do a forage budget	43	5	38	6	9

Discussion

When considering workshop results, they can be compared to the benchmarks maintained by MLA for delivery of similar industry training programs. A key performance indicator (KPI) for producer adoption programs is to maintain satisfaction and value scores >7.5/10, indicating that this course far exceeded that benchmark with the above listed value and satisfaction scores of 9.1 and 9.4/10 respectively. The consistency of module value ratings is also quite significant in demonstrating the relevance of all three course modules and the consistent high quality of delivery.

Some key learnings gained though the delivery of this project include:

- The target audience and intended learning outcomes must be clearly established at the start of the course design process.
- Having deliverers involved in course development ensures consistency between workshop design and delivery, streamlining progress from one stage to the next.
- Partnering and collaborating with local service providers is highly beneficial in accessing local networks to ensure strong attendance, provision of locally relevant resources and ground truthing of course material prior to delivery.
- Consider course content order to deliver the 'hook' upfront in the workshop. In this instance, the livestock nutrition session was of high interest to producers so was delivered first. This contributed to early and sustained engagement throughout the day.
- The structure of the workshop reinforced the value of activities for engagement, including outdoor, hands-on, 'on your feet' type exercises.

The course supported participants to identify opportunities to enhance their business productivity, resilience and sustainability in relation to livestock and land management. By providing information alongside practical activities, participants were encouraged to consider how they could apply management concepts to their own business. Combined with the expertise of regional service providers, workshop deliverers and peers, participants were also given an opportunity to discuss, share and learn from the experience of other livestock producers and land managers.

The objective of creating an actionable capacity building product specific to the southern rangelands was achieved. Its success is validated in evaluation data that indicates a very high portion of participants intend to implement a change in management practice as a result of course attendance. This course now provides a valuable resource, accessible to producers right across the Australian southern rangelands through a commercial delivery model.

Initiated through an industry partnership and executed through broad collaboration, this project has demonstrated the value of co-design practices to develop and deliver high impact extension and adoption products.

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Transformation of tacit knowledge into recommendations for ranchers through rural extension in Uruguay.

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Key words: living laboratory; open innovation; extension; grassland management.

Abstract

Grasslands cover more than half of the Uruguayan territory. The Instituto Plan Agropecuario (IPA), a national extension agency, is implementing a project to systematize and promote good grassland management practices (2021-2025). The project considers the knowledge that ranchers have (tacit knowledge) and thanks to which they have been able to successfully develop in a changing and unpredictable environment. This initiative uses an open innovation framework through 26 "living laboratories" installed in different parts of the country. Through a monitoring and evaluation system, 28 key grassland management practices have been identified, which are classified into five macro-variables, which interact with each other and with the broader context. The macro variables are: infrastructure, strategic productive areas (EPA), grazing management, livestock management, and monitoring system. The rancher is responsible for decision-making. Due to limited cognitive abilities, incomplete information, and the complexity of the context, ranchers often adopt a "satisficing" approach rather than "maximizing" when making decisions. To conclude, a conceptual model was developed that describes the main macro variables related to good grassland management practices. Monitoring these macro-variables would allow ranchers to establish their current situation and co-design a route of action together with ranchers and extension technicians. Paddocking is highlighted in the case of infrastructure, the proportion of improved area in the strategic production areas (EPAs), the proportion of the ranch over 5 cm (PRO5) in the case of grazing management, strategic supplementation for livestock management and the importance of having a monitoring system. The work balance reveals that there are agents who have two hours a day to "think" about the management of macro-variables and there are others who, due to the dedication required by routine work, do not have this possibility. Extension has an important role in promoting learning, through integrating and sharing different types of knowledge, and reflective processes and group strategies.

Introduction

Grasslands currently occupy 55 percent of the national territory (MapBiomas Uruguay, 2024), constituting the main feed source for livestock in Uruguay. There is scientific evidence of the importance of grasslands management in determining good economic, productive and environmental results (Torres et al. 2024).

Recognizing that ranchers have an important capital in accumulated tacit knowledge, which is valuable, little known and little understood, the Instituto Plan Agropecuario is implementing a project called “Grassland Management”, which aims to rescue this knowledge, systematize it and make it explicit to the rest of the national livestock industry.

Methods

Twenty-six ranches (cattle and sheep) located throughout the country were selected. The sampling was done by convenience, choosing ranchers who managed grasslands in a way that allowed them to obtain outstanding results.

Under a theoretical framework of open innovation and adaptive management (Holling 1978), each ranch was taken as a “living laboratory” (Higgins et al., 2011) and monitoring was initiated that covered productive, economic, environmental and social aspects (fiscal years 2021/22, 2022/23, 2023/24).

The variables monitored and their frequency were: sward height of each paddock (seasonally), weight of cattle (seasonally), weight of sheep (seasonally estimated); from this information an index was used to estimates a forage balance, Food Plate Index (Duarte et al. 2021). Net primary production area (NAPP) was also estimated. All this information was recorded in a platform called iPasto (Lombardo et al 2021).

Information was collected to estimate meat production, economic results and environmental performance indicators. A typology of ranchers was made, through semi-structured questionnaire, since it combines open-ended questions with a general consultation scheme, allowing flexibility to go deeper according to the answers given by the interviewee to characterize the manager's vision of the aspects that affect grassland management, and the work balance was calculated (Dieguez et al., 2009). The environmental livestock tool (EMAG) (Becoña, 2020), the index of ecosystem integrity (IEI) (Blumetto, 2021) and environmental performance indicators included in the livestock environmental footprint (Paruelo et al., 2023) were applied.

This information was managed in 150 dialogue workshops - biannual frequency - with ranchers neighbouring each laboratory. They were evaluated with a focus on learning.

The database was analysed through descriptive statistics, performing linear regressions and multivariate analysis, using the statistical package Infostat/L version 2017.

Results

The farms analysed were dedicated to cattle ranching, with an average area of 1,295 hectares, ranging from 60 to 5,500 hectares. Regarding production systems, 40% of the farms focused on breeding, 24% operated a complete cycle, while the rest were divided among incomplete cycle (12%), backgrounding (12%), and finishing (12%). The average improved pasture area was 23%, with some farms heavily relying on improvements; 11 of them had over 90% grasslands, and three operated entirely on improved pastures.

Grazing methods varied across the farms. While 24% implemented rotational grazing, 28% combined continuous grazing with rest periods and rotational modules. Another 19% practiced continuous grazing with paddock rest, whereas 7% maintained continuous grazing without rest. Sheep were present in more than half of the farms (52%), with an average sheep-to-cattle ratio (S/C) of 1.21. Meat production levels averaged 114 kg/ha, fluctuating between 70 and 248 kg/ha, while capital income (CI) stood at 92 USD/ha, with values ranging from 28 to 171 USD/ha. The economic input/output ratio was 0.6, with a variability between 0.4 and 0.8.

Net aboveground primary production (NAPP) for the 2021/22 season aligned with the historical average recorded between 2000 and 2024. However, in 2022/23, NAPP was 9% lower, whereas in 2023/24, it exceeded the average by 18%.

A survey conducted during the study identified 28 good practices related to grassland management. These were grouped into five key macro-variables: infrastructure, strategic productive areas (SPAs), grazing management, livestock management, and monitoring systems. Infrastructure included watering points, paddock subdivisions, shade, roads, handling facilities, and the strategic use of attractions based on vegetation heterogeneity. Strategic productive areas (SPAs) incorporated modules designed for high forage production

(MHFP) (Pereira Machín, 2017) and those for preventing forage crises (MFCP) (Pereira Machín et al., 2018), which functioned as deferred forage reserves. Grazing management extended beyond specific methods and instead considered morphogenic factors essential for maintaining plant function under grazing pressure. Livestock management encompassed breeding strategies, ewe management, genetics suited to field conditions, and the strategic use of supplementation to enhance grassland efficiency. Lastly, monitoring systems served as tools to track activities closely, allowing for informed decision-making and proactive adaptation.

At the core of this conceptual model is the decision-making agent, which could be a rancher, a company board, a rural manager, or a family unit overseeing the system.

Data from the monitoring process highlighted important aspects of grassland management. The balance of work showed that while some managers dedicated at least two hours per day to analysing macro-variable management, others were entirely absorbed in routine tasks, limiting their ability to plan strategically. The variation in paddocking and infrastructure played a significant role in explaining fluctuations in meat production. Differences in the improved pasture area were closely linked to the stocking rate, the proportion of the ranch with pastures exceeding 5 cm (PRO5), and overall meat production levels. The proportion of the ranch with pastures above 5 cm was also strongly correlated with stocking rate and meat production.

Strategic supplementation was implemented only in specific cases, and its impact on economic performance was evident only in years of good pasture availability. The proportion of native grassland contributed positively to environmental performance indicators. However, although increasing improved pasture areas resulted in higher sward heights, excessive reliance on pasture improvement came with trade-offs, as it led to higher greenhouse gas emissions due to increased input usage.

Discussion

Grassland management can neither be seen in isolation nor fixed. It is necessary to have a systemic view that considers its changes in the temporal dimension. For the discussion of the results, we will use an analogy with the evolutionary approach developed by Charles Darwin (1859). The interesting thing about Darwin was that he managed to explain the phenomenon of why evolution occurs (Vorzimmer, 1969).

The theory of evolution is based on three pillars: variability, natural selection and heredity (Mayr, 2002). For evolution to operate, there must be variation. In the case of grassland management, if we weight each macro variable as the producer in each of them can be bad, good or excellent; there are 243 possible combinations, where some give very good results, and the worst determine that the companies are out of the game.

In the case of grassland management, the selection is given by the context, and the companies that “learn” survive. Such learning positions them better for future events, because it is based on a better understanding of their ranch and contextual factors. We call this “sustainable adoption”.

In the case of the “selected” ones, for them to endure, there must be a mechanism that transmits these characteristics (*i.e*., the self-replication of DNA in the theory of evolution), here through what we call “cultural transmission” (Cavalli-Sforza et al 1981), which can occur vertically from parents to children or horizontally among ranchers.

Extension must devote efforts to achieve learning and encourage cultural transmission, to “prevent” natural selection from operating wildly.

The producer manages the different macro-variables through a “filter” that is constituted among other things by his purposes, his age, education, production system, and the external context. It is necessary to dedicate time to “think” this management and for that the organization of the work and its planning is important. Decisions are always made with insufficient information, which is why it is said that it is a process with limited rationality, where the result is satisfaction (Simon, 1957). Optimization implies considering the 5 macro variables and it is more realistic to think that the agent prioritizes one or some of them.

One of the key benefits of the conceptual model is its ability to provide guidance through monitoring, helping to assess the current situation and determine the most appropriate decisions for each macro-variable. This process enables self-referencing, which, when combined with a forward-looking vision, establishes a clear course of action.

In this context, infrastructure plays a crucial role, as highlighted by ranchers. Its proper implementation facilitates improved forage management by optimizing grazing distribution and access to key resources. Strategic productive areas are reflected in the extent of improved pastures and their influence on grass height, meat production, and the proportion of the ranch with pastures above five centimetres. These areas also support high concentrations of cattle while maintaining good performance, which indirectly contributes to the regeneration and relief of natural grasslands.

Regarding grazing management, the PRO5 variable emerges as a critical determinant of meat production. Its reference values exceed those traditionally used, suggesting a shift towards more effective and productive management strategies.

Livestock management, which involves both cattle and sheep, along with adapted genetics and strategic supplementation, plays a crucial role as it interacts with all other aspects of the system.

Having a monitoring system is essential for making proactive decisions, allowing for adaptation and course correction when necessary. Without a monitoring system, self-referencing becomes impossible.

Conclusions

A conceptual model was elaborated that describes in a systemic way the main macro variables that make up good grassland management practices. It can be used as a tool for self-evaluation in its different macro variables so that, through monitoring, decisions can be made in advance to improve management. Paddocking is highlighted in the case of infrastructure, the proportion of improved area in the EPAs, PRO5 in the case of grazing management, strategic supplementation for livestock management and the importance of having a monitoring system.

In the case of the improved area, these must be implemented efficiently, taking care of the use of inputs. The role of the grassland as a determinant of good environmental performance indicators is evident, providing the systems with resilience and resistance.

The persistence of the ranches in the long term is based on adapting to the changes of the context (learning in ascending scale), within the framework of the designed route of action. To this end, it is necessary to promote: i) reflective processes (critical thinking) that necessarily require time and ii) group strategies that promote cooperation. The organization of work in a simple way and delegation collaborate, to the extent that it generates time for reflection.

Extension has an important role in fostering learning, through integrating and sharing different types of knowledge, and reflective processes and group strategies.

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Carbon in the rangelands: Developing a training package for pastoralists

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Key words: carbon; emissions; agriculture; extension; training

Abstract

Agriculture accounts for approximately 17.4% of Australia's national greenhouse gas emissions, of which around 68% is attributable to enteric fermentation (DCCEEW 2022). In line with national and global climate commitments, the pastoral industry will play a significant role in helping to reduce emissions, whilst also acting as a major sink for carbon storage in vegetation and soils.

The ability for pastoralists to be able to calculate, demonstrate and manage their enterprise based on their carbon footprint is becoming important to maintain social license and market access. Enterprises with a low carbon position may also be presented with opportunities around value-adding and business diversification.

When it comes to on-farm emissions reductions or carbon sequestration, Australian pastoralists express concern and confusion, and are unsure what actions to take or who to trust for independent information, thereby stalling adoption. Carbon EDGE, a new training program for the red meat industry, was born out of the need to scale up industry capacity, responding to these adoption challenges.

The process involved the co-design of a two-day workshop with supporting resources by a Working Group of livestock producers, service providers, supply chain representatives and researchers.

Six pilot workshops and two train-the-trainer sessions were delivered in different regions to seek feedback from over 100 industry participants representing 2.9 million ha under management. This included a specific focus on ensuring the program was relevant for rangeland environments.

Covering key terminology and concepts; supply chain and policy drivers; environmental markets; carbon accounting and on-farm interventions, the program aims to provide participants with information to make confident decisions and form an action plan aligned to their own production system and business goals. The success of the program was reflected in satisfaction scores averaging 8.5/10. The need for continued extension in this space was reflected in the project outcomes, with participant confidence levels sitting between 3-3.5 out of 5, and over 90% of attendees indicating their intent to take action following the workshop.

Introduction

Whilst many livestock producers and industry service providers recognise the need to demonstrate action on decarbonisation, there are several barriers to on-farm emissions reductions, sequestration and reporting (Henry unpublished; Farners for Climate Action 2023):

1. An absence of policies or incentives for sustainable practices, whether those be government, supply chain or market-driven.
2. High upfront costs and limited access to capital for investing in sustainable practices.
3. Uncertainties in the methods for measuring and validating on-farm change.
4. Confusion due to mixed messaging and difficulty sourcing information from independent (non-commercial) sources.
5. A lack of independent advisors with the expertise to support on-farm reporting, planning and implementation of emissions-reduction strategies.
6. The pace of research and development for technologies to support on-farm emissions reductions.

Carbon EDGE, a new training program for the red meat industry, was born out of the need to scale up industry capacity, targeting several of these adoption challenges (in particular, points 4 and 5, above).

Consistent with the Adoption Strategy of Meat & Livestock Australia (MLA), Carbon EDGE was designed to increase knowledge and skills of participants, building on other awareness-raising activities already on offer across the sector (MLA 2024). Developed in the context of whole-farm business planning, Carbon EDGE was also designed with a focus on increasing participants' business sustainability, profitability and/or productivity.

Method

This project was undertaken with a team made up of MLA staff, expert service providers and a Working Group. The ways of working were established early in the project, with the implementation of project management protocols and regular project meetings. The project was divided into two stages, with service providers selected to deliver each stage:

1. Stage 1 involved the development of a technical manual. This underpinned the development of other resources in Stage 2.
2. Stage 2 involved the design of the training package using best-practice extension principles. This included the development of training resources, delivery of two train-the-trainer sessions and six pilot workshops, and the project evaluation.

The Working Group, comprising of livestock producers, advisors and technical experts, was used as a sounding board for both stages. The group was formed through an Expression of Interest process, with participants representing different regions and production systems, including the southern and northern rangelands.

Stage 1

The Working Group determined the outline for a "master" technical manual, which could be used with supplementary material to ensure relevance for different regions and production systems. The service provider subsequently undertook a review of Australian and international literature for the development of five modules: Greenhouse gases 101; Greenhouse gas accounting; Carbon credits and carbon neutrality; On-farm emissions; and On-farm sequestration. MLA staff provided additional content for the manual with a focus on livestock production. It was reviewed by the project management team and Working Group before being finalised.

Stage 2

The design of the training package was based on a set of learning outcomes determined by the Working Group:

- Improving carbon literacy and understanding of carbon farming, carbon sequestration and greenhouse gas emissions.
- Increasing participants' level of confidence around the carbon accounts for their business.
- Participants have identified short and long-term actions to reduce their emissions and increase the sequestration occurring within their farming business.
- Participants have the tools and knowledge to critically assess actions which fit within their business.

Information was presented through a mix of visual, auditory, reading, written reflection and activity-based learning. Activities were designed to incorporate a mix of individual reflection, small group work, teamwork, presentation and role play.

An important outcome of the Carbon EDGE program was for each participant to develop an Action Plan to align to their own business objectives and opportunities. The Action Plan was broken down into step-by-step activities to complete throughout the workshop, set out in a participant workbook.

During this stage, the workshop resources were also developed. This included a participant manual (a simplified and more visually engaging version of the technical manual), a slide deck, run sheet, evaluation forms, activity information, and supplementary regional materials for deliverers (e.g. datasheets, case studies).

Based on the content developed in Stage 1 and the learning outcomes identified in Stage 2, it was determined that the program should be delivered in person over two days. The training program was designed using a "flipped learning" model in which participants are provided with information prior to attending and are given the opportunity to revisit the material during the workshop. The flipped learning model for Carbon EDGE was designed to leverage existing online training programs, tools and 'how to' videos.

Pilot workshops were run over a five-month period in different regions of Australia. The pilot workshop deliverers were service providers already involved in the project via the Working Group, who undertook online train-the-trainer sessions before the workshops. Extensive preparation was required for deliverers to familiarise themselves with the material and customise the information for each region (environment, production system, livestock enterprise, markets etc). Two deliverers, and MLA staff, were present at each pilot workshop.

Updating the training program was an iterative process, with adjustments tested after each of the pilot workshops. A major revision of the training package was completed following collation of the workshop feedback from all six pilots, taking into account the reflections of workshop deliverers. An additional train-the-trainer workshop was offered in person for new deliverers after this process had been completed.

Results

Six pilot workshops and two train-the-trainer sessions were run in different regions to seek feedback from over 100 industry participants representing 2.9 million ha under management (see Table 1). Participants travelled extensive distances to workshops, with representatives from rangeland production systems present at four of the six sessions – Mackay, Roma, Narrabri and Alice Springs.

Table 1. Pilot Carbon EDGE workshops delivered

Pilot location	Date	Producers	Others
Mackay, QLD	9 – 10th November 2023	10	0
Benalla, VIC	5-6 December 2023	15	5
Roma, QLD	15-16 February 2024	20	1
Narrabri, NSW	20-21 February 2024	16	2
Coonawarra, SA	27-28 February 2024	15	4
Alice Springs, NT	18-19 March 2024	9	10
Totals		85	22

Participant feedback

Pilot workshop participants completed feedback and evaluation forms to support the review of the program. The forms included questions related to their knowledge, attitudes, skills and aspirations (KASA), completed before and after the workshops. The average percentage change in KASA across all workshops was 7.6%. Base knowledge, as evidenced by the pre-course answers, was quite high, and the course led to an improvement in the level of correct answers. However, it was also determined that the knowledge questions were too simple, and the forms have since been updated. Participants in all workshops improved their attitude/confidence in carbon farming and greenhouse gas related topics by an average of 23%, with post-workshop confidence levels sitting between 3–3.5 out of 5 (self rated).

Participants rated overall average satisfaction in the workshop delivery and content as 8.58/10. Over 90% of attendees also indicated their intent to take action following a workshop. When participants were asked what action they would take, common responses included: completing a carbon account; exploring on-farm interventions (cited examples of these interventions were highly dependent on location and production system); further self-educating on the topic or; in the case of advisors, looking for opportunities to support primary producers by offering similar training.

Deliverer feedback

Thirteen advisors were trained as deliverers. Advisors in the first cohort were involved in online train-the-trainer sessions and the delivery of the pilot Carbon EDGE workshops. They reiterated the need for at least two deliverers per workshop to effectively support participants during activities, especially with carbon accounting. The complement of two deliverers also proved useful to be able to cover the material in depth – particularly if one deliverer has expertise in livestock production and the other in carbon farming.

Participants in the second cohort completed a one day in-person training session which they rated 9/10, on average, for meeting their expectations. They will be paired with accredited deliverers to complete workshop delivery as part of their training.

Discussion

Feedback from the pilot workshops reflects a positive response to Carbon EDGE. The results demonstrate the importance of ongoing extension on this subject, with significant scope still to increase confidence levels across the industry and high numbers of participants expressing an intent to take action. The continued success of Carbon EDGE and broader industry adoption relies on several factors:

Delivery model

MLA's EDGEnetwork workshops are typically delivered under a fee-for-service model. With the availability of no-cost or low-cost extension programs – and in some cases a perception that the support for emissions reductions should come from government or supply chain – there was mixed appetite from producers to pay to attend (the pilot workshops were heavily subsidised). This issue would be alleviated if supporting organisations, such as government, industry bodies, NRM groups or corporate agriculture, could provide ongoing subsidies. To secure this type of funding, the program would need to ensure it meets the needs of these organisations, and complements (rather than duplicates) other extension services on offer.

The extension ecosystem

It is likely that complementary models of extension will be required to support on-farm adoption, taking the training knowledge and concepts into the field. This may include, for example, advisor upskilling, long-term practice change programs, grower/producer groups, or the incorporation of relevant information into existing and well-established industry programs (e.g. BMP programs).

Currency

Given the frequency of change and the level of investment in new R&D in this space, Carbon EDGE will require regular updating to remain current. This is particularly pertinent for rangelands environments where less is known about the interventions available to livestock producers to reduce their emissions, and information in Carbon EDGE is lacking (which could further exacerbate confusion and/or low confidence of pastoralists).

It will also be important to reflect developments in Australia's Carbon Market and emerging Nature Repair Market. As methodologies are retired and released, producers will want to understand the options available to them. The possibility for interactions between carbon projects and biodiversity projects are yet to clarified.

Additionally, as new extension programs such as the Federal Government's Carbon Farming Outreach program become available, Carbon EDGE will need to be reviewed to ensure consistent, reliable and accurate information is presented to industry. Engagement with relevant research and extension providers will be essential.

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A life in the Central Australian pastoral industry starts here – creating future land managers through Rangeland Management Courses

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Key words: training; pastoralism; rangeland management; careers

Abstract

The Central Australian Rangeland Management Course (RMC) is a free, one-day workshop that is delivered on-station for new staff. It has been designed specifically for the beef cattle industry operating in arid regions with an extremely variable climate and land capability. The course introduces pasture dynamics, species identification, carrying capacity, cattle nutrition, poisonous plants, weeds and fire management. Participants learn about arid zone ecological processes and climate characteristics that drive pasture production.

The course has a strong practical component and one of the most popular activities involves taking participants into the paddock to find and identify pasture species. Participants also learn how to assess land capability and land condition. For many participants, who are often new to the region, these activities are their first introduction to the plants that form the basis of the grazing enterprise, and they are often amazed at the variety of species.

The first course was conducted in early 2024. Overall, the feedback shows a positive response to the course. Many participants did not feel they had good prior knowledge but found the course very valuable; with the accessibility of the course attracting participants who would not normally attend on their own accord. There has been considerable interest for ongoing connection and support for graduates of the course in the form of WhatsApp groups or a similar platform.

Delivering the courses in a familiar 'home' environment, surrounded by peers, facilitates a positive and relevant introduction to rangeland management. In addition, it introduces people new to the industry to Extension Officers and other professionals they might work with throughout their career.

Introduction

The Central Australian Rangeland Management Course (CARMC) is a free, one-day workshop created by the Northern Territory Department of Agriculture and Fisheries (DAF) designed to upskill early career station hands in Central Australia. It is based on the highly successful Rangeland Management Courses that have been offered on the Barkly Tablelands and the Katherine district for the past 20 years. The courses offer an introduction to pasture dynamics, species identification, carrying capacity, cattle nutrition, poisonous plants, weeds, fire management and biosecurity. However, the northern courses are designed for a pastoral system that is based on a relatively reliable wet season and on extensive, uniform Mitchell grass pastures, quite different to the highly variable climate and landscapes of the arid Centre. With funding from the Northern Western Australia and Northern Territory Drought Resilience Adoption and Innovation Hub (Northern Hub), we customised the Rangeland Management Course to address the unique, environmental challenges of grazing cattle in arid regions.

The course is specifically designed to suit early career station staff. For many participants, this is their first time working in arid Australia. While they bring plenty of enthusiasm and energy to their work, and perhaps some experience handling cattle, they often haven't yet had the opportunity to gain any arid rangeland management knowledge. The course contains lots of practical activities and is designed to be delivered on-station.

Methods

We used the existing RMC as a starting point for designing the Central Australian version. To make it regionally relevant we reviewed the content of existing publications which are aimed at the station management level. The primary resources included the Central Australian Grazing Land Management (GLM) EDGE workshop (Chilcott et al. 2005), various field day presentations designed for Central Australian cattle producers (Kain, pers. comment.), case studies and recommendations from local reports on fire and weed management (Edwards and Allan 2009, DEPWS 2021) and historical documents relating to poisonous plant events in the region. We also took advice from local producers about the information they wanted their staff to know.

While the northern RMC describes a grazing model designed for a relatively predictable wet/dry season, the CARMC needed to describe the fundamental ecology of the arid environment in Central Australia.

One of the strengths of the original RMC is that it is designed to be delivered on-station. On the very large, Barkly properties it is quite common for stock camps to have 10 or more early career staff. It makes sense to train them in a group and on-property, as there is no travel time and the benefits of working with their peers are two-fold; participants are often more relaxed around people they know, and they can share their learnings and experiences after the course. However, in Central Australia, many properties only have 2 or 3 staff which isn't enough to support good group learning. Sometimes it is possible for neighbouring stations to get together and host a course. However, we also had to find a way of getting larger groups together.

Results

Course content

We have created a series of modules using an updated PowerPoint presentation with plenty of practical activities. The Pasture Dynamics module is the first of its kind in explaining the fundamentals of arid Australian ecology and how it relates to pastoral activities to early career station hands.

Our primary focus was to describe the variability of rainfall (within and between years), the importance of understanding 'pasture growth events', the effect of winter rain vs summer rain, how to distinguish between a seasonal rainfall response and land condition, identify different land types and their capability, and identify pasture species (Photo 1) and their grazing value.

Photo 1: Early career station hands use pasture identification guides to identify native grass species and their grazing value.

While most people associate Central Australia with low rainfall, the reality is much more complex and variable. Very high rainfall years do occur, but long periods of low rainfall are more common. When it does rain, almost half the rainy days will occur as isolated occurrences, just enough to settle the dust but not grow any pasture. Hence the concept of *growth events*. Soil moisture levels need to remain conducive to growth for at least a week to stimulate plant growth and germination of new plants. For plants to reach maturity and grow a good bulk of pasture, soil moisture needs to be available for about 4 weeks. In central Australia, this requires at least 60mm of rain and on average, to occur once per summer – critical information for people who rely on pasture growth for their business!

We also discuss the characteristics that make Central Australia pastorally productive. The landscape is old, highly weathered, and often nutrient poor, creating significant landscape variability and areas of low pastoral capability, but also patches of moderate soil fertility. The combination of moderately fertile soil and low rainfall results in plant growth with high nutrient concentration and some of the highest quality pasture in the Northern Territory. In addition, the landscape supports a suite of vegetation that can take advantage of both summer and winter rain, small rainfall events and floods. Building an understanding of landscape function allows us to explain how grazing can influence land condition and ultimately pastoral production.

We have also updated the course to include a module on Biosecurity. In recent years, the pastoral industry has become more acutely aware of the threat of foreign disease incursions into Australia (e.g. Lumpy Skin Disease, Foot and Mouth Disease). It was considered timely and appropriate to include a new module into the RMC syllabus to address this emerging issue and it has been well received.

Table 1: Examples of feedback from Central Australian Rangeland Management Course participants.

'It's okay to take a day away from work, when the course is so interesting and directly relevant to our everyday jobs'.
'I found it interesting how you worked out the amount of grass in the paddock.'
'I'd love to have done this as a first-year ringer – I think it would have changed my perspective on everything.'
'It was useful to identify the weeds and grasses growing out in the paddock.'
'It was interesting to learn about the impact phosphorus deficiency can make to cattle.'
'Working out carrying capacity, forage budget and identifying land types was interesting. Learning about nutrition and how to maintain optimal gut health was a standout.'
'The paddock walk was interesting, getting a better understanding of pastures in the area.'
'Explaining the value of all the different grasses was interesting. Carrying capacity, land condition and how they affect management was useful.'

The course has a strong practical component, well suited to an audience who often choose their career based on a love of adventure and outdoor activity. Perhaps surprisingly, the pasture identification activity is the one that everyone loves the most (Table 1). For many participants, who are often new to the region, these activities are their first introduction to the plants that form the basis of the grazing enterprise, and they are often amazed at the variety of species. We talk about the species that cattle prefer, how grazing can change the pasture composition and what you can do to maintain healthy pastures.

Talking about land condition can be a sensitive subject, but learning how to identify change and the impacts it has on production is important. It is exciting when we go out into the paddock and assess land condition and see the participants analyse how the grazing business and the ecosystem function together. It's one of the things that station managers asked for, to give their staff the skills to distinguish good land condition (desirable, perennial, abundant pasture species) from a flush of green, but short-lived species that won't last long.

Course delivery

Presenting the RMC on-station is ideal because participants get to test their learning immediately on their own country and often the manager will attend too. Ideally, we would have between 8-14 participants however, some stations only have 2 or 3 early career station hands on the property and that would be a very intense learning environment. To ameliorate this, we offer regular courses on the DAF operated Old Man Plains Research Station (OMP). The courses are also offered sub-regionally, for example, in the dining room at roadhouses, so that participants from several stations can gather, see land types familiar to their home station for practical exercises and not have to travel too far.

We have also initiated a program of learning for graduates to keep them informed of current activities and seasonal observations, as well as encouraging them to share their personal experiences around the course content.

Discussion

Being the only truly customised course on pasture dynamics in Central Australia makes this an important addition to livestock production in the region. The realities of long-term rainfall variability and the management implications of discreet growth events are important for pastoral managers and their staff. The human memory is often unreliable and while we certainly remember the very dry years, it's easy to forget that the very good rainfall experienced in recent years is not the 'new normal'.

For managers, this course provides a unique opportunity to train new staff in the fundamentals of rangeland management directly relevant to the station they work on. While the early career staff member isn't likely to be making any high-level decisions about grazing management or cattle health, they are a valuable set of eyes-on-the-ground that become far more useful with increased knowledge. It also helps with job satisfaction, performance, and staff retention when staff understand why they might be asked to do certain jobs and better understand their environment. Participants in the course consistently report that the information they gain is relevant to their daily work, interesting and increases their knowledge.

Offering courses on the Old Man Plains Research Station (OMP) has provided several unexpected benefits. It encourages participants to interact with research and farm staff and learn a bit more about current research projects and results. When the courses are held at OMP, we can offer presentations from other Department of Agriculture and Fisheries staff e.g. Regional Veterinary Officers. Creating relationships between industry support staff and the next generation of land managers leads to beneficial future collaborations. In addition, talking about land condition decline and recovery is often easier to do on neutral ground. This leads to critical thinking and robust discussion about how grazing can impact landscape processes.

Ultimately, some of today's new staff will go on to become the next generation of experienced managers in the Northern Territory pastoral industry. Graduates from the original Barkly Rangeland Management Course from the early 2000's are doing just that and when DAF staff work with them now it's clear that their knowledge and experience of grazing management principles has grown with them (Pettit, pers. comment.). It is hoped that the Central Australian Rangeland Management Course is just the start of a lifetime in the pastoral industry for our next generation of land managers.

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Land tenure, land rights, land-uses, conflicts & governance

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Joint village land use planning across administrative boundaries protects shared grazing lands and water points in Tanzania. Lessons learned from fifteen years of development and policy influencing

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Key words: land use planning, pastoralism, pastoralists, rangelands, conflict, policy, Tanzania

Introduction - Context

Land use conflicts are increasing as land pressures grow due to population increase, existing land degradation and access to previously restricted lands is opened. This is particularly the case in pastoral areas often assumed to be ‘free lands’ and where pastoralists are poorly equipped to protect their lands from sale or encroachment with poor tenure security. Where land is taken by government for infrastructural or agricultural schemes, rarely is compensation provided. Appropriate land use planning at different levels – local to national – that considers the needs, interests and priorities of different land users including normally marginalized groups such as pastoralists is needed.

Participatory Land Use Planning in Tanzania

In Tanzania where land and land use planning policy and legislation is relatively progressive, local (village) level, participatory land use planning is formalised through the *1999 Village Land Act No. 5* and the *2007 Land Use Planning Act No. 6*. However, due to a lack of resources and capacity, undertaking VLUP has been slow: in 2016 only 1,640 villages out of a registered 12,788 villages had undergone land use planning (Massey 2016). Where VLUP has taken place, it may not have been done in an adequately consultative way, and particularly when connected to large-scale land investments (Engstrom et al., 2022; Kayera, 2024). Strong gaps and concerns exist in pastoral areas and where land-use conflicts occur, and individual VLUP can fragment shared grazing lands and block movement of livestock between villages (Flintan, 2013; Flintan, 2021).

In 2010 the Sustainable Rangeland Management Project was established (Flintan et al., 2022) originally focused on supporting individual village land use plans, but it soon became clear that where grazing lands were shared across village boundaries a different approach was needed. A review of policy and legislation revealed that the Land Use Planning Act No. 6/2007 (Section 33 (1)(b)) states that where such resources are shared a “resource management sector plan” should be established with bylaws for the continued sharing of resources. To facilitate this plan, the Project supported the development of joint village land use planning, later taken up by ILRI and the CGIAR Livestock and Climate Initiative as part of a bundle of approaches to improve participatory land use planning in pastoral areas (Flintan et al., 2022).

Over the next fifteen years ILRI and partners developed the approach with an independent evaluation (Sulle, 2021) appreciating the support provided to the Tanzania government and a second evaluation highlighting benefits for communities (Waweru et al., 2021).

Today, ILRI and partners are supporting JVLUP across more than 400,000 hectares of village land, which includes approximately 166,000 hectares designated for grazing. This not only benefits village livestock keepers and pastoralists, but also the 100,000 residents gaining from reduced conflicts. In 2024 the JVLUP approach was incorporated into the National Land Use Planning Commission's guidelines on participatory land use planning. This article describes the impact pathways leading to these outcomes.

Outcome impact pathways
i) Developing and piloting JVLUP

Piloting started in four clusters of villages in Kiteto District, Manyara region enabled by a strong international and national partnership. National, regional and district land officers were strongly involved, together with those responsible for grazing lands in the Ministry of Livestock and Fisheries. Ensuring that the process followed government guidance was vital for its success, and for holding up to later scrutiny. JVLUP is an integrated approach bringing together neighboring villages to jointly agree on use of land, based on current land use and land potential. The final plan is a legal document valid for ten years, after which renewal is required.

A clear joint vision and incentives is important to bring together different stakeholders i.e. government and communities want reduced land use conflicts. A sense of collective was established that has held to this day assisted by the shared grazing lands being made up of the names of the villages involves – and led to names such as OLENGAPA (the first grazing land secured) (Amos and Flintan, 2019) becoming 'household' names. Other important factors included ensuring a steady flow of resources through the process (stalling cost us dearly) and working around local and national elections as land (and even the JVLUP process) is an emotive topic and could be used for political persuasions.

In 2022 JVLUP was successfully carried out in two new clusters of villages in Chalinze district, Coastal region. Though the area of these lands was relatively small (totalling under 1000 ha) they now provide a strategic anchor or foothold for pastoralists in the area experiencing increasing land pressures. ILRI and partners are now supporting the application of JVLUP in areas where individual village land use planning has taken place, to explore options for joining up what have become fragmented parcels of grazing lands.

ii) Building capacities to implement JVLUP

The development of JVLUP has been a joint capacity building process for all involved. Trainings were undertaken with and for different stakeholders ranging from conflict resolutions through to necessary financial reporting supported by manuals, learning routes and films. Additionally, community members capacity to protect their lands and defend them in the courts (e.g. in the case of farmer encroachment) has been supported, together with their exposure to decision making forum such as national Livestock Keepers Association meetings (Flintan et al., 2021).

JVLUP was grounded in principles of good governance and gender equity from its inception (Daley et al., 2017) incorporating CGIAR innovations such as community conversations (Bullock, 2024) and women's leadership forums (Dungumaro and Amos, 2019). These strategies have led to significant outcomes, such as over 30% participation of women in decision-making bodies for JVLUP and women's assertive collective actions (Flintan, 2024a).

iii) Influencing the policy environment

The continued success of JVLUP requires an enduring enabling policy environment and has required ongoing engagement with policy actors (Kalenzi, 2016). A key strategy in this regard was supporting engagement and joint learning between land use planners in Tanzania, Kenya and Ethiopia including their joint attendance at international conferences.

In 2022 an MOU Was established between ILRI and the NLUPC. USAID (US$464,487) and the EU (US$450,000) supported the Tanzania Natural Resource Forum to expand the approach. And in 2024 a national guideline on joint village land use planning was launched, with the validation workshop officiated by the Deputy Minister of Lands, Housing and Human Settlements Development Hon. Geoffrey Pinda (Flintan, 2024b).

Conclusions

Influencing policy through the technical development of an innovation that serves the interests of multiple stakeholders across a nation is challenging, takes time and needs a strong cross-sectoral partnership. It took a decade and a half from the initial joint village land use planning innovation idea, to then being piloted, validated and finally incorporated into the national guidelines. The final challenge, and the biggest one we face now is implementing the approach at scale, with continued limited government allocation of resources to the approach despite increasing land use conflicts.

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Toward a new methodology for conceptualizing mobile pastoralists' and pastoralist women's tenure and mobility rights

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Key words: community-based governance; land rights; pastoral livelihoods

Abstract

Despite the global importance of mobile pastoralism to rangelands management, the mobility and tenure rights of pastoralists remain under-recognized and undervalued in policy and practice. This paper proposes a comprehensive methodology to assess the security of pastoralists' mobility and tenure rights, using a framework grounded in community-based tenure regimes (CBTRs). The framework considers mobility, access, use, management, participation, and exclusion rights, and proposes indicative indicators—both positive and negative— to evaluate the extent to which laws, policies, and customary practices uphold or undermine these rights. The framework also assesses the specific rights of women across three domains: mobility and land access, livelihoods and resource use, and governance participation. By integrating legal analysis and community-level insights, this paper provides a pathway for nuanced, comparative assessments of pastoralist systems, fostering equitable and sustainable policy interventions.

Introduction

There are as many as half a billion pastoralists worldwide, and an estimated 1.3 billion people who benefit from pastoralist value chains (World Bank, 2021). Rangelands cover more of the earth's surface than any other land use type, and pastoralism forms the basis of community livelihoods in over 100 countries, on all inhabited continents (Manzano et al, 2021). The United Nations Environment Programme has identified Pastoralism and rangelands as globally significant, but under-recognized and undervalued (Johnsen et al, 2019).

Mobility is central to the livelihoods, cultural identity, and climate adaptation strategies of Pastoralists and Mobile Indigenous Peoples, and includes social, political, economic, and philosophical and religious dimensions (Hempstead and Rodgers, 2023). Despite its critical importance, mobility is often neglected or actively suppressed in national and regional land-use policies, through measures such as forced sedentarization (Semplici and Rodgers, 2023). Such restrictions on mobility have historically inflicted severe impacts on pastoralist communities, with especially adverse effects on women, who are typically the holders of community knowledge and traditions (See e.g. Kaur et al, 2023. Balehey et al, 2018). Furthermore, restrictions on mobility contribute to environmental degradation through overgrazing, and impair pastoralists' ability to adapt to shifting social and environmental conditions (Messmer et al, 2024; Elias, 2023; Liao et al, 2020).

This paper proposes an indicative methodology for conceptualizing and analysing the robustness of pastoralists' mobility and tenure rights. Here, "mobility rights" are understood both as a distinct category of rights, directly affecting the ability of these communities to move seasonally, and as a defining characteristic of other rights, influencing their recognition and realization beyond a fixed area, thus impacting the security of community mobility.

In this paper, we understand pastoralism as a livelihood system primarily based on the extensive management of domesticated animals, characterized by mobility as an adaptive strategy to optimize resource use in variable environments. It involves the close relationship between people, livestock, and landscapes, typically guided by traditional ecological knowledge and social institutions that ensure sustainable use of common-pool resources. Pastoralism encompasses culturally embedded practices that rely on communal or shared land tenure systems.

Tenure rights are conceptualized here using a bundle of rights, drawing on Schlager and Ostrom (1992) and similar methodologies developed by the Rights and Resources Initiative (RRI). The present methodology applies the same unit of analysis as other RRI tenure tracking analyses: the Community-Based Tenure Regime (CBTR), defined as the set of national and state-level laws and regulations governing situations in which rights to terrestrial natural resources are held at the community level. Here, the CBTR concept extends to laws and regulations governing all situations in which the rights of use, movement, and access of mobile pastoralists are collectively held. Critically, this analysis also considers whether rights are static – that is, inhering only to a fixed area of land – or dynamic, inhering to the community itself and thus applicable across their annual migratory routes.

Proposed Methodology

The methodology proposed here identifies two broad, interrelated sets of bundles of rights as areas of assessment. The first is a bundle of mobility and tenure rights held by pastoralists at the community level. The second is a cross-cutting bundle of the specific rights of women within pastoralist systems, which is elaborated in the following section. Each area of analysis identifies key issues and indicative indicators, offering a baseline that facilitates cross-contextual comparison while allowing for context-specific tenure and mobility arrangements in different jurisdictions.

The areas of analysis at the community level include: Mobility and Access Rights; Use and Management Rights; Participation and Exclusion Rights.

Mobility and Access Rights:

Legal recognition of mobility, such as through bilateral and regional transhumance protocols or national policies, forms the baseline for analysis. Barriers to mobility include land-use conversion, infrastructure development, and conservation policies that conflict with traditional pastoralist corridors. Similarly, access rights hinge on whether pastoralists can legally and practically access resources seasonally or communally. The framework evaluates recognition of overlapping and reciprocal access rights, distinctions between human and livestock access, and provisions for cross-border access. Positive indicators for these rights include legal protections for mobility, frameworks for customary and seasonal access, and recognition of Free, Prior, and Informed Consent (FPIC) (Hempstead & Rodgers, 2023; Davies, 2024). Negative indicators include sedentarization policies, inconsistent infrastructure planning, and the criminalization of mobility.

Use and Management Rights:

The sustainable use and governance of rangelands, water points, and other critical resources are foundational for pastoralist livelihoods (Natural Resources Institute, 2017). This framework evaluates the extent to which pastoralist resource use is legally protected, whether for subsistence, commercial, or cultural purposes. Barriers such as fees, permits, or procedural restrictions are analyzed alongside provisions for community-based resource management.

Positive indicators could include the presence of legal protections for different resource use types, state investment in pastoralist infrastructure, and mechanisms for joint resource management. Negative indicators include procedural restrictions on resource access and incidences of conflict.

Participation and Exclusion Rights:

Pastoralists' participation in land-use planning and decision-making processes is a critical component of equitable governance. The analysis includes consideration of legal provisions for FPIC, representation in governance bodies, and the inclusion of pastoralists in national and regional policy frameworks. Exclusion rights are understood as pastoralists' ability to regulate and negotiate third-party access to their grazing lands (See Hempstead & Rodgers, 2023; Robinson et al, 2017). Positive indicators include robust participatory mechanisms, legal requirements for FPIC and provisions for communal land governance. Negative indicators include unilateral state actions that undermine pastoralist mobility without consultation, and the use of enclosures.

Gender and Women's Rights

In addition to rights held at the community level, the framework also considers the specific rights of women within pastoralist tenure systems through three interrelated areas of analysis: Women's Mobility and Land Access Rights; Women's Livelihoods and Resource Use; and Women's Governance Rights. Within each of these areas of analysis, we also propose indicative indicators

Women's Mobility and Land Access Rights

Indicators of progress include gender-sensitive laws that ensure equal mobility rights and access to safe infrastructure like water points. Barriers include laws or regulations restricting women's independent movement or rights to land.

Women's Livelihoods and Resource Use

Positive indicators include legal recognition of women's rights to own or co-own livestock, women's specific rights to access water and pasture, and their equal inheritance rights. Negative indicators include restrictions on women's livestock ownership or control of income from livestock production.

Women's Governance Rights

Positive indicators include established quotas or minimum participation thresholds for women in community executive and decision-making bodies, and quorum requirements for binding resolutions or votes. Negative indicators include exclusionary practices such as requiring male consent for women's participation.

Discussion and Implications

This framework offers a novel contribution to understanding and evaluating the mobility and tenure rights of pastoralists, a globally significant but under-recognized system of livelihoods. By applying the concept of a bundle of rights within the context of transhumance, it bridges critical gaps in existing analyses of rangeland governance and mobile pastoralist rights.

Through a consultative and collaborative process, RRI proposes to operationalize this framework in diverse pastoralist landscapes by applying the methodology across regions and refining indicators to better capture nuanced dynamics. Policymakers and advocates can use these global insights to strengthen governance systems and support the equitable development of pastoralist communities in the face of mounting environmental and socio-political challenges.

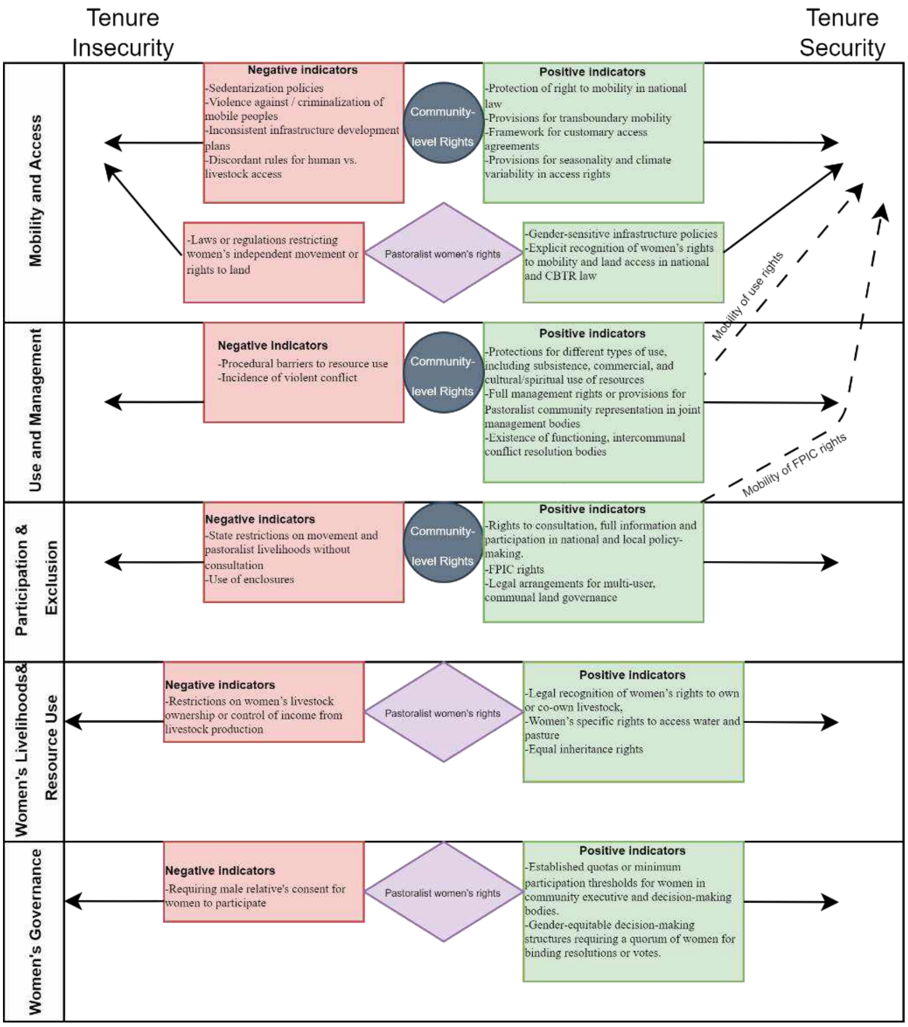

Figure 1 - Diagram of Methodology

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XII INTERNATIONAL RANGELAND CONGRESS
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Documentary film - stories of American rangelands: meeting the challenges of a changing climate & culture

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Key words: IYRP North America; film; outreach

Abstract:
In honour of the International Year of Rangelands and Pastoralists (IYRP2026), members of the North America IYRP Support Group and the Rangelands Partnership initiated an effort to produce a feature-length documentary film about North American rangelands. This documentary, to be premiered in 2026, focuses on their importance for meeting 21st Century environmental, cultural, and economic challenges; and specifically, reducing the effects of climate change (https://www.iyrp.info/north-america/film-projects/documentary-film). Storytelling is the vehicle used for highlighting the historic and intrinsic values of these lands within the context of indigenous knowledge and current science. The long-term goal is to change public perceptions, notably held by urban populations, policymakers, and youth, regarding the value of these lands and the need to conserve them. By presenting real-life stories about the people whose livelihoods depend on these lands, viewers will learn about new technologies for land management, collaborative conservation efforts, and the many ecosystem services provided by rangelands. These include food and fibre production, clean water, wildlife habitat, wildfire control, carbon storage, renewable energy, and recreation. With input from the film's Advisory Board, overall themes were identified:

1. Rangelands and pastoralists defined.
2. History of rangelands and their management including Native American perspectives.
3. Climate solutions:
    a) Soils/carbon sequestration, extensive vs. intensive agriculture, land fragmentation issues.
    b) New technologies & strategies, i.e. virtual fencing, drones/remote sensing, regenerative grazing.
    c) Ecosystem services: food and fibre production, clean water, wildlife habitat, recreation, wildfire control, and renewable energy.
4. Connecting people to rangelands; keeping working lands "working"; how we can help protect our rangelands.

Landmark Stories, an award-winning filmmaking team based at the University of Arizona, is producing the film (https://landmarkstories.arizona.edu/). This team has experience in documentary storytelling on natural resources themes and also positive working relationships with members of the IYRP coordinating groups and the Rangelands Partnership.

Introduction

Rangelands occupy 54% of all land on Earth (UNEP 2014) and at least 30% of land in the United States (NRCS 2024) and are home to an estimated 200 million people worldwide. Yet, people from urban areas are often disconnected from the importance of rangelands to their health and wellbeing. The mission of the International Year of Rangelands and Pastoralists (IYRP2026) is to promote an understanding and appreciation of rangelands around the world, the people who manage them, and their contributions to all communities. In North America, rangelands are particularly important for livestock production, wildlife habitat, and recreational activities as well as valuable sources of clean water, carbon storage, fresh air, open space, and renewable energy resources. As important as rangelands are, they are increasingly impacted by land fragmentation, residential encroachment, and cultural change that divide these landscapes into less functional ecosystems and impact their ecological and economic opportunities. Furthermore, misconceptions about rangelands are numerous. Some people may see them as wastelands that make little, if any, contribution to public needs, while others consider all livestock grazing as detrimental and leading to irreparable degradation. However, these views are not supported by either current science or day-to-day experience. The IYRP2026 presents a unique opportunity to highlight the incredible value of rangelands to the people and communities that rely on them while at the same time helping focus attention on the challenges and potential consequences if these vital ecosystems and pastoralist communities are lost. To reach out to the public with these messages, the North American (NA) IYRP Support Group and members of the Rangelands Partnership initiated an effort to produce a feature-length film about North America's rangelands focusing on real-life stories about the people whose livelihoods depend on these lands and the nature of their stewardship. Highlights include new technologies for land management, collaborative conservation efforts, and the many ecosystem services provided by rangelands.

Methods

An initial research phase found considerable evidence that the medium of film can reach millions of people quickly and effectively (Filbin 2020; Schimmel 2021; Veritzman 2023) and that documentaries, specifically, are often used as teaching resources from grade school to higher education (Vaughan-Lee 2024). Thus, it was determined to pursue this means for bringing attention both to the promise of American rangelands and to the IYRP2026. From the start, multiple groups and individuals have been directly involved in producing the film. The Landmark Stories Production Team is an award-winning filming crew based in the Cyber and Communications Technologies Lab at the University of Arizona (https://landmarkstories.arizona.edu/). This team has experience and expertise in documentary storytelling on natural resources themes and positive working relationships with members of the film's many advisors. The Project Team of advisors includes four groups who represent various aspects of rangeland science, education, and outreach. (1) The Rangelands Partnership is a 25-year collaboration of rangeland extension professionals (providing non-formal science-based education and learning activities), science librarians, and information technology experts from 19 Western and Great Plains Land Grant universities. The Partnership's primary product is the Rangelands Gateway (https://rangelandsgateway.org). (2) The IYRP NA Support Group is composed of more than 50 rangeland experts from three countries, all committed to assisting with IYRP outreach initiatives. (3) The Western Association of Agricultural Experiment Station Directors (WAAESD) is one of five regional organizations that plan and manage multistate research activities throughout the U.S. Its membership includes university deans, directors, and administrative officers. (4) Lastly, the film's 30-member Advisory Board is made up of rangeland science experts, filmmakers, and members of IYRP coordinating groups. The Advisory Board has been integrally involved in guiding and reviewing progress in the film's development. The full Project Team represents a cross-section of key stakeholders from diverse backgrounds and perspectives. At the same time, members have direct linkages with the most current science, innovative educational programming, and inspiring storytellers with practical knowledge and experiences to share.

The initial phase in the development of this film project was an ambitious fundraising effort. Through WAAESD, early contributions were received by land-grant universities and individuals. However, reaching the goal of $300,000 has proved to be elusive so the project coordinators began submitting proposals wherever appropriate. Grants were received from the U.S. Department of Agriculture's Renewable Resources Extension Act and the National Grazing Lands Coalition, and other grant opportunities are being evaluated at the time of this writing. A description of the production phases follows:

Phase 1: Pre-production (initiated January 2024) – directors and writers a) research and explore themes; b) gain input from Project Team members at multiple stages of story development; c) determine best approach for gaining the broadest exposure, i.e. potential locations and interviewees; and d) create a compelling narrative that informs about big issues through personal stories.

Phase 2: Production (Summer 2024 through Spring 2025) – a) review themes with all partners and producers; discuss ideas and options for the most relevant and compelling stories that align with the overarching theme of "climate change;" b) determine and finalize list of locations, characters and actions for each scene to be filmed; c) create a working shot list for each scene; d) determine and secure production crew and their availability; review production gear requirements and requests based on the story treatment; e) review and adjust shot list with the Director of Photography; incorporate partners and producers' visions into the treatment of scenes and overall visual style; f) determine schedule for travel to the selected locations, confirm interviews and actions to be filmed; secure travel and lodging for film crew; and g) commence filming and continue until completed.

Phase 3: Post-Production (Summer 2025 – Winter 2026) – a) film editing commences until a rough cut is achieved; b) sound mixing, design, effects, and musical soundtrack edited by Sound Designer in cooperation with Editor and Director; c) computer graphics, maps, after-effects, and motion effects created by the Graphic Designer in cooperation with the Editor and Director; d) rough cut is submitted to partners and key stakeholders for review and feedback; the post-production team digests and addresses partners' comments and suggestions and makes any necessary changes; e) trailer is finalized and distributed to partners and key stakeholders for review and feedback; the post-production team digests and addresses partner comments and suggestions and makes any necessary changes; and f) film and trailer are finalized for final review by partners and key stakeholders; changes made, if necessary and possible.

Phase 4: A fourth phase for an "**impact campaign**" will include marketing activities, a launch event, press release, and a guide for viewers and educators. Members of the Project Team have already agreed to publicize the film through their regular programming activities and social media outlets and will track results as part of an assessment of the film's impact. The projected release date is tentatively scheduled for March 15, 2026.

Based on input from all Project Team members, the following themes and sub-themes were determined as the preliminary approach for the film's stories.

1) Rangelands and pastoralists defined drawing on imagery from North America.
2) Historical summary of rangelands and their management in the context of Native American perspectives.
3) Climate solutions:
    a. Soils/carbon sequestration, extensive vs. intensive agriculture, fragmentation issues.
    b. New technologies & strategies, i.e. virtual fencing, drones/remote sensing, regenerative grazing.
    c. Ecosystem services: food and fibre production, clean water, wildlife habitat, recreation, wildfire control, and renewable energy.
4) Connecting people to rangelands; keeping working lands "working"; how we can help protect our rangelands.

Film has been proven to be an effective medium for influencing people's attitudes in a constructive way (Kashani 2016; Kubrak 2020), and specifically for understanding and engaging people round the issue of climate change (McGreavy & Lindenfeld 2014). However, while there are many videos on YouTube on a variety of aspects of climate change and rangelands, most are quite short, tend to be academic, and have had a limited number of views. An extensively marketed and distributed feature-length film provides a unique and possibly game-changing opportunity to grab the attention of people at a national, and even international, level to inform and influence their perceptions and understandings of the importance of rangelands.

The first media product of the film project will be a trailer that will be posted on YouTube and other social media outlets to build interest in the feature film. A preliminary trailer will be provided to the members of the film's Advisory Board, the NA IYRP Support Group, and members of the Rangelands Partnership for review and comment. After receiving this input, the trailer will be finalized and distributed along with a "Guide for Use" and a brief viewer survey to identify any new perceptions identified after the release of the film. Project members will be requested to show the trailer to their constituencies during extension-focused events such as workshops and seminars, as well as with marketing the trailer and the film's date of release. The trailer, along with a "Coming Soon" announcement, will also provide the means for promoting the film to independent theatres and to public television. A similar marketing and distribution process will be undertaken and documented when the feature-length film is nearing completion towards the end of 2025. Additionally, it is expected the film will be entered in various film festival competitions such as Jackson Wild, Sundance, and Telluride Mountain Film Festival.

Results

The long-term goal is to change perceptions of the public, particularly new audiences such as youth and urban populations as well as policymakers, regarding the value of rangelands and the need to conserve them. Post-viewing surveys will be made available after selected viewings, particularly those presented at independent theaters, and on social media outlets. By presenting real-life stories about the people whose livelihoods depend on these lands and the nature of their stewardship, viewers will learn about innovative new technologies for land management that can contribute to climate solutions, collaborative conservation efforts, and the many ecosystem services provided by these lands to people across the continent and throughout the world.

Discussion

The target audience is the general public, including agricultural producers, educators, students, and recreationists, both from urban and rural areas. In addition, a major focal group will be agency personnel and policymakers as many of the film's themes are relevant to current policies. To address the profound impacts of climate change at environmental, economic, and social levels, a greater understanding of the role of natural resources, specifically rangelands and grasslands, is needed if their potential as a climate solution is to be realized. To this end, the film will have the possibility of widely and positively influencing collective action to increase climate resilience. Through real-life stories, our target audiences will have new information that can lead to an improved understanding of rangeland ecosystems, technological processes, and promising management technologies and strategies to reduce the effects of climate change.

Acknowledgements

As noted above, many people and organizations have provided intellectual and financial support for this documentary film. Financial contributors are noted on the IYRP documentary film webpage - https://www.iyrp.info/donations-received. In addition, individuals serving on the Advisory Board as well as members of the Rangelands Partnership have provided considerable help in identifying key people to interview throughout North America. Finally, approvals were obtained from the University of Arizona Human Subjects office for conducting interviews and guiding the process for obtaining consents.

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ESRM Planning, delivering NRM action and direction through collaboration

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Key words: NRM; Rangelands; WA; Collaboration; Landscape.

Abstract

The Ecologically Sustainable Rangelands Management (ESRM) process has evolved over the past 17 years, from a federally funded Western Australian Natural Resource Management (NRM) project to a commercial service available to land managers across the Australian rangelands. At its core is collaboration and innovation to deliver positive NRM outcomes for areas that are subject to multiple management motivations. To date, the process has delivered over 120 management plans for areas under pastoral, mining, indigenous and conservation management. The plans represent over 23,200,000 hectares in Western Australia (WA) alone, which equates to 10% of WA rangelands and 27% of the WA pastoral estate. ESRM is now the dominant environmental planning process within the WA rangelands, and the program is being extended to other states.

Grounded in science, the process maps and documents a land manager's own ideas and goals for the management of an area, and devises strategies and activities to help them achieve those goals, while maximising the positive NRM outcomes for the area. Where stakeholders have conflicting management ideas and goals, the process allows for frank discussions and identification of commonalities to generate a strategy that provides a sound compromise for all, whilst working within accepted best practice NRM frameworks. The process incorporates well-proven rangelands management with emerging technology to deliver a whole-of-landscape plan that is practically implementable.

This paper will outline the ESRM process, and how it promotes a collaborative approach to sustainable land management to maximise positive NRM outcomes while improving productivity and profitability.

Introduction: The evolution of ESRM

The rangelands of Western Australia (WA) encompass much of the arid and semi-arid zone, and accounts for approximately 87% of the state's total area (DPIRD 2022). Approximately 39% of the rangeland area consists of Crown land pastoral leases (DPIRD 2022), which are leased to pastoralists and gives rights to graze authorised livestock on the natural vegetation (Government of Western Australia 2023). The rangelands have seen extensive modification to the landscape function, soils, flora and fauna as a result of the long history pastoralism, particularly of sheep and cattle grazing (Brandis 2008). The pastoral industry contributes significantly to our economy however a legacy of significant environmental degradation from prolonged overgrazing since the mid 1800s remains to this day, from which many parts of the landscape have not fully recovered (e.g. Burnside et al. 1995; Alchin 2011; Tinley and Pringle 2014).

In January 2000, the federally funded Ecosystem Management Unit (EMU) extension program was initiated as part of the Gascoyne-Murchison Strategy, underpinned by the concepts of ecological management and biological conservation. This extension program involved over 120 properties from the Carnarvon coastal plain and Gascoyne, Murchison, and north-east Goldfields to the Nullarbor over a period of seven years before federal funding was terminated in 2006 (Tinley and Pringle, 2012 Pers. Comm.). A short time later, the Department of Agriculture and Food WA (now Department of Primary Industries and Regional Development (DPIRD)) established the Ecologically Sustainable Rangelands Management (ESRM) extension program, with its foundations and approach based on the EMU extension program, and an aim to improve the profitability and productivity of rangelands enterprises by improving grazing systems, resource sustainability and conservation (Tinley and Pringle, 2012 Pers. Comm.). Over a period of four years the ESRM program covered 40 stations in the Gascoyne, Carnarvon coastal plain and Pilbara.

These extension programs have demonstrated that improving productivity and profitability and maximising positive NRM outcomes can be achieved simultaneously. As the saying goes, ‘Look after Country, Country will look after you’ (Weir et al. 2011). If we are to minimise adverse impacts to the environment well into the future, we must continue to engage and collaborate with land managers and provide them with the knowledge and tools necessary to maximise positive NRM outcomes in such a way that also protects their bottom line. In recognising this, Contour Environmental and Agricultural Consulting have refined and developed the ESRM process into a commercially deliverable service. The process is highly adaptable with respect to location and the ability to integrate the findings of relevant scientific research and technologies, and broadly involves: a preliminary desktop assessment; a facilitated property visit involving the lessee/property manager; and the development and delivery of the ESRM Plan. To date, the process has delivered over 120 management plans for areas under pastoral, mining, indigenous and conservation management. The plans represent over 23,200,000 hectares in WA alone, which equates to 10% of WA Rangelands and 27% of WA Pastoral Estate. The service has been in constant demand in WA and is now being extended to South Australia, which is a testament to both the successful track record and adaptability of the ESRM process.

The ESRM Process

Preparing for an ESRM property visit

In preparing for an ESRM property visit a preliminary desktop assessment of the subject property is undertaken. With permission from the station’s lessee, any government-held information and spatial data relating to the property is accessed and examined, such as previous rangeland condition assessments, rangeland monitoring system and pastoral monitoring sites. Spatial infrastructure data and land system and/or vegetation mapping is used to prepare paper-based maps for markup during the property visit. Long-term median rainfall figures are compared to figures from the past 20 years to gain a more accurate understanding of more recent rainfall patterns, and the implications this has for land management and stocking decisions on the ground. A cumulative rolling rainfall graph benchmarked against the median rainfall for the subject station is created, with indicative cues for adjusting stock numbers based on the amount of rainfall received, relative to the median. This is presented to the land manager during the property visit as an additional tool which can be used to assist in making stocking decisions.

ESRM property visit

Discussions with the lessee typically commence over the prepared paper-based maps and a cup of tea. This serves several purposes; it facilitates open discussion, allows mapped spatial data to be checked with the land manager for accuracy, highlights areas of interest which will give direction to the inspection of the property, and starts to ‘build the story’ to be told in the ESRM plan. The lessee is asked to draw out: current tracks and infrastructure present and state of repair/disrepair; stock numbers and distribution across the property; mustering areas; productive/overutilised grazing areas; areas of conservation or cultural significance to the lessee; and areas with specific issues or concerns such as track erosion, scalding, fire, weed invasion, stray cattle/feral herbivore ingression. The lessee is also asked to map out planned future works for the lease, such as infrastructure or conservation areas, including any ‘wish list’ items which fit with their overall production and NRM goals for the lease. Existing alternative enterprises occurring within the lease, or opportunities for potentially suitable alternative enterprises (such as carbon farming projects or eco-tourism, for example), are also discussed. This ensures that all aspects are captured to develop a cohesive ESRM plan, where recommended future management activities are complementary and aligned with the lessee's goals for the property.

Depending on the size of the property, an inspection is undertaken ideally over a period of days. For both parties, maximum benefit is derived when the lessee is present for the inspection with the facilitator. This allows for any issues or concerns raised during the mapping exercise to be ground-truthed and explored in-situ. Potential remedial actions can also be considered in a specific context and how they may be implemented. Potential Case Study Areas are selected from points of interest traversed during the inspection, with the intention that remedial actions be trialled at a small scale with minimal investment of resources, and then applied to other areas of the property if proven successful or revised if unsuccessful. There is also opportunity for the facilitator to raise issues or concerns which the lessee may be unaware of. The scale of some issues which affect landscape condition and function, such as erosion, may not be obvious or visible from the ground, and may not even be occurring from a trigger point on the subject property, in which case there may be a need to address the issue at a larger scale over multiple properties, or the wider catchment. In the past aerial surveys of a property were often undertaken by plane or helicopter to cover large areas in a short amount of time, however the risk exposure and costs associated with this method can be prohibitive. With recent advancements in technology, aerial surveying has become far more accessible and efficient through the use of drones, which are becoming an increasingly powerful tool for landscape assessments. Characteristics of the vegetation and landscape condition and function are noted and photographed on the ground and by drone where appropriate during the inspection. Global Positioning System (GPS) coordinates and photographs are also taken at waterpoints and points of interest, which may include areas experiencing issues with erosion, overutilisation/underutilisation, productive/unproductive areas, fire-affected areas, and conservation or other areas of cultural significance to the lessee. Covering as much ground as possible in the allotted time is desirable for developing a robust whole-of-landscape ESRM plan.

Development and Delivery of the ESRM Plan
The ESRM plan is a synthesis of all information collated prior to the property visit and of the discussions, photographs and GPS points collected during the property inspection. It then presents suggested remedial management actions and strategies, tailored to the circumstances occurring on the property. The plan assigns a suggested priority and outlines a timeline for implementation based on the land manager's current situation and aspirations. Case Study Areas selected from the property inspection are mapped and annotated images are marked up to outline the current situation, and the proposed works needed in these specific areas to remediate the issue. Remedial works are described in detail and approximately costed to give the lessee an indication of the investment required.

The plan also captures the lessee's current land management strategies relating to grazing, stocking rate and fire where applicable, and introduces proposed strategies for each, while giving consideration to future plans for the property. This ensures that management strategies are not temporally restricted in their application. A key focus of the ESRM process is to develop a proposed grazing and stocking strategy that puts rainfall into context of the carrying capacity for the property in its current condition. Carrying capacity estimates are made for the entire property and individual paddocks/grazing areas, based on the land systems/vegetation in their current condition, and are converted to stock days and a recommended stocking rate per 10 or 100mm of rainfall, which has been benchmarked against the median rainfall for the property.

Any alternative enterprises discussed during the property inspection are worked into the overarching strategy for the property. If alternative enterprises, such as carbon farming for example, have not yet been implemented but are being considered by the lessee, an assessment is undertaken and commentary made on the suitability and feasibility of such an enterprise.

Fire is a natural and important part of landscape ecology. Where fire management on a property is necessary, the proposed management strategy breaks the property into fire management zones, which are allocated a burn order or are designated no-burn areas, based on their position in the landscape and other management priorities for the property. Land managers are encouraged to engage with the regions' Indigenous Ranger groups, or other Indigenous groups with connection to the land by way of Native Title, to support them in fire management capacity building.

A proposed monitoring programme and monitoring schedule is provided to the lessee, which includes specific locations where photographs and condition changes should be repeatedly recorded, and at what time intervals, to track the success or otherwise of any remedial works undertaken.

After being reviewed and agreed upon by the lessee, the final ESRM Plan is delivered along with a poster which summarises the proposed works outlined in the ESRM Plan. Displaying the poster in a visible location increases motivation to implement the proposed works, and is a quick way to cross-check works completed and those yet to be completed.

Conclusion

A primary goal for pastoralism is about managing a '…profitable livestock business, while maintaining the land and vegetation in good condition' (DPIRD 2022). This is no easy feat, given that many pastoralists are already managing the rangelands under challenging and often unfavourable conditions. Many are still suffering to some extent from the consequences of historical overgrazing by sheep and cattle over many decades, while also contending with the effects of a highly variable climate, such as prolonged periods of drought. It is essential that pastoralists continue to be provided with the tools and up-to-date knowledge necessary to achieve their goals and to make the best decisions for managing their business and land in a sustainable way; the ESRM process is one such way this can be achieved. The ESRM process promotes a much-needed collaborative approach to sustainable land management, bringing pastoralists, ecologists and other field experts together to maximise positive NRM outcomes while improving productivity and profitability.

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Poster presentations – Theme 1

Trend of *Stylosanthes hamata* seed production in India

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Key words: Rainfed Cultivation, Drought Tolerance, Market Volatility, Anantpur, Seed price

Abstract
This study examines the trends and factors influencing Stylosanthes seed production in Anantapur district, Andhra Pradesh, a region characterized by arid conditions and low rainfall. The area under Stylosanthes cultivation increased significantly from 2011 to 2020, driven by its drought tolerance and suitability for rainfed lands. However, irrigated areas declined as farmers opted for more lucrative crops. Seed production showed a seven-fold increase, while seed yield and selling price exhibited minimal and volatile changes, respectively. The study highlights the importance of policy support and technological improvements to stabilize and enhance Stylosanthes seed production. Market volatility and government demand fluctuations were identified as key factors affecting seed prices. Overall, the research underscores the potential of Stylosanthes as a resilient crop for arid regions.

Introduction
Seed is the most critical input to enhance the production potential of all agricultural crops, including fodder. In India, fodder is produced from 8.34 million hectare of cultivated and 10.39 million hectares of permanent pasture. Fodder yield from these lands is lower than the potential yield and the availability of good quality seeds are estimated to be around 15-25 percent only for cultivated forages (Chauhan et al, 2017). Availability of quality seed is vital because the forage crops have been bred for enhanced vegetative potential as they are shy seeders with very low seed productivity. Therefore, assured supply of fodder seed of improved varieties/hybrids to farmers at reasonable price is crucial for enhancing fodder production.

Stylosanthes is a legume fodder crop rich in crude protein that can be cultivated as grassland or pasture. Animals can feed on it directly. It is adapted to tropical climates and tolerant to low fertility, drought, acidic soils and poor drainage. The highly palatable *Stylosanthes hamata* species is preferred by animals. In India, Stylosanthes seed production started during the late 1970s by government departments. In the mid 1980s small farmers in the Rayalseema region, Ananthapur district in Andhra Pradesh, started Stylosanthes seed production to meet rising demand from government agencies for their wasteland development programs. Some farmers from the Palasamudram village in Ananthapur were trained in Stylosanthes seed production at the Raddipalli state farm of the Department of Animal Husbandry and Veterinary Services (Rao 2004). Over the years the improved seed production technology spread to surrounding villages through farmer-to-farmer exchange of seeds and technical knowledge. Stylosanthes seed production today is largely concentrated in three mandals of Hindupur and Penukonda Division of Ananthapur district comprising a network of 40–50 villages (Biradar et al, 2013). So, seed demand for this crop is met predominantly by farmers which is not so in other crops. Farmers as seed producers of Stylosanthes are concentrated in the Ananthapur district of Andhra Pradesh and over the years this crop emerged as an important crop of the region. These aspects which provide entirely different scenario as compared to other crops intrigued researchers to understand the current production and the trend of this economically important crop of this arid region.

Methodology

Ex-post facto research design was used. This design was considered as appropriate because the phenomenon of Stylosanthes seed production by farmers has already occurred. The Research study was conducted in Hindupur region of Anantapur district of Andhra Pradesh state, as Stylosanthes seed production is predominantly carried out in this region. Three blocks viz., Gorantla, Chilamathur and Somandepalli were selected based on earlier studies conducted by ICAR-IGFRI, Jhansi where Stylosanthes seed production is practiced predominantly. TFour villages having maximum area under Stylosanthes cultivation were selected from each block. In total, 12 villages were selected. They were Gollapalle, Palasamudram, Vadigepalli and Mallapalle from Gorantla block, Settipalli, Kodikonda, Morasalapalli and Reddicheruvapalli from Chilamathur block and Bramhasamadram, Edulabalapuram, Chalakur and Julukunta from Samandepalle block. From each village, ten respondents were selected randomly, constituting a total sample size of 120. A structured interview schedule was developed by consulting experts and referring to the relevant literature. Pretesting of the schedule was carried out in a non-sample area for its practicability and relevancy. The final schedule was prepared by making necessary corrections based on pre testing results. The primary data was collected from the farmers through personal interview method in an informal atmosphere. Data was analysed using a compound growth rate analysis method.

Results and Discussion

Percentage change in Stylosanthes area cultivated by the respondent from 2011-2020

The total area under Stylosanthes cultivation by the respondents was 58 acres in 2011 and increased to 377 acres in 2018 and remained same till 2020 (Fig 1). Average annual increase in area was 55 per cent while compound annual growth rate of area under Stylosanthes was 28.46 per cent. Stylosanthes is a very hardy crop. It is credited with very high drought tolerance and is almost free from pests and diseases. The study area is characterized by very scanty and low rainfall, consisting of an arid and treeless expanse with poor red soils. Anantapur district is the second driest district in the country, after Jaisalmer district in Rajasthan. The average annual rainfall here is just 520 mm, which is the lowest in Andhra Pradesh and the second lowest in India.. Rainfall distribution is erratic, uneven, and irregular throughout the year. The study area is deprived of both the monsoons and subjected to seasonal drought. Variations in climate, in terms of temperature and rainfall, have become more and more evident in the last decade. Challenging weather accompanied by changes in climate parameters might have led respondents to increase the area under Stylosanthes in rainfed lands.

However, there is a decline in the irrigated area under Stylosanthes. Stylosanthes cultivation in irrigated areas was just 20 acres in 2011 and reduced to 8 acres in 2020. The availability of groundwater enhances the opportunity to grow varied crops. Farmers might have cultivated commercial and more remunerative crops like groundnut, maize, etc to obtain more income under irrigation. In addition, the price of Stylosanthes seed depends on demand from government agencies and, thus is volatile. Farmers of irrigated areas might instead grow those crops which would fetch them more stable price. This might be the reason for the decline of irrigated area under Stylosanthes.

A similar study by Biradar et al (2003) reported that the first survey taken up in 2002-2003 showed increase in area and the second survey taken up in 2012 to document changes in area from 2002-2012 showed decline in the area asthe purchase of Stylosanthes seed for watershed programs in Karnataka and Andhra Pradesh was discontinued.

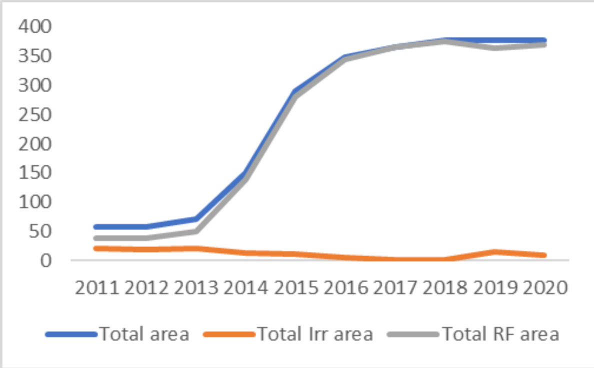

Figure 1 Average Irrigated and Rainfed area under Stylosanthes seed production 2011-2020

Percentage change in Stylosanthes seed production, yield and sale price from 2011 to 2020

Stylosanthes seed produced in 2011 was 36.25 metric tons which increased to 266.162 metric tons in 2020. However, seed production was greatest in 2017 (273.768 t) and in 2019 (274.079 t). There was a more than sixfold increase in area under Stylosanthes in the study area from 2011 to 2020. Correspondingly seed produced showed more than 7-fold increase. The increase in seed production was thus attributed to an increase in rainfed areas under Stylosanthes. There was a slight increase in seed yield (productivity) in different years with a minimum of 0.625 t/acre in 2011 to 0.727 t/acre in 2019. This minimal difference in seed yield might be due to favorable weather during flowering and seed set stage. Seed selling price in 2011 was USD 136.40/t. It increased to USD 308.40/t in 2018. The seed selling price, however, decreased in 2019 and 2020. Stylosanthes seed is traded by the respondents mainly through informal marketing channels. Middlemen who are in contact with different user agencies, mainly of public sector, get the orders. The price rise is directly related to the quantum of orders received by the middlemen. An increase in selling price thus might be attributed to the rise in demand for the seed. However, the selling price decreased in 2019 and 2020 due to a decrease in government orders for seeds as the increase in government expenditure to address the pandemic situation reducing allocation for agriculture and watershed projects. The average annual growth rate for seed production was 63.42 per cent, for seed yield 1.30 per cent and for selling price it was 1.16 per cent. Corresponding values for compound annual growth rates were 29.86 per cent (seed production), 1.09 per cent (seed yield) and 4.48 per cent (selling price). These findings indicate that changes in selling price was minimum in 10 years period while production showed good growth.

Decomposition analysis of Production Variability in Stylosanthes

Instability analysis on the area, production and productivity of Stylosanthes for a period of 10 years was carried out using Coppock's Instability Index (PII) as a measure for instability in Stylosanthes production. The results of the analysis indicated that about 52.90% of the total area was instable in the study area. Among the Stylosanthes, irrigated area was observed to be more instable compared to rainfed area. Production instability was observed to be 53.76 per cent. Seed yield and selling price were instable to the extent of 37.56 per cent and 55.1per cent. These findings confirm that the increase in Stylosanthes seed production was mainly because of an increase in area under Stylosanthes cultivation but not due to increase in yield level of the Stylosanthes.

Conclusion and Implications

The study highlights the significant growth in Stylosanthes seed production in Ananthapur district, driven by increased rainfed area cultivation due to its drought tolerance. However, irrigated areas declined due to preference for more lucrative crops. Market volatility and government demand fluctuations affect seed prices. Policy support and technological improvements are crucial for stable and enhanced production.

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Impacts of grazing pressure and rangeland ecological potential on the degraded rangeland recovery of dry steppe

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Key words: rangeland resilience, cover, grazing practice, livestock, carrying capacity

Abstract

The uncontrolled livestock population growth and increasing pressure on rangeland have led to a decline in rangeland productivity and shrinking of previously underused grazing areas. These rotational grazing practices have become increasingly difficult as heavy grazing accelerates the degradation of seasonal rangeland. Therefore, there is a critical need to identify community-supported and ecologically advantageous strategies for the recovery of degraded rangeland in the steppe zone, which is home to over 60 percent of the national herds. Efforts must be multidisciplinary, considering heterogeneous ecological sites to better understand the state of rangeland and to experiment with grazing regimes suited to the specific steppe climate and soils.

This study investigates the long-term (12 years) impacts of adjusted grazing pressure based on pre-study carrying capacity on the recovery of rangeland with varying degrees of degradation. The overall objective was to integrate grazing management practices informed by these findings into the rangeland management strategies of local herder organizations. Specific research goals included:

1. Determining how degraded rangeland could recover through grazing management tailored to its initial state and carrying capacity;
2. Understanding the interrelation of ecological site descriptions and the recovery class concept of degraded rangeland;
3. Determining the impact of grazing on the recovery of degraded rangeland in the steppe zone;
4. Assessing the effect of ecological potential on the restoration of degraded rangeland;
5. Developing a grazing model based on rangeland recovery and state change;
6. Piloting the optimal use of recovered rangeland at the herder community level.

Introduction

The decline in rangeland condition and productivity, which forms the foundation of livestock production and Mongolia's economic development, has been severe over the past 20 years. The steppe grasslands, which make up 66.12 percent of Mongolia's natural grasslands, are especially affected, with 30.8 percent categorized as dry steppes. Over 60 percent of the country's livestock graze in these areas. Degradation in this zone is expanding rapidly, underscoring the urgent need to develop and implement mechanisms for maintaining and recovering pastures at various degradation levels.

The national report on rangeland health of Mongolia (2015, 2018) noted that 80 percent of degraded pastures could recover naturally, emphasizing the importance of adjusting pasture use loads and regimes scientifically. Rangeland productivity, carrying capacity, and recovery potential vary depending on climate, geography, and vegetation. Therefore, research suggests aligning pasture use and recovery measures with the ecological capacity and degradation level of each site.

The continuous rise in livestock numbers has decreased the availability of underused pastures, limiting seasonal and rotational grazing possibilities. Consequently, it is critical to introduce practices that support the resilience and recovery of pasture ecosystems by balancing grazing pressure with environmental capacity. This study piloted the uniform use of degraded pastures in Undurshireet soum, Tuv aimag, from 2013 to 2022.

Methods

Field research focused on Steppe zone areas (n=4), representing typical pasture types. Data collection occurred between August 2009 and 2022. Enclosure and control plot pairs were established, with fenced plots measuring 25 m x 25 m. Three transects were set outside the enclosures and six inside. Samples were collected from 1 m^2 plots, with biomass and vegetative cover assessed and species diversity quantified using Shannon’s diversity index (SHDI). Data were analyzed using one-way ANOVA and Non-Metric Multidimensional Scaling (NMS) ordination.

Results

The study found that moderately degraded Stipa krylovii-Poa-Caragana steppe rangeland in deep sandy alluvial plains could support an additional 31 sheep units through controlled grazing. Long-term consistent grazing pressure over 12 years established sufficient forage resources for controlled herd management.

The ecological potential-based approach increased herder income by 10-15% through improvements in the livestock product value chain and certification based on set criteria. Moderately degraded pastures transformed into slightly degraded pastures within two years with balanced grazing loads.

Changes in total vegetation cover showed an increase to 97 percent under uniform use, while frequent use led to a decrease to 37 percent. Dominant plant species, such as Krylov's sedge, increased by 19-57 percent with uniform use but decreased by 7.5 percent with frequent use.

Discussion

The recovery of degraded grasslands in the steppe region is heavily influenced by annual rainfall and degradation levels. Studies indicate that once a threshold is exceeded, natural recovery within five years becomes unlikely. Recovery also depends on the dominant species' grazing tolerance and the balance between above-ground and underground biomass. Effective recovery requires methodologies that assess both visible and subsurface transformations.

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Advocacy instrument to voice pastoralism: experiences and lessons learned from Ethiopia

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Key words: Pastoralist Day, IGAD, Lobbying, Partnership, Networking

Introduction

In Ethiopia, pastoralists are over 14 million citizens (NDRMC 2018:2). They live in 182 Woredas[1] (23% of the total) across seven Regional States and Dire Dawa City (MoFPDA 2016; USAID 2018; NDRMC 2018). Pastoralists inhabit the country's lowlands, which are 60% of its land (IGAD 2017; MoFPDA 2018; DFID 2018). Almost all the pastoral inhabitants are considered rangelands. The pastoral population is diverse in ethnicity and social structure. 90% belong to the Afar, Oromo, and Somali groups. Most of these groups are in the country's peripheries. They have similar ancestry to those in the bordering countries. IGAD (2020:9) estimated the value of pastoral livestock at ETB 256.0 billion ($US 8.5 billion) in 2019. This includes cattle, camels, goats, and sheep. Pastoralists have faced marginalization and exclusion from decision-making. This is despite the benefits of their livestock-based livelihoods.

This paper

This paper aims to share lessons from advocating for pastoralism. We sought to improve the voice of pastoralists in Ethiopia's policy-making. We did this through a specific activity: the Ethiopian Pastoralist Day (EPD). Over the years, EPD's partners have developed the paper by reflecting on their work. The questions are: How much has the EPD helped mobilize pastoralists? Has it let them share experiences with each other and others? How much has EPD raised the profile of, and concern for, pastoralists? Has it created a supportive policy for their development at all levels? local, regional, and national? What have been the key successes and challenges of EPD? What did we learn from the lessons? This includes those for other pastoral communities outside Ethiopia. It also includes organizations that want to help them. The paper has been developed through a self- and peer-reflective process by individuals and partners who have been involved in the development of EPD since 1999.

The Birth and Development of Ethiopian Pastoralist Day

In 1996, elders and leaders from the Somali and Oromo groups in Ethiopia, along with the local NGO PCAE, organized a conference. They aimed to discuss the situation of pastoralists, marginalized and excluded for ages. They called for inclusive development, highlighting their unique pastoral system. That was the birth of the

[1]In Ethiopian Woreda administration equivalent to district

Ethiopian Pastoralist Day (EPD) in 1999 and its later development. Since the first celebration on 25th Jan 1999, EPD has been celebrated nineteen times. EPD is an *integrative* advocacy instrument. It is a unique event and process.

EPD brings together almost all pastoral actors in Ethiopia for a common cause. The Day is marked in the presence of pastoralists, policymakers, and Ethiopian dignitaries. EPD seeks to sway policymakers, the media, and development actors to change their policies and practices. PCAE and pastoral representatives organized the first three EPDs (1999-2001). They aimed to recognize pastoralism as a way of life and a viable production system. Ethiopia's pastoral groups are diverse in identity, location, and problems.

As a result, PFE has taken the role of spearheading EPD at the national level. Government and PFE collaborated on EPD from 2008 to 2022's 18th edition. The 19th EPD (25th Jan 2024) celebrated in Eastern Africa level, in partnership with IGAD, in Addis Ababa, Ethiopia. We believe that the collaboration among these institutions makes EPD a powerful advocacy tool.

Key Successes and Challenges of EPD

EPD mobilized pastoralists and created a platform for sharing experiences. It has been celebrated in rotation at national and Ethiopian regional levels. The pastoralists share customs, environments, and development from each avenue. Pastoralists from different areas can discuss their issues and present to the government. The local word, Zelan, means "wanderers and lawless." It's a derogatory term. It's been fading away. They are now called *Arbetoader* (pastoralists). It was in 2008 (eight EPD) that the Government of FDRE recognized EPD as a National Day. This is a milestone in the advocacy and lobbying work of the PFE and partners.

EPD raised awareness of pastoralists and improved policies. At each EPD, pastoralists made resolutions. They called for recognition of their unique livelihoods. They also requested pastoral-focused institutions. The EPD influenced the Federal Parliament's establishment of the PASC. In 2021, the Ministry of Irrigation and Lowland (MILL) was established. Various regional pastoral governments have also been formed. Later national plans (e.g. poverty reduction or growth-transformation papers) included pastoralism. They also increased pro-poor services (health, education, water) threefold. So far, we see two challenges. First, EPD is not well-institutionalized. It lacks a clear monitoring and evaluation system. Second, EPD is slow to move to the regional and continental levels. This would benefit pastoralists in neighboring countries by creating opportunities.

Fig. 1. 19th EPD and East Africa Pastoralist Expo celebration in the presence of high-level government delegates in Ethiopia, pastoralists and guests

Lessons Learned for Other Countries

EPD's multi-pillar approach has opened new opportunities to influence policy. EPD has united disadvantaged groups by working with various actors. These include national and local governments, elders, representatives of marginalized communities, Civil Societies and media. They now have a common voice that supports pastoralism.

Conclusions and Implications

The EPD has proved a challenging but innovative way to raise the voice of pastoralists. It aims to boost the profile and investment in pastoralism. It is a way of life, a productive livelihood, and a land use system. EPD has changed social development. It included a pastoral agenda in policy work.

The FDRE Government has recognized EPD as a "national day." High-level officials, including the Prime Minister of Ethiopia, attend the celebration. However, some compromises and trade-offs have had to be made along the way in order to address some of the challenges faced. Though the situation for pastoralists has improved, much remains to be done. We must fully recognize and support their potential and livelihoods. The continental and regional African bodies would use EPD's lessons to promote integration and peace.

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XII INTERNATIONAL RANGELAND CONGRESS AUSTRALIA 2025

Increasing education and awareness on grassland ecosystems through the development of curriculum

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Key words: education; outdoor learning; curriculum development; temperate grasslands

Abstract

Temperate grasslands are among the most endangered ecosystems globally, a situation mirrored in Canada, where significant portions have been lost. In British Columbia (BC), temperate grasslands cover less than 1% of the province but are crucial for over 30% of its species at risk. Despite their importance, there is limited awareness and education about grassland ecosystems and their services. Many teachers hesitate to focus on grasslands due to a lack of understanding and an absence of developed lesson plans that align with curriculum requirements. A project aimed at developing and piloting an elementary school curriculum on BC's temperate grasslands was therefore undertaken. The goal was to educate students and teachers about this endangered ecosystem in their region, foster local involvement, and gather support for grassland stewardship. The interdisciplinary curriculum meets the learning outcomes required for BC's public elementary schools, including embedding First Peoples Principles of Learning. Each of the three units contains ten independent lessons, which will all be available online. This will allow teachers to use the entire curriculum or select individual lessons to study. Portions of the first unit, "Grasslands: Grounding in Place," were piloted in grade 4 classes in fall 2023, complemented by field trips with elementary students. Feedback was positive, leading to a full-scale pilot in fall 2024. An outcome of this initiative was a partnership with the creators of BC Tomorrow, a free simulation tool that enables students to explore resource use and consider social, economic, and environmental factors. BC Tomorrow now includes a learning module about grassland ecosystems, which is available nationwide. This work is vital for raising awareness about grassland ecosystems and promoting further stewardship. Educating students and teachers about the significance and conservation of temperate grasslands will help ensure that these critical habitats are preserved for future generations.

Introduction

British Columbia's temperate grasslands are endangered and cover less than 1% of the province's land area, yet they provide many ecological goods and services (Iverson 2004). These include diverse habitats for plants and wildlife, flora for pollinators, nutrient cycling, carbon sequestration, and opportunities for recreation and outdoor education (Iverson 2004, Gayton 2013). However, there is a lack of awareness of the importance and function of grassland ecosystems in BC, especially within the public school system.

Many educators are hesitant to focus on grasslands due to a lack of understanding and the absence of developed lesson plans that align with curriculum requirements. Furthermore, recent updates to the BC Curriculum (PoBC 2024) have prioritized flexible learning environments and inquiry-based learning. The BC curriculum redesign has therefore heightened educators' existing interests in experiential and place-based learning and their desire to take students outdoors (Asfeldt 2021, Gruno and Gibbons 2022). Additionally, this curriculum redesign may allow for increased collaboration between teachers and community groups or organizations whose priorities include education.

Flexible learning environments may also include the use of virtual, interactive resources. BC Tomorrow is a non-profit society that has developed a peer-reviewed simulation tool, which allows students to explore the impact of land uses on environmental, social, and economic variables (BCTS 2024). Their mission is to "help students and teachers explore sustainability when considering land use decisions in BC," (BCTS 2024). In addition to the simulator, there are opportunities to extend student learning with 'quests' that encourage students to explore the outdoors and create and upload personal field observations. The BC Tomorrow simulator features watersheds and a variety of ecosystem types, however, it lacks a grassland learning module.

To acknowledge the demand for outdoor education resources and address resource gaps, a collaborative pilot project aimed to develop and deliver an elementary school curriculum about BC's temperate grasslands. The objectives of the pilot project were to create an interdisciplinary elementary-level curriculum and complementary outdoor learning opportunities that aligned with BC's curriculum and embedded First Peoples Learning Principles throughout. A secondary objective was to collaborate with BC Tomorrow to develop a grassland module to complement the elementary-level curriculum lessons.

Methods

The curriculum was developed as part of an arts-based Master's in Environmental Education and Communications thesis (Rokosh 2024). A literature review of existing grassland-themed education resources was initially conducted by undergraduate students at Thompson Rivers University in Kamloops, BC. Semi-structured interviews were then conducted with local environmental non-profit organizations to address grasslands specific to the Thompson Okanagan. This literature review, coupled with the overview of the BC curriculum, helped identify gaps that could be addressed in the interdisciplinary grassland-themed curriculum.

Classroom planning involved preparing an 'Introduction to Grasslands' presentation and various interactive grassland-themed activities. First, a sensory 'smell box' (Annnenberg Learner 2020) contained fresh sprigs of big sagebrush (*Artemesia tridentata*), a shrub native to BC's grasslands, for students to experience. Next, we modified an outdoor colour scavenger hunt (Staten 2024) by completing the activity indoors and asking students to relate the colours to their local grassland area. Lastly, students were provided with various pressed grassland plant samples to showcase growth forms and colours, then asked to identify one similarity and two differences. Following the station-based activities, students completed a 'Know, Wonder, Learn' (KWL) activity (TLA 2024).

Field trip reconnaissance took place in September 2023 and locations were selected based on bus accessibility, trail difficulty, the grassland plant community, and outhouse access. Juniper Park, located in Kamloops, BC is a community park with a playground and a network of marked grassland trails and was selected for field trips in 2023. The 2023 field activities included a grassland-themed bingo game, a colour-chip scavenger hunt, and a nature journalling session (John Muir Laws 2017). In 2024, field trips were in Lac du Bois Grasslands Protected Area (Lac du Bois). Lac du Bois is located north of the Kamloops city center and is a Provincial Protected Area that captures 15,712 hectares of grassland, forest, and riparian ecosystems (BC Parks 2023). Lac du Bois field activities included exploring land uses, a 'create a creature' journalling exercise (ASTCSWS 2024), and a grassland eye-spy game.

Results

Unit 1 of the "Explore and Understand the Grasslands!" curriculum is titled "Grounding in Place" and includes ten interdisciplinary lessons (Table 1). Each lesson captures at least two learning objectives that align with BC curriculum and has First Peoples Learning Principles embedded throughout (Table 1).

In 2023 the curriculum was piloted in four classrooms at South Sahali Elementary School on September 29th and October 11th. Complimentary follow-up field trips were held on October 18-19th where 45 grade 3-5 students participated each day. In 2024, Marion Schilling Elementary School and South Sahali Elementary school grades 3-5 participated in the in-classroom presentation and field trip sessions to Lac du Bois. Four classrooms were visited on October 4, 2024, with field sessions occurring on October 11th and 18th.

Table 1. The lesson plan and learning objectives for the "Explore and Understand the Grasslands!" elementary-level curriculum Unit 1 - Grounding in Place.

Lesson #	Lesson Title	Learning Objectives
Lesson 1	What is a biome?	1) Students will identify the seven major biomes of the world. 2) Students start to explore interconnectedness within biomes i.e., food webs and cycles)
Lesson 2	An Introduction to Grasslands	1) Students will learn the location and broad features of grasslands both globally and locally 2) Students will reflect on what they wondered and what they now know
Lesson 3	Grasslands and Tk'emlúps Place Names	1) Students will listen to stories of the area to gain a deeper understanding of the history and feeling of the place. 2) Students will practice expressing a story (either their favorite story, or a version of a place-name creation story)
Lesson 4	Introduction to Journaling	1) Students will start to create their own field journals and gain understanding of the many purposes of journals 2) Students will make observations, ask questions, make connections, and learn about something that piques their interest.
Lesson 5	Observing our Landscapes and Outdoor "Mapping"	1) Students will spend time outside with their journals and record observations of their local landscapes 2) Students will create a map of their surroundings 3) Students will learn/explore elements of maps (orienteering, scale, legends, etc.)
Lesson 6	Indoor Mapping Activity	1) Students will see how their local area has changed over time and what it could look like when they get older. 2) Students see that human activities on the land impact water.
Lesson 7	Watersheds Part 1: What are those?	1) Students locate their watershed on a map using satellite imagery. 2) Students identify key places or significant features that exist in their watershed.
Lesson 8	Watersheds Part 2: What will this watershed look like in the future?	1) Students see how their local area has changed over time and what it could look like when they get older. 2) Students see that human activities on the land impact water.
Lesson 9	Introduction to Adaptations, Relationships and Interconnectedness	1) Students explore how grassland soils, plants, animals and climate/weather are connected. 2) Students observe how grassland plants and animals are adapted to their
Lesson 10	Field Trip to the Grasslands	1) Enhance students' understanding of grassland ecosystems by exploring them in person 2) Students learn and practice how to be a responsible land user while exploring the grasslands or any outdoor space

The KWL activity demonstrated that some students 'knew' that grasslands are hot and dry and knew about grassland plants (i.e., drawings of flowers, grasses, with few trees) and the variety of animals that live in grasslands. Other students 'wondered' what animals and plants live in grasslands and how living things survive and grow there. Following the grassland in-class presentation, students 'learned' that grasslands are endangered, how plants and animals adapt to living in hot and dry environments, and how we can help take care of our grasslands through stewardship efforts (i.e., walking on trails and cleaning up garbage).

The BC Tomorrow Society collaboration resulted in a 7.38-minute-long video that details the role of grasslands in supporting biodiversity and sustaining local communities that will be used to complement the grassland curriculum lesson plans.

Discussion [Conclusions/Implications]

The objective of this pilot project was to develop an elementary-level curriculum to help educate students and teachers about grasslands in their region. A secondary objective was to collaborate with BC Tomorrow to develop grassland-focused learning modules to supplement the curriculum. This project highlights the importance of providing outdoor learning opportunities for elementary-level students. Students were highly engaged in the grassland curriculum and clearly expressed an admiration of their surroundings when exploring in Juniper Park and Lac du Bois. Studies have found that outdoor learning can increase a students' appreciation for nature, amongst other benefits such as improved self-confidence, physical and social skill development, and enhanced creativity (Boileau and Dabaja 2020). We also observed that grade 3-5 students are resilient to variable weather and maintain an overall positive attitude while exploring and learning in the outdoors.

The next steps in this project are to develop a diverse steering committee composed of educators and First Nations community representatives to help review and provide feedback on the curriculum. Furthermore, follow-up classroom visits will occur that will involve the BC Tomorrow grassland video and learning modules using the virtual simulator. Lastly, educators involved in the project will also continue expanding dissemination of curriculum through conference opportunities.

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Educating rangeland ecology and management professionals in the 21st century

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Key words: rangeland sciences; online education; experiential learning; early career professional development and networking; Bachelor of Science

Abstract

Essential knowledge and skills required of rangeland managers have traditionally been taught on land-based campuses with access to field sites. However, as the demand for online education has grown and enrollment in traditional rangeland sciences programs has declined, Oregon State University (OSU) has adapted by offering an online program (Ecampus) and hybrids of on-campus and online programs to enhance enrollment and maximize the availability of faculty to students in all modalities. The Animal and Rangeland Sciences Department at OSU currently educates ten percent of all undergraduates earning a rangeland sciences, or related degree, as accredited by the Society for Range Management (SRM).

A description of the degree, the required coursework and quality assurance through accreditation are detailed. Student advising practices and the availability of extracurricular activities, including participation in SRM are included. Despite the OSU Rangeland Sciences program's design to capture an ever-increasing number of students who seek online education, low enrollment and lengthy periods for degree completion are viewed as impediments to maintenance of the multi-campus program.

Introduction

The Rangeland Sciences program in the Department of Animal and Rangeland Sciences at Oregon State University (OSU) educates students by offering a Bachelor of Science degree as well as educating non-degree-seeking, post-baccalaureate, students. This model of educating traditional undergraduates and working professionals provides a diverse learning environment for all learners. Professionals working on rangelands gain knowledge of ecological principles while their classmates gain from the professional experiences of their classmates seeking continuing education for career advancement. Degree-seeking students can earn the Rangeland Sciences degree via three different pathways which include: 1) coursework on the Corvallis campus, 2) coursework on the La Grande campus or 3) coursework via the online offering, Ecampus. Students can attend via any combination of these three pathways. Many students are post-baccalaureate who are fulfilling requirements needed to advance in their careers as per the Office of Personnel Management (OPM) requirements for positions with the US Federal government.

To enrich the learning options for all students, faculty have developed 'field hybrid' courses in which students from any of the three pathways can enroll. The current trend is increased Ecampus enrollment with growth of 4%, year-over-year, to 11,430 in the fall of 2023 (Nealon, 2023). Concurrently, there has been a decline in enrollment on the Corvallis and La Grande campuses.

Educational Program (Methods)

Degree Description

Rangeland Sciences at OSU is an undergraduate degree which focuses on the ecology and management of rangelands across a variety of arid and semi-arid ecosystems including shrublands and grasslands (Rangeland Sciences Undergraduate Major 2024). This program uses a multi-disciplinary approach to provide advanced scientific knowledge of ecological processes and social drivers influencing rangeland ecosystems around the globe. Students gain the skills and knowledge needed to understand and effectively manage rangelands for improved productivity and enhanced ecosystem resilience. The goal is that graduates of the program will be able to integrate contemporary rangeland ecology and management principles into a systems-based decision-making framework that promotes ecological resilience, sustainable societies, and thriving economies in rangeland systems.

Required Coursework

To earn the Bachelor of Science, students must complete eight upper division courses within the Animal and Rangeland Sciences Department as well as the usual mathematics, statistics, life sciences, chemistry, writing and humanities electives. Departmental faculty members teach rangeland ecology principles, wildland plant identification, ecology of grasslands, ecology of shrublands, rangeland ecohydrology, vegetation monitoring and analysis, restoration and management, rangeland-animal relations and rangeland management planning principles and processes (Rangeland Sciences Undergraduate Major 2024). Electives in wildlife habitat analysis, riparian ecohydrology and management and pastoral systems of the world are also offered. Related coursework in Botany, Soil Science and Fisheries and Wildlife Conservation are offered by those Departments, also in the College of Agricultural Sciences.

Teaching Modalities

All courses are offered on-campus and via Ecampus with the same student learning objectives for all sections. This requires innovation on the part of faculty as the asynchronous online learning environment changes the nature and timing of faculty-student and student-student interactions. The usual dialog in on-campus courses is conducted in a modified manner via Discussion boards within the learning management system (LMS). Questions within Ecampus Discussion require application of course content as well as interaction with peers and faculty. Recorded lectures, with captioning, are part of every weekly Module in the Ecampus sections of the courses. Incorporation of research faculty work and research outcomes are shared across the courses with guest lectures and accompanying required reading. When courses are developed, and updated through a 're-development' process, specialists in online education work with the Rangeland Science educators to ensure up-to-date resources are used. Most courses are taught by one or two individuals across the three campuses.

Maintaining Quality

The Rangeland Sciences degree is aligned with the US Office of Personnel Management (OPM) standards which allows graduates to begin careers with the US Federal government in various agencies including the US Department of Agriculture and the US Department of the Interior. Graduates are also sought by State land management agencies, private land trusts and private landowners such as livestock producers.

The undergraduate degree program at OSU is accredited by the Society for Rangeland Management (SRM) with the most recent review in 2023. The seven SRM Accreditation Standards for University Accreditation include criteria for the education of the faculty, role of faculty within the university, degree name, depth and breadth of the curriculum, advising of students, extracurricular opportunities for students, continuing professional development of the faculty, self-assessment of program effectiveness and university support for the program. The SRM criteria-based system is valued by educators as well as rangeland ecologists and managers. This and other endorsements of university programs are highly valued by university administrators. OSU (2024) is a member institution of the Northwest Commission of Colleges and Universities (NWCCU) and shares this information with the public via web pages and reports. This is a critical component of maintaining public trust.

To meet the requirements for accreditation of OSU by the NWCCU, a set of five programmatic learning outcomes was established by the teaching faculty. These are aligned with SRM standards. Student performance data are collected from all sections of courses in which the programmatic learning outcomes are taught. Faculty review performance on an annual basis with guidance from the Assessment Lead who is a peer in the academic unit. Comparisons across campuses and across time are used to revise teaching and assessment methods.

Orientation and Advising

All students who enroll as freshmen at OSU are required to attend a START new student orientation session whether on campus or in a virtual session (Office of Student Orientation 2024). These sessions introduce students to academic, financial and social resources. Family members can also attend specialized sessions which include how to support the student and family transitions when sending a student to college.

Each student meets with an assigned Advisor to review course selection for the upcoming academic term. Extracurricular activities, including summer internships or employment are also discussed. These regular interactions ensure that students enroll in courses for which they are prepared and those which are most suited to the degree. Post-baccalaureate students have diverse educational goals and so advising them is complex as it requires consideration of past collegiate level coursework and work-life balance concerns.

Field-based Learning and Faculty Innovation

Four of the eight required courses included multi-day field trips to locations in northeast, central and southeast Oregon, prior to 2011 when two academic units were merged. Although field trips are still required in some on-campus courses, budgetary pressures and the transition to include the Ecampus program have been challenging for faculty. Concurrently with Ecampus course development, on-campus enrollment declined and over the past decade the number of courses with required field trips has declined as well.

To address the need for experiential learning, Ecampus and many on-campus sections now include activities that require students to explore rangeland ecology principles, no matter where the student lives. These assignments require students to select a field site to explore. Careful, step-by-step instructions must be followed and students document their work with photos, descriptions and video clips of their efforts, observations and conclusions. Complete work is uploaded into the online learning management system for view by faculty and peers. Peer evaluation is incorporated where appropriate. In this way, a student can see a location not available to them and receive feedback on what their classmates observe. Students in urban areas are provided coaching on how to select a park or natural space that is most suitable. In the grassland ecology course, a student living in Las Vegas, Nevada was directed to conduct the grassland ecology activity in the riparian zone of a local river. Site characteristics had to meet the requirements of the assignment. While the student was not exploring an established grassland, the site provided a suitable stand-in for the examination of deeply-rooted perennial grasses and the other components of the assignment.

Another innovation to address the need for hands-on learning is the 'field hybrid'. Faculty based at the OSU Eastern Oregon Agriculture and Natural Resources Program office a 'field hybrid' version of the vegetation measurement and analysis course (see **Required Coursework** above) in which students spend a week at the Starkey Experimental Forest and Range and the Zumwalt Prairie in Northeast Oregon. This intensive week-long session is open to students enrolled at the Corvallis, La Grande or via Ecampus. Following the field week, students complete course content in a merged Ecampus section. A Corvallis-campus based faculty member has also developed a section of rangeland-animal relations course as a field hybrid which includes tours of cattle ranches, Bureau of Land Management Wild Horse Corrals and interaction with rangeland conservationists in Oregon's sagebrush steppe.

Results

Degree Completion

As rangeland sciences programs face declining enrollment at many educational institutions, faculty have adopted methods of program delivery to suit the twenty first century learner. Several trends are evident. Many students require more than the historic norm of four years to complete a degree. Others seeking professional development related to their current employment enroll in courses on a sporadic basis. This might be one course per academic year or a few courses over three-four years. Students seeking a degree in this manner are not counted in the traditional manner universities use to document student success, i.e., degree completion and years required for completion. Thus the benefits provided by the Rangeland Sciences program go unrecognized because they do not meet traditional metrics of success.

While hundreds of students have earned degrees on the Corvallis and La Grande campuses, only twenty students have earned a Bachelor of Science in Rangeland Sciences via Ecampus since its inception (Duerfeldt, 2024). All other Ecampus enrollees are post-baccalaureate or are on-campus students seeking particular faculty or flexibility in their academic schedules.

Employment of Graduates and Professional Networking

A formal record of graduate employment following the awarding of a Bachelor of Science in Rangeland Sciences (Rangeland Ecology and Management prior to 2011) is not available. However, current and retired faculty members interact with graduates and thus anecdotal information is available. Students are employed by the US Forest Service, US Bureau of Land Management, State land management agencies, land trusts and on private ranches.

Students benefit from faculty introducing them to their professional networks, particularly within the Society for Range Management. These relationships are reinforced at annual International SRM meetings such as the February 2025 meeting in Spokane, Washington. In some instances, due to Ecampus enrollment, the first face-to-face interaction between students and faculty occurs at a SRM meeting.

Discussion

Declining enrollment in the on-campus programs has challenged university administrators and teaching faculty for at least 15 years. Numerous factors contribute to this trend including faculty attrition, lack of awareness and promotion of the on-campus degree programs and competition due to other similar degree programs such as Environmental Sciences in the College of Earth, Oceanic and Atmospheric Sciences and the Natural Resources degree in the College of Forestry. Students in other degree programs take advantage of the rangeland sciences coursework to meet the breadth requirements of their degrees yet do not complete the Rangeland Sciences degree. Faculty in the Rangeland Sciences degree program report anecdotally that some students would have chosen to earn Rangeland Sciences degrees had they been aware of the opportunity earlier in their undergraduate educational career.

It is anticipated that the Ecampus program will remain a strength whether those enrolled seek a Bachelor of Science degree or enroll as post-baccalaureate students completing continuing education as part of their professional development. Because the Rangeland Sciences program provides essential content for other natural resources-related degrees at OSU, the faculty in this academic group will continue to provide relevant applied ecology education for those students.

Conclusion & Implications

Continuation of the Bachelor of Science in Rangeland Sciences degree at OSU will demand innovation, increased enrollment and collaboration across departments and with other universities. Increased use of simulations could enrich online course offerings and expansion of the field hybrid course offerings would enhance undergraduate learning with hands-on coursework.

Despite the prominent level of faculty collaboration with other universities, land management organizations and the ranching community, increased student enrollment and increased degree completion are the factors that will make the Rangeland Sciences degree program valuable to administrators who must justify its costs.

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Sustainability and resilience of the Mongolian indigenous rangeland

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Key words: Mongolia's rangeland culture, adaptability.

Abstract
Mongolia's indigenous civilization relies on the rangeland system for grazing the livestock. Three main risks to traditional animal husbandry exist including pasture degradation, unnatural livestock deaths, and negative impacts of new civilization unfavourable to animal husbandry. Mongolia's traditional animal husbandry has sustained through managing these three risks, and animal husbandry production has continued to grow. The second risk has been mitigated traditionally by pastoralists through generations. Accordingly, herds of adult animals can recover quickly as environmental conditions improve. The third risk is successfully mitigated by the modern animal husbandry sector. This is evidenced by the fact that Mongolia's rangeland culture is still considered sustainable, adaptive, and resilient despite intensified agricultural, infrastructure, and mining developments, as well as urbanization during the past 100 years.

Introduction
Mongolia's traditional pastoral culture has evolved by adapting to the favorable and unfavorable conditions of nature. Mongolia's gross livestock output has continuously been on the rise since the year 2000. In this paper, we explore how Mongolia's traditional pastoral culture has adapted to and stabilized in response to the challenges and opportunities presented by modern urbanization and technological advancements. On the one hand, Mongolia's livestock behave like wildlife, independently foraging for grass and grazing selectively; on the other hand, it represents society and culture as it is an integral part of the life of pastoralists. Thus, it is entirely possible to view Mongolia's traditional pastoralist civilization as a model of harmonious coexistence between nature and society.

The sustainability of traditional animal husbandry is primarily due to its spread across more than 1.5 million square kilometers and its ability to maintain the vastness and sufficiency of its pastureland. Livestock herding follows four main procedures, each carefully adapted to the specific conditions of the four seasons. Each season involves a distinct set of activities, while preparations for the next season begin during the current one. The effectiveness of the preparations will determine how successfully the new season is managed. In this way of following a one-year cycle of four seasons, traditional animal husbandry production differs markedly from the production of other commodities and goods. The animal husbandry industry is complex and encompasses a wide range of activities, including livestock herding, herd management, pasture selection and utilization, seasonal livestock migration (plus otor), winter camp facilities management, livestock birthing and raising, feeding, and fat deposition, reserving fat, overwintering, watering, salt supplementation, hay and fodder management, sheering, milking, etc. Knowledge and expertise in these complex operations are essential to the success and sustainability of the pastoralist business.

Methods

Using livestock statistics from Mongolia (National Statistics Office, 2024), the data were processed using simple mathematical calculations, and key indicators were calculated for presentation in tables and graphs, which were subsequently interpreted to draw conclusions. Approximately, 10 tables and graphs are included in this study and will be featured in the poster presentation.

Results

The number of herder households in Mongolia fluctuates by approximately 12%, influenced by natural conditions, with an average of 170,000 households over the past 32 years. 'Herder Households-I' has grown to 188,000, while 'Herder Households-II' has declined and stabilized at 60,000. Livestock distribution varies across soums, with an average of 735 livestock-owning households per soum. Mongolian pastoralist communities maintain a strong cooperative culture, supported by modern communication. Traditional livestock management practices, including breeding control and risk management, have contributed to stable livestock survival rates, even during environmental challenges such as dzuds and droughts. Over the past 51 years, the average annual livestock mortality rate has remained below 8%, highlighting the resilience of Mongolian pastoralism.

Discussions

In the age of globalization, where the cultures of many countries are being introduced to Mongolia, it may seem that the country's traditional pastoral animal husbandry is at risk of being overshadowed and potentially destroyed due to conflicts with urbanization, crop farming, transportation, and mining development. On the contrary, the gross livestock output is constantly growing. So, where does the secret behind the stability, adaptability, and regenerative capacity lie? The results of our research several potential answers, outlined below.

1. Interest in livestock herding remains strong among families, and the number of herder households tends to fluctuate by approximately 12%, depending on favorable or unfavorable natural conditions. Based on data from the past 32 years, the average number of herder households is 170,000, with fluctuations occurring approximately every 7 years. Furthermore, during one-quarter of the 32 years, the number of herder households declined, while it increased during the remaining three-quarters of the same period. The number of herder households increased by up to 21,000 during three years of favorable climate conditions, while it decreased by nearly 26,000 over three years of unfavorable weather.

The number of 'Herder Households-I' (households primarily engaged in livestock farming) increased by 45,000 compared to 1992, stabilizing at 188,000. In 2001 and 2010, marked by severe drought and dzud, the number of herder households declined, followed by a subsequent resurgence. On the other hand, the number of 'Herder Households – II' (households that participate in the official livestock census and rely on a combination of livestock and non-livestock income sources) declined for approximately 10 years, from 158,000 in 1992, when livestock was privatized, to 60,000 over the past 20 years, where it has since stabilized. The number of households participating in the livestock census appears to be less affected by dzuds, likely because they raise fewer animals with adequate hay and fodder reserves or engage in more intensified farming practices. Further study is needed to explore this in more detail.

2. Households with livestock are distributed throughout Mongolia, with 200-400 households in 34 soums, 450-950 households in 224 soums, and 1,000-2,000 households in 72 soums. The average number of livestock-owning households per soum is 735. The distance between herder families varies, depending on factors such as the four-season cycle of the year, precipitation, pasture yield, and the need for cooperation and collaboration. During winter, this distance ranges from 5 to 20 km, with a family possibly moving between two to three winter camps to access pasture.

3. The moves of livestock and herder households, coupled with the communal use of pastureland, have fostered the development of a unique pastoral community culture. The pastoralist community has a concentric structure,

with herder households sharing a common pasture at its core and allies from soum and provincial centers forming the outer layers. IIn the outermost circle are relatives and friends living in the capital city of Ulaanbaatar, other provinces and soums, and even abroad. A herder family may be familiar with other families within a 100 - 200 km radius. This layered structure of pastoralist communities is rooted in a traditional culture where the brotherhood among pastoralists is strong, and there is a sincere commitment to helping one another within the shared pasture. In Ulaanbaatar and other provinces, the 'Nutag/Local Councils' are established at the intersection of nomadic and settled cultures uniting Mongolians with a pastoralist way of thinking. The modern-day layered structure of pastoralist communities enables herders to access a wide range of information, goods, and services without the limitations of space and time by using information technology.

4. Livestock breeding, or the suspension of breeding, is integral knowledge embedded in Mongolian traditional herding practices. Breeding management is carried out with consideration of summer precipitation, winter snow, and cold forecasts, the availability of labor within the herder family, and the livestock's condition, including fat reserves and strength. Traditionally, measures have been implemented to limit the number of breeding livestock, particularly during years of drought and dzud. Suspending the breeding of mother animals can be a strategic measure to reduce fat loss for the livestock during harsh winters and to lessen the workload associated with birthing and rearing in the spring. During 2019-2021 with the COVID-19 pandemic, Mongolian herders suspended livestock breeding, increasing the number of non-breeding mother animals by 6-7 times compared to the average in previous years. This measure significantly eased the burden on herders, allowing the animal husbandry sector to remain stable throughout the pandemic and even achieve overall production growth. In contrast to restrictions on production processes in some countries, where workers protested to express their desire to work, Mongolian herders continued their usual herding activities.

5. Statistics from the past 53 years show that practices related to the delivery of animal babies and newborn care have been passed down through generations and have remained consistent. Livestock rearing refers to the proportion of animals successfully raised out of every 100 born. Except for two major drought and dzud in 2001 and 2010, respectively, livestock rearing has remained stable over the past 53 years. Even during the COVID-19 pandemic (2018-2022), the rearing rate remained stable on average, without any decline, which is a testament to the effectiveness and resilience of Mongolian traditional livestock-rearing methods.

6. The risk management techniques of Mongolians have a centuries-old tradition, as key risks to animal husbandry, such as droughts and dzuds, have long shadowed pastoralists since the earliest days of herding. This can be likened to the experience of countries with cultures of resilience in overcoming natural disasters, such as hurricanes, earthquakes, and tsunamis. Drought risk management involves a broad range of activities, including weather forecasting, livestock migration (otor), pasture management and scheduling, hay and fodder preparation, setting breeding caps, culling animals, and preparing infrastructure such as fencing and water points, as well as salt supplies. Orkhon, Selenge, and Darkhan-Uul provinces are key areas for hay and crop production, with numerous entities and cooperatives operating in fodder preparation, sale, and transportation. The degree of dzud disaster varies for the Gobi and Khangai regions. There have been occasional instances in the Khangai region where summer conditions were relatively favorable, and severe winter and spring conditions, including sudden snowfall and dzud, have led to significant livestock losses. In contrast to the Khangai provinces, the Gobi region experiences lower livestock loss, suggesting that summer conditions in the Gobi may enable better winter predictions, allowing drought-affected herders to prepare more effectively. The National Emergency Management Agency of Mongolia has experience taking swift action during droughts and dzuds to minimize livestock losses and support herders.

7. The primary goal of livestock grazing and herding in Mongolia is to ensure the survival of livestock through all four seasons without losses/mortality. Overwintering involves two key priorities: ensuring that animals gain sufficient fat and strength and minimizing animal mortality. Grazing is a fundamental aspect of Mongolian livestock management, as animals rely on pastureland to acquire the necessary nutrients for growth, fattening, and other outputs. As a result, herders pay significant attention to pasture selection and effective herding practices. Livestock that have access to high-quality pastures and receive proper herding care are more likely

to survive the winter and yield higher-quality products, such as wool, cashmere, and milk. A grazing animal roams freely in a pleasant natural environment, with access to fresh air, clean water, and new grass. This daily activity promotes the animal's health and supports its overall well-being. Among the many plant varieties that thrive in dry conditions, the best are consumed by livestock. The vast pastures are also home to numerous medicinal plants. Meat, milk, and dairy products from livestock fed with nutritious plants, and not stressed are true natural Mongolian products—high in quality, though produced in limited quantities. Improved animal well-being and higher outputs bring happiness to the herder.

Converting mobile pasture-based livestock to a settled farming system presents several challenges. Above all, pasture livestock have a very different temperament than the farmed animals. With an introduction to fenced pastures, they may experience physical changes and emotional stress due to their limited mobility.

The main goal of Mongolia’s traditional animal husbandry is to maintain or increase the livestock population. Accordingly, herders often focus more on the high survival rate of their livestock during the winter than on quantifying meat sales. Over the past 51 years, statistical data show that the average annual livestock mortality rate is less than 8%. Although herd sizes decrease during dzuds and droughts, they recover and grow again in cycles of favorable weather. This ability to reproduce and restore is inherent in traditional pasture livestock. It provides herders who have faced losses from droughts and dzuds with confidence in the future and the motivation to rebuild their herds.

Conclusion

Mongolia's traditional pastoral livestock system has demonstrated remarkable resilience, adaptability, and regenerative capacity despite pressures from urbanization, mining, and crop farming. The stability of the herding population, strong communal ties, and effective risk management strategies have allowed pastoralism to persist as a vital economic and cultural practice. Time-tested breeding management, disaster preparedness, and sustainable pasture use contribute to stable livestock production, even in the face of environmental challenges such as dzuds and droughts. These factors underscore the enduring viability of Mongolian pastoralism in the modern era.

Implications

The resilience of Mongolia’s pastoral system suggests that policies should continue to support traditional herding practices while integrating modern technology and sustainable resource management. Strengthening local herder networks, improving access to weather forecasting and fodder reserves, and preserving communal pasture use can further enhance adaptation to climate variability. Additionally, recognizing the economic and cultural value of pastoralism may encourage efforts to balance development with the preservation of Mongolia’s unique herding heritage. Further research is needed to explore how intensified farming practices and alternative income sources can complement traditional pastoral livelihoods.

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Pastoralist at the crossroads: the struggle for land ownership and forceful relocation. A case of the Maasai pastoralists of Loliondo and Ngorongoro in Tanzania

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Keywords: The Maasai; Eviction; Indigenous; Land rights; Tenure Security

Abstract

The interplay between land tenure and governance significantly impacts the stewardship of rangelands, affecting Indigenous peoples and pastoral communities. This paper explores the evolving dynamics of land rights, particularly in areas like Ngorongoro and Loliondo in Tanzania, where communities face challenges due to land appropriation under the guise of conservation and economic development. The study urges equitable governance and emphasizes recognizing land rights and promoting participatory governance to empower local communities. Sustainable land practices can support marginalized communities' environment and livelihood by integrating traditional ecological knowledge into policy-making. A collaborative approach involving multiple stakeholders in decision-making processes is advocated, aiming to achieve more inclusive and just governance systems while addressing conflicts and promoting resilience among Indigenous and pastoral communities facing economic and environmental challenges.

Introduction

The forced displacement of local communities and Indigenous peoples from their ancestral lands in the name of conservation and development is a pressing issue that has garnered global attention, particularly in developing countries, disrupting their social fabric, cultural heritage, and livelihood (Maddox, *et al* 2023; Indígenas 2023; and Dawson, *et al* 2021). Starting in the mid-20th century, a series of land and wildlife laws aimed at conservation in Northern Tanzania pushed the Maasai off large tracts of their traditional land, including present-day Serengeti National Park (The Oakland Institute 2021; Jama and Mesfin 2024; Goldman 2011).

The Maasai pastoralists have long been custodians of the land, relying on traditional pastoralism for sustenance and cultural preservation. However, the encroachment of external interests often leads to dispossession, marginalization, and the erosion of centuries-old cultural practices (IWGIA, 2022a; Jama & Mesfin, 2024; THRDC, 2023). The displacement of these communities exacerbates existing inequalities, perpetuating cycles of poverty and insecurity. The stark contrast between the interests of local communities seeking to maintain their way of life and external actors prioritizing economic gains underscores the complexities inherent in land ownership struggles.

The history of Tanzania's Land Tenure System and its legal frameworks

Tanzania's land tenure and laws can be traced back to the colonial era, particularly the time between 1884/85 and 1917 and 1918 to 1961 for German and British administrations, respectively (The Oakland Institute 2021). During the Germans era, the Land Decree was passed, allowing all territorial land to become crown land controlled by the German Empire, investing the power over land to a governor as a "custodian" permitting him to take away the land for certain uses assumed of the public interest (Shaudo *et al.* 2022). Under this decree, any land without evidence of ownership or continued use is considered vacant and ownerless. In 1903, the Land Registration Ordinance was passed, allowing the land to be allocated to individual, mostly white settlers through the land registration bureau. Although the bureau allocated the land to the white settlers, traditional and Indigenous lands were recognized as they fell under the village boundaries (Shaudo *et al.* 2022).

In 1923, Land Ordinance No.3 was passed, declaring all land public and giving a governor the power to control the natives' lands for the "use of common benefit," leading to the local communities losing large areas of land to the government (The Oakland Institute 2021). Between 1923 and 1926, the traditional communities lost approximately 120,000 hectares of land to foreigners (Barume 2010).

In 1940, the Game Ordinance was enacted to create the national parks and reserves, including setting the original boundaries of Serengeti National Park and imposing the first restrictions on settlement and use of the surrounding lands (The Oakland Institute, 2018). Later, in 1957, the community of inquiry led by the British recommended that the existing Serengeti National Park be split into two, whereby the first part is the present-day Serengeti National Park(SENAPA) and the second part became the famous Ngorongoro Conservation Area (NCA). They further recommended the total restriction on human habitation, including the Maasai (natives of the land) in the first part, while the latter allowed multiple land use with three goals of conservation, tourism, and protecting the interest of Indigenous groups (Shaudo *et al.* 2022; Fraser 2019). The National Parks Ordinance in 1959 led to the Maasai losing their customary rights, forcing them to other lands such as far east to Ngorongoro and Loliondo areas (Fraser 2019; Shivji and Kapinga 1989; Lissu 2000).

Additionally, the NCA Ordinance of 1959 established the Ngorongoro Conservation Area, allowing the Maasai settlement rights with the Ngorongoro Conservation Area Authority (NCAA) as the governing body. The NCAA was given the ability to prohibit, restrict, or control various activities in the region, including cultivating land, grazing cattle, and creating settlement dwellings (Shaudo *et al* 2022).

Through the Arusha manifesto of 1961, the government pushed wildlife conservation with a bold promise of dedicating more land for conservation and wildlife parks, creating a specific role for international conservation groups to provide technical expertise in the planning and management of conservation areas in Africa (The Oakland Institute 2018; Burnett and Conover 1989). These groups, such as Frankfurt zoologists and the International Union for Conservation of Nature (IUCN), later lobbied to restrict the rights of the Maasai to cultivate, graze, and move within their residence (Shaudo, *et al* 2022; Fraser 2019; Burnett and Conover 1989). In 1974, the Wildlife Conservation Act was passed, creating three types of conservation lands *(GCA, wetland reserves, and Wetland areas)* in addition to the game and parks, with significant restrictions placed on activities within these areas.

The vital legislation on land governance and tenure is the 1999 Land Act & Village Land that replaced the 1923 Land Ordinance, categorizing Tanzania Land under three categories, namely general land, village land, and reserved land (Veit 2019; URT 2022). Although the Village Act No. 5 of 1999 recognizes customary tenure and empowers village authorities to manage lands, many communities still lack security in their customary land, with the president holding the power to declare the village land under other categories of land for what is called "public interest" the same way the 1923 land ordinance did (Gailo, *et al* 2014; Jama and Mesfin 2024).

Losing their land: Eviction of the Maasai from their Lands from 1940s -2023

The Maasai have inhabited the Serengeti plains and the Ngorongoro highlands since the 15th century, even before the Swahili trader's encounter in the 17th Century. They were expelled from their homeland when

Serengeti was made a National Park towards the end of the colonial period (Arhem 1985; Faurler 1882; Lissu 2000).

Contrary to some claims that the Maasai were offered Loliondo for Serengeti, they have inhabited it since time immemorial (Pearsall 1956; The Oakland Institute 2021). During the negotiations for the relocation of their relocation from the Serengeti plains in 1948, the British made a solemn to them that they had a right to be consulted, engaged, heard, and respected on matters related to land rights, with the promise of not breaking that pledge (Shaudo, *et al* 2022; Shivji and Kapinga 1998). Referring to the Ngorongoro Conservation area, when addressing the Federal Council of the Maasai people in 1959, Richard Turnbull, the British governor of Tanganyika, stated that;

> " ...should there be any conflict between the interests of the game and the human inhabitants, those of the latter must take precedence" (Shaudo, et al 2022)

The laws that established the NCA in 1959 did not extinguish the customary land rights of Indigenous residents but rather preserved them. In this view, the Maasai in NCA are, therefore, rightful landholders under the deemed customary right of occupancy (Shaudo, *et al* 2022; Shivji and Kapinga 1998).

After the failed evictions in the Loliondo and Ngorongoro areas, the government, in the middle of 2022, initiated the military operation to demarcate and evict residents living within the 1502 Km^2 along SENAPA, affecting about 15 villages in Sale and Loliondo Divisions, paving a way for the establishment of Pololeti Game Reserve. Moreover, the residents of NCA were forcefully relocated to more than 600 kilometers away in the Handeni District in the Tanga region (Shaudo, et al. 2022; IWGIA $2022_{a;}$ IWGIA 2022_{c}).

What does this eviction mean for the social, cultural, and economic well-being of the Maasai Pastoralist?
In the words of Matthiessen (1972), the African landscape is not just a backdrop but a living entity that shapes the lives, cultures, and survival of its inhabitants. The Maasai and their cattle depend entirely on land for pasture and hence family livelihood (Jama and Mesfin 2024; Rabinovich *et al* 2022). Shaudo, *et al* (2022) highlighted the connection of the land to the community livelihood and economic implications, cultural ties, and loss of their Identity. The ongoing restriction and forceful relocation have led to the community suffering from hunger, absolute poverty, violation of human rights, social conflicts, loss of land access and user rights, disruption of social structure, and limited community cohesion (UN 2022; Shaudo *et al* 2022; THDRC 2023). The Maasai lost most of the irreplaceable ceremonial and ritual sites affecting the community's belonging and identity with no opportunity to practice their culture, rituals, and traditional ceremonies such as rites of passage and rites of retirement, which are vital for their identity and tradition.

Additionally, the loss of access to fertile land led to serious consequences, resulting in poverty and starvation, limiting their economy and exacerbating vulnerability (Jama and Mesfin 2024; Sørensen and Vinding 2016). Shaudo *et al* (2022) reported that the Maasai pastoralists evicted from the Mkomazi Game reserve have experienced livestock loss, leaving them in dire poverty, and their fate might be shared by those of Ngorongoro. Due to a lack of enough fodder and grazing areas, the evicted Maasai have lost 70 –100% of their herd, leaving them in absolute poverty (Gailo *et al* 2014). Wickham *et al* (2014) highlight that due to climate variability, diseases, inadequate grazing and water resources, and unsuitable conditions for livestock keeping around the villages, they re-settled the Maasai and lost 95 percent of their livestock.

Conclusions and recommendation
One might ask, what then is there for the pastoralist communities in Tanzania? One should understand the reason behind this dilemma. Factors such as poor land use policies, political will in respecting the existing legal frameworks, fortress conservation, and the underlying impacts on the pastoralist communities. Most of the lands have no title deeds making it more easy to be taken by the state.

Addressing the challenges faced by the Maasai requires a comprehensive understanding of the complex interactions between social, economic, and environmental factors. With the major factor of displacement and forceful relocation from their homes being wildlife conservation backed by the state, the move has failed to take into consideration the far greater impacts on the community and existing relationship with their natural environment

The governing bodies should consider local communities' participation, encourage sustainable land management practices, foster community resilience, and respect Indigenous people's rights. There is a need for friendly and inclusive policy frameworks that allow pastoralist communities to engage and participate in land use plans and have a say on matters related to their land.

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History of the Pastoral Board of South Australian and the *Pastoral Land Management and Conservation Act 1989.*

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Key words: Pastoralism; Conservation; Board; Act; Sustainability

Abstract
South Australia's Pastoral Board (the Board) has a vital role in overseeing the sustainable management and conservation of the state's pastoral lands for a diverse range of uses, which continue to evolve over time as new markets and industries emerge, as the climate changes and communities evolve.

Pastoralists and other land managers play a critical role in managing and conserving vast areas of the state's land which holds both productive and ecological values as well as cultural and social values.

Originally formed under the Pastoral Act of 1893, the Pastoral Board of South Australia has a long history and extensive experience in the administration of pastoral land (Donovan P. 1995). The current *Pastoral Land Management and Conservation Act 1989* enables the Board to manage land in a contemporary context.

The Act aims to:

- ensure that all pastoral land in the State is well managed and utilised sustainably;
- provide for monitoring of land condition, prevention of degradation and rehabilitation of the land;
- provide a form of tenure suitable for the pastoral industry (42-year leases reviewed every 14 years);
- recognise and provide for the rights of Aboriginal people to follow traditional pursuits on pastoral land; and
- enable community access to and through pastoral land.

The Board aims to achieve the world's best managed pastoral country, by working with pastoral land managers and communities to develop, adopt and promote practices that sustain the state's pastoral lands for current and future generations.

The Board's immediate priorities include delivering an effective and fit for purpose land condition assessment program, effective compliance, and sound policies informed by community input, to support certainty for pastoral lessees, and reduce risks of degradation that affects the long-term sustainability of pastoral lands. It works closely with other regulators to achieve aligned management for a range of outcomes, including complementary legislative regimes for new industries.

Introduction

The *Pastoral Land Management and Conservation Act 1989* (the Act), and the establishment of the Pastoral Board of South Australia, mark transformative points in the history of land management and conservation in South Australia. Together, they represent a governmental commitment to addressing the complex demands of pastoral land use in one of the world's most arid and ecologically sensitive regions. South Australia's pastoral industry, a cornerstone of the state's economy since the mid-19th century, has historically centered on grazing in vast, arid and semi-arid landscapes. While pastoralism contributed significantly to economic growth and settlement, the expansion of grazing activities into semi-arid and arid regions led to severe environmental consequences, including soil erosion, vegetation loss, and ecosystem disruption (Donovan 1995).

In response to these challenges, the Act introduced a comprehensive legal framework aimed at balancing economic interests with sustainable land use and environmental conservation. This landmark legislation empowered the Board with responsibilities that include overseeing land leases, monitoring ecological health, and ensuring compliance with sustainable practices. The Act was notable for its emphasis on conservation principles, promoting practices that would protect biodiversity and preserve the natural resources critical to both the pastoral industry and regional ecosystems.

Pastoral Land Management and Conservation Act 1989

The *Pastoral Land Management and Conservation Act 1989* represents a significant legislative milestone in South Australia's efforts to manage its arid and semi-arid lands sustainably. This Act was introduced as a comprehensive response to the unique environmental, economic, and social challenges of pastoral land use in a state where extensive grazing is a critical economic activity but one that often conflicts with ecological preservation. Prior to this Act, pastoral land management in South Australia was governed by earlier regulations that largely focused on promoting agricultural expansion and economic development, often at the expense of environmental sustainability. Over time, however, it became clear that these policies had led to issues such as land degradation, biodiversity loss, and the depletion of essential resources.

The Act reshaped the legislative framework, introducing measures that prioritised both economic viability and ecological integrity. By emphasising sustainable land use, biodiversity conservation, and responsible resource management, the Act sought to address the long-term health of South Australia's pastoral regions. It established the Board as a key regulatory body with authority over land leases, monitoring, and the enforcement of sustainable practices. The Act also promotes collaboration between the government, pastoralists, and environmental organisations, fostering a more holistic approach to land management. The advent of renewable energy has seen amendments to the legislation allowing for establishment of other land uses such as wind and solar farms and hydrogen projects.

Pastoral Board Establishment

The Pastoral Board (the Board) has played a pivotal role in shaping the state's pastoral landscape, evolving in response to environmental, economic, and social changes since its inception. Established in 1895, the Board was initially appointed to manage the allocation, leasing, and regulation of vast tracts of land used for grazing in South Australia's arid and semi-arid regions. As settlers expanded into harsher, less hospitable areas, issues of land degradation, overgrazing, and water scarcity began to surface. The creation of the Board was a government initiative aimed at addressing these challenges by overseeing land use, ensuring sustainable practices, and balancing economic interests with environmental stewardship. Over time, the Board's responsibilities expanded, adapting to changes in agricultural technology, environmental policy, and indigenous land rights. Its policies and regulations have had lasting impacts on South Australia's land use patterns, biodiversity conservation, and rural communities.

Pastoral Board Today

The Board consists of six members from diverse backgrounds appointed by the Minister under the Act for a 3-year term, which can be renewed. Each member brings a distinctive skill set to the Board's deliberations.

Collectively the Board has an extensive knowledge of the administrative, environmental and economic issues of the South Australian pastoral lands (Pastoral Board of SA, 2023).

The Board administers pastoral leasehold tenure on 322 pastoral leases over 40% of the state (approximately 422,000 km^2). The Board is a statutory authority responsible to the Minister for Climate, Environment and Water in administration of the Act for:

- managing and enforcing lease terms and conditions
- supervision of the pastoral lease system
- defining management conditions, including the number and types of stock to be managed
- assessing and reporting on the condition of leased land
- implementation of property plans and other measures to prevent land degradation
- managing and recording submission of annual stock returns
- producing an annual report
- assisting the Valuer General in determining pastoral lease rents
- administration of the Pastoral Land Management Fund
- administration of alternative land uses for pastoral land
- providing advice to the Minister on policies and other general advice.

In discharging its responsibilities, the Board must have regard to plans or guidelines of other relevant government bodies, and to the terms of any Indigenous Land Use Agreement (ILUA) on pastoral land. The Board has established a Strategic Plan which guides its direction and priorities to meet its legislative responsibilities, and community and industry expectations (Pastoral Board of SA, 2023). The plan outlines the Board's vision, goals and strategic outcomes and was developed through consultation with key stakeholders. The work of the Board is supported by the Pastoral Land Management Unit (Pastoral Unit) based in the Department for Environment and Water. The Strategic Plan provides guidance for the Pastoral Unit in supporting the operation of the Board.

One of the Board's primary responsibilities is to oversee the lease agreements, which outline sustainable land use practices and set conditions for grazing activities on state-owned pastoral lands. This is achieved through regular inspections and assessments carried out by the Pastoral Unit. The Act requires that the Board must conduct land condition assessments at least once every 14 years for each pastoral lease.

The Board ensures that leaseholders adhere to environmental standards, helping to prevent overuse and degradation of land. The Board also collaborates with stakeholders, including pastoralists, environmental agencies, and indigenous groups to foster a cooperative approach to land management. The Board works closely with other regulators to achieve aligned management for a range of outcomes, including complementary legislative regimes for new industries (Pastoral Board of SA, 2024).

In addition to its regulatory functions, the Board serves an advisory role, providing resources and support to pastoralists to promote conservation practices that align with both economic productivity and environmental sustainability. This includes facilitating relevant research, advocating for land management innovation, and promoting best practices that enhance landscape resilience in the face of climate variability and other pressures. By focusing on sustainable practices, the Board aims to maintain the ecological health of South Australia's pastoral lands, ensuring their viability for future generations, and aspires to achieve the world's best managed pastoral country.

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The significant contributions of women in ethnobotanical studies enhance the diversity of wild edible plant uses

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Keywords: Rangelands; Wild food plants; Gender; Shahrood; Ecosystem services

Abstract

Food and nutrition security represents one of humanity's most significant global challenges. Rural communities in developing countries depend on edible wild plants to fulfill their nutritional needs during periods of food scarcity. The objectives of this study are: a) to review the existing information regarding the nutritional contributions of wild edible plants, and b) to assess the role of women in the utilization of wild edible plants as food in rural communities within the Shahrood region of Iran. Semi-structured interviews and participatory observations served as the data collection methods. The data were analyzed using usage report indicators. A total of 1,086 use reports were compiled from 44 interviews (20 men and 24 women), covering 67 wild edible plants and one fungus consumed by local communities. Knowledge of wild edible plants was greatest among women, comprising a total of 646 usage reports. Three species-*Allium iranicum* (Wendelbo) Wendelbo, *Mentha longifolia* L. Huds, and *Allium umbilicatum* Boiss-with reports numbered 75, 66, and 65 respectively, accounted for the highest usage reports. Our findings emphasize the significance of women's traditional knowledge in utilizing wild edible plant resources in this region.

Introduction

Wild edible plants (WEPs) are usually considered to constitute all plant resources that are neither cultivated nor domesticated (Biri et al. 2024). These plants grow in many different habitats (Wang et al. 2020; Khakurel et al. 2021) and play a vital role in ensuring food security for countless families around the world (Biri et al. 2024). Some rural communities in mountainous areas rely on these plants to meet their nutritional needs (Khakurel et al. 2021; Jalali et al., 2024) These plants and the food they produce are integral to the cultures of these societies, playing a crucial role in their lives (Jalali et al. 2024). WEPs assist the livelihoods of the local people in energy sources, construction, medicines, ecological services, aesthetics, income generation, and household utensils (Anbessa et al. 2024). They are also regarded as a means of survival for these local communities, particularly during times of drought, famine, and danger (Wang et al. 2020), Studying these plants is necessary not only to preserve ethnobotanical knowledge but also to conserve their populations genetic resources (Khakurel et al. 2021). Many ethnobotanical studies have shown differences in the knowledge and practices held by men and women (Acosta-Naranjo et al. 2021). Decades of ethnobotanical observations have shown that knowledge varies significantly according to the identity attributes of participants, such as their religion, occupation, status, income level, geographic origin, and gender (Wall et al. 2018).

Iran is an ecologically diverse country with exceptionally rich botanical diversity (Noroozi et al. 2019). Many plant species in Iran are used for human consumption, most of which fall under the broad category of WEPs (Jalali et al. 2024). The food and nutritional contribution of WEPs has not been fully investigated in Semnan Province. Therefore, the objective of this review is to explore available information about WEPs nutritional contribution and examine the role of women in the use of WEPs in Semnan Province.

Methods

Study area and ethnobotanical data collection

The study area is located in northeastern Iran in the Semnan Province, Shahrood municipality, in the Bastam rangelands (36°33′41″–36°35′37″ N and 54°40′39″–55°32′39″ E). Ethnobotanical data were compiled through semi-structured interviews during field walks guided by informants and participatory observations. During these guided field walks, the informants were asked information about the collection and utilization of WEPs. A total of 44 informants were selected from 12 villages: 3 from Tash, 4 from Negarman, 11 from Abarsij, 2 from Ali Kahi, 1 from Hosseinabad, 3 from Meyghan, 3 from Qaleh Now-e Kharaqan, 3 from Proo, 7 from Abr, 4 from Khij, 2 from Mazj, and 1 from Gilan. Among the informants were 11 males and 13 females (see Fig. 1).

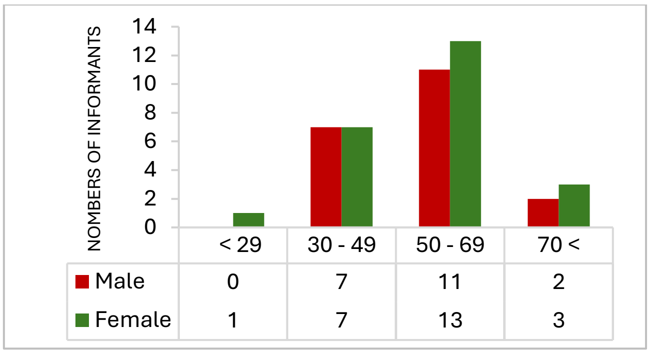

Fig 1. Age distributions of informants.

Data Analysis

The collected data were structured using reports in an Excel spreadsheet. The ethnobotanical importance indicator, including the use report, was calculated. Analyses were done using the ethnobotany R package in R.

Results

Diversity of WEPs in the study area

The 44 informants (20 men and 24 women) reported a total of 66 WEP species and one fungus from 54 genera and 24 families. Ethnobotanical information about these plants, including food categories and use reports, is listed in Fig. 3, while Fig. 4 (B) shows images of some WEPs found in the study area. A total of 1,086 use reports were documented from 44 interviews, of which 440 were related to men and 646 were related to women, as shown in Fig. 2 (A).

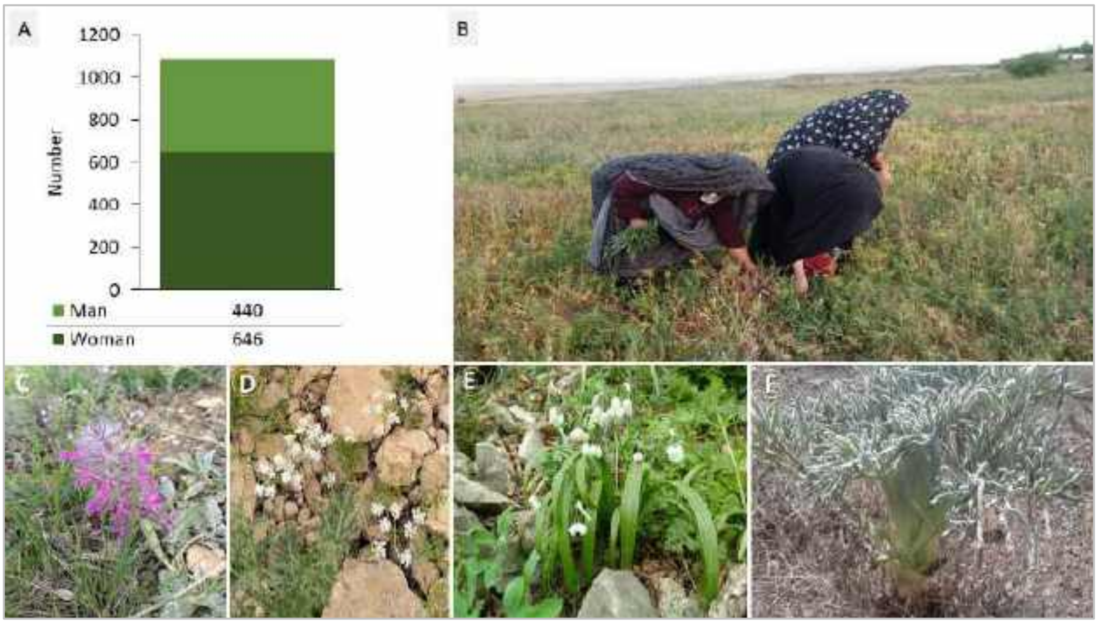

Fig 2. (A). Indicator of use report of plants (UR), (B). Collection of WEPs by rural women, and pictures of some WEPs in the study area: (C). *Stachys lavandulifolia*, (D). *Elwendia cylindrica* (Boiss. & Hausskn.) Pimenov & Kljuykov, (E). *Allium paradoxum*, (F). *Ferula foetida* (Bunge) Rege.

Dietary diversity

In this study, 1086 consumption reports based on the eating habits of people in the study area were classified into thirteen usage categories (Fig. 3). Among these categories, rice vegetable was the most cited consumption category with the most usage reports (37 species, 268 usage reports, 24.7%) (Fig. 4, Bb). By rice vegetable, we refer to WEPs that are prepared by boiling and mixed with rice dishes, followed by coco sabzi (28 species, 186 use reports, 17.1%) (Fig. 4, Ba). Coco sabzi is a traditional dish made from WEPs fried with eggs and spices. soup (39 species, 162 use reports, 15%), herb stew (32 species, 120 use reports, 11%), yogurt (16 species, 75 use reports, 7%), kashk (8 species, 71 usage reports, 6.5%) Kashk is a dish made from WEPs combined with dairy (kashk). salad (11 varieties, 47 reports of use, 4.3%), herbal tea (5 varieties, 43 reports of use, 4%), vegetable bread (10 varieties, 40 reports of use, 3.7%) (Fig. 4, Bc), pickled (9 varieties, 23 reports of use, 2.1%), ripe fresh fruit (9 types, 23 usage reports, 2.1%), snack (10 types, 22 usage reports, 2%) and finally jam (3 species, 6 reports of use, 0.5%).

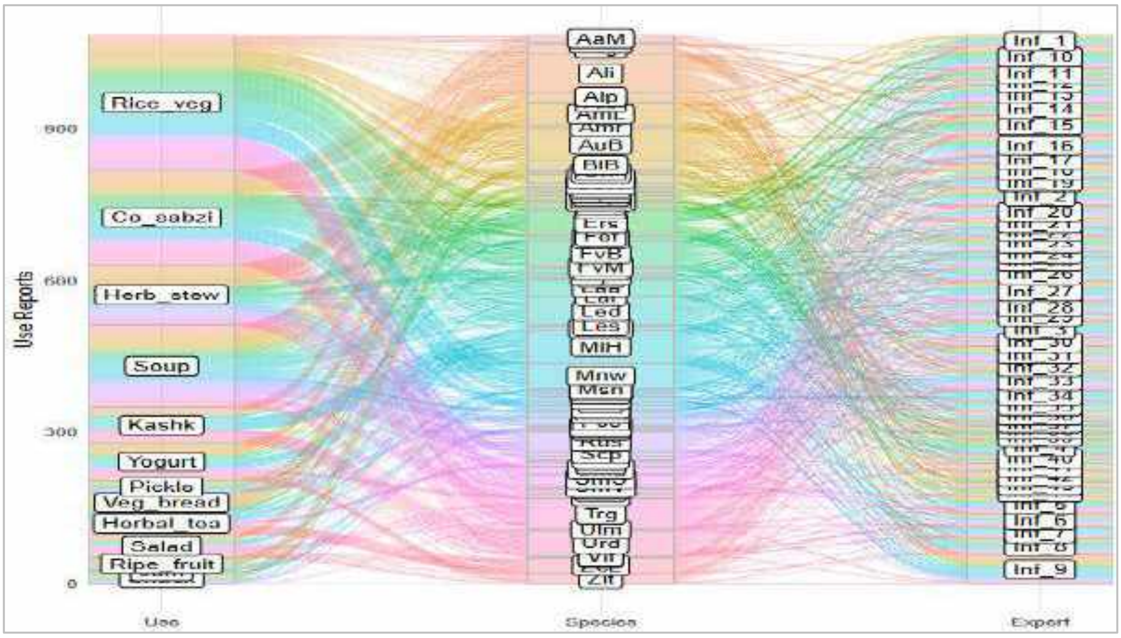

Fig 3. Usage report (UR) of 67 WEPs for 13 different food categories by 44 interviewees in 12 villages of Semnan, Iran.

Gender roles

We found differences in the total number of known WEP species and used reports between genders (Fig. 2, A, and 3). The respondents explained that women play a prominent role in using wild plants, as they are easily accessible around the village, and rangeland (Fig. 4, A). However, men showed greater knowledge of species in forested areas due to greater access to forested areas for their work.

Fig 4. A). Women collect wild edible plants for nutritional purposes, B). Food prepared from WEPs that are ready for consumption: (a). Coco sabzi, young leaves of *Allium grande Lipsky*, (b). Rice vegetable, leaves of *Eremurus* sp., and (c). Bread, different organs of *A. iranicum*.

Discussion

The importance of wild plants in feeding rural populations is widely recognized through various studies (Anbessa et al. 2024; Jalali et al. 2024). In our study region, the WEPs showed a wide range of variation, not only in the number of species but also in different categories of consumption for nutritional purposes. When compared to other studies (Luo et al., 2019). However, our research uniquely documented the use of these plants across 13 different nutritional categories, with a significant emphasis on the role of women in utilizing these plants, which has not been reported in studies conducted within Iran. The local people's WEPs collection calendar demonstrates valuable indigenous knowledge rooted in their rich culture of edible plant utilization. These species are facing growing threats such as over harversting, drought and grazing, emphasizing the urgency of implementing stronger protection measures and adopting sustainable management practices.

Notably, our study sheds light on how collaborative activities in rural settings are especially important for women. Despite the gender imbalance in studies of neighboring countries (Hussain et al., 2023), due to religious and patriarchal family structures, which prioritize males as family heads and resource holders, our study of ethnographic knowledge has shown an important role of women in this field. They actively participate in the collection and utilization of WEPs and contribute to the seasonal household economy by using WEPs as a supplemental food source. Also, women are the primary decision-makers for food preparation in study area and can get to know more plants through gathering and cooking. Gender equality is seen as a goal and a means in achieving the Sustainable Development Goals (SDGs) (Duflo 2012). Overall, our study shows that these species play important role in household diets and have great potential to contribute to food and nutritional security. However, these results show the major contribution of women in linking knowledge between the food cultural domains. The women continue to play a key role in maintaining gastronomic cultural heritage in present days.

Acknowledgements

The authors thank the people of Bastam for their cooperation in documenting their information, for their hospitality and generosity and Tarbiat Modares University for the support.

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Adaptation strategies of pastoralists to degradation of Banni grassland in India through livelihood diversification

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Key words: Arid region; *Banni* buffalo; income security; livelihood security; *Prosopis juliflora*.

Abstract

Pastoralism is the predominant livelihood in *Banni* grasslands. However, combination of factors (livestock population pressure, overgrazing, severe droughts, rapid invasion of *P. juliflora*) has led to severe degradation of the grasslands. This has increased the risk of pastoralism as a profitable and sustainable livelihood. In this context, this socio-economic study investigated the livelihood diversification process adopted by pastoralists in *Banni* grasslands. Primary data were collected from 280 households from 13 villages using stratified random sampling technique. Out of these, detailed livelihood diversification analysis of 50 households (case studies) was undertaken. Results found that pastoralists diversified into combination of eight non-pastoralism based livelihood options (charcoal production, labour, services, leather work, embroidery work, honey & gum collection, tourism and trade) for livelihood security. Based on the combination of pastoralism and other income generating activities, there were eight different household typologies in the region viz., (i) Buffalo rearing + 7 activities (66%); (ii) Buffalo & Goat rearing + 1 activity (4%); (iii) Buffalo + Cow rearing + 3 activities (4%); (iv) Cow rearing + 2 activities (4%); (v) Camel rearing + No additional activity (2%); (vi) Sheep & Goat rearing + 1 activity (4%); (vii) Goat rearing + 5 activities (12%); and (viii) 5 activities without any livestock (6%).

The adaptation strategies of pastoralists to degradation of *Banni* were reduced dependency on pastoralism (reduction in herd size of buffaloes, moving out of buffalo rearing, goat rearing in small herds) and diversification into non-pastoralism based livelihood options. Buffalo rearing households earned highest annual income. Goat rearing and livestock-less households were the poorest. It indicated that moving out of pastoralism (even after income diversification efforts) was associated with low incomes. Therefore, increasing the carrying capacity of the grasslands through scientific management and development of supply and value chain are the most sustainable options for risk reduction and enhancing income of households.

Introduction

Banni grassland in Kachchh district of Gujarat in India is a socio-culturally unique and ecologically significant ecosystem. Agriculture is not practiced in the grassland and pastoralism is the main livelihood option for more than five centuries (BCPMB 2010, RAMBLE 2024, *B*anni 2024). However, significant changes in the recent past such as the declaration of *Banni* grasslands as Protected Forest, rapid invasion of *P. juliflora*, salinity ingress, successive and severe droughts, increase in livestock population and overgrazing have led to its' severe degradation (Safriel and Vijay Kumar 2021, Manjunatha et al. 2022, Singh et al. 2023). *Banni* grassland once covered an area of 3800 sq. km (Bhandari 1990) but decreased to 2618 sq. km (Rawat and Adhikari 2015).

Banni grassland is a heterogeneous ecosystem, which has wetland, grassland, and dryland habitats. Forest department introduced *P. juliflora* (a shrub native to Mexico and South America) in 1960's to stop the advancement of Rann. However, the invasion of *P. juliflora* is slowly converting it to shrubland (Sharma et al. 2024). Further, there is a shift in livestock composition in favour of buffaloes over cows. The livestock population in *Banni* grasslands during 2021-22 is estimated to be 1,01,235 heads with the composition of buffalo, cattle, sheep and goat at 77, 13, 5 and 5% of the population respectively (Projected from Manjunatha et al. 2019a). These ecological and policy changes along with increased access to organized dairy industry have contributed to the gradual shift from migratory pastoralism to semi-migratory and sedentary animal husbandry. In this context, the objective of this study was to understand the adaptation strategies of the pastoralists to mitigate the impact of degradation of *Banni* grassland on their livelihood security.

Methods

Research design: An ex-post facto survey research design and case study method were used.

Locale of the study, sample and sampling procedure: *Banni* grassland located in Bhuj taluka (subdivision) in Kachchh district of Gujarat State in India was purposively selected as the study area. Thirteen villages were selected for the study using stratified sampling technique to represent different parts of *Banni*.

Data collection tools and analysis: A structured interview schedule was developed for the study. The primary data were collected between January 2015 and June 2017 by personally interviewing 280 households selected randomly from these 13 villages. Out of these, detailed livelihood diversification analysis of 50 households was undertaken using case study method. The primary data collected from pastoralist households were supplemented and validated with other research techniques such as participant observation, Focussed Group Discussions (FGDs) and synthesis of secondary data. Extensive field visits were made to *Banni* grasslands and pastoralists' livestock yards at their home and during migration. Charcoal production units were visited. Embroidery and leather work units were visited at the selected respondents' houses and exhibition stalls during *Rann Utsav* (A tourism event organized by the Government of Gujarat every year at Rann of Kachchh). FGDs were held with key pastoralists in each village and other stakeholders such as representatives of the *Banni* region (Banni Breeders Association) and researchers and organizations working on *Banni* grasslands. Annual incomes were calculated for the agricultural year 2016-17 based on the prices prevailing in the *Banni* region in April 2017 (Manjunatha et al. 2019b). The guidelines on methods for estimating livestock production and productivity developed FAO were followed (FAO 2018).

Results

Upto 94 percent households in Banni grassland were associated with pastoralism/ animal husbandry. The adaptation strategies adopted by pastoralists to reduce the impact of degradation of Banni grasslands were reduction in herd size of buffaloes, moving out of buffalo rearing, goat rearing in small herds and diversification into non-pastoralism based livelihood options. The pastoralists diversified into combination of eight non-pastoralism based livelihood enterprises (charcoal production, labour, services, leather work, embroidery work, honey and gum collection, tourism and trade) for livelihood security. Based on the combination of pastoralism and other income generating activities, there were eight different household typologies in the region viz., (i) Buffalo rearing + 7 activities (66%); (ii) Buffalo & Goat rearing + 1 activity (4%); (iii) Buffalo + Cow rearing + 3 activities (4%); (iv) Cow rearing + 2 activities (4%); (v) Camel rearing + No additional activity (2%); (vi) Sheep & Goat rearing + 1 activity (4%); (vii) Goat rearing + 5 activities (12%); and (viii) 5 activities without any livestock (6%).

Rearing of Banni buffaloes along with other livelihood options was the dominant typology (Figure 1). Households rearing cows and camels exclusively were very few in number (6%) but their incomes were equivalent to buffalo-rearing households. Buffalo/cow/camel rearing households represented traditional pastoralist households and they earned >70% of their income from pastoralism/animal husbandry (Figure 2). Migratory sheep rearing involving large herds (with few goats in the herd) is a traditional occupation practiced by poor pastoralists. Backyard goat rearing in small herds is a relatively recent extra income generating activity practiced by poor households. It is an indication of shifting away from traditional pastoralism and lack of ownership of buffaloes, cows, camel and sheep. Livestock-less households represented extreme end of continuum who have completely shifted away from pastoralism. Goat rearing and livestock-less households constituted 18% households and earned their major income from non-pastoralism based activities (charcoal production, unorganized services and labour). Goat rearing and livestock-less households were the poorest indicating that moving out of pastoralism (even after income diversification efforts) was associated with low incomes. Charcoal production is mostly based on cutting of *P. juliflora.*

Households engaged in buffalo-based pastoralism earned highest annual income and had choice to engage in high-income generating livelihood options such as tourism and trade. Livestock-less and goat-rearing households earned lowest annual income and were dependent on low-income generating activities such as charcoal production, unorganized services, labour and honey and gum collection for want of better employment opportunities.

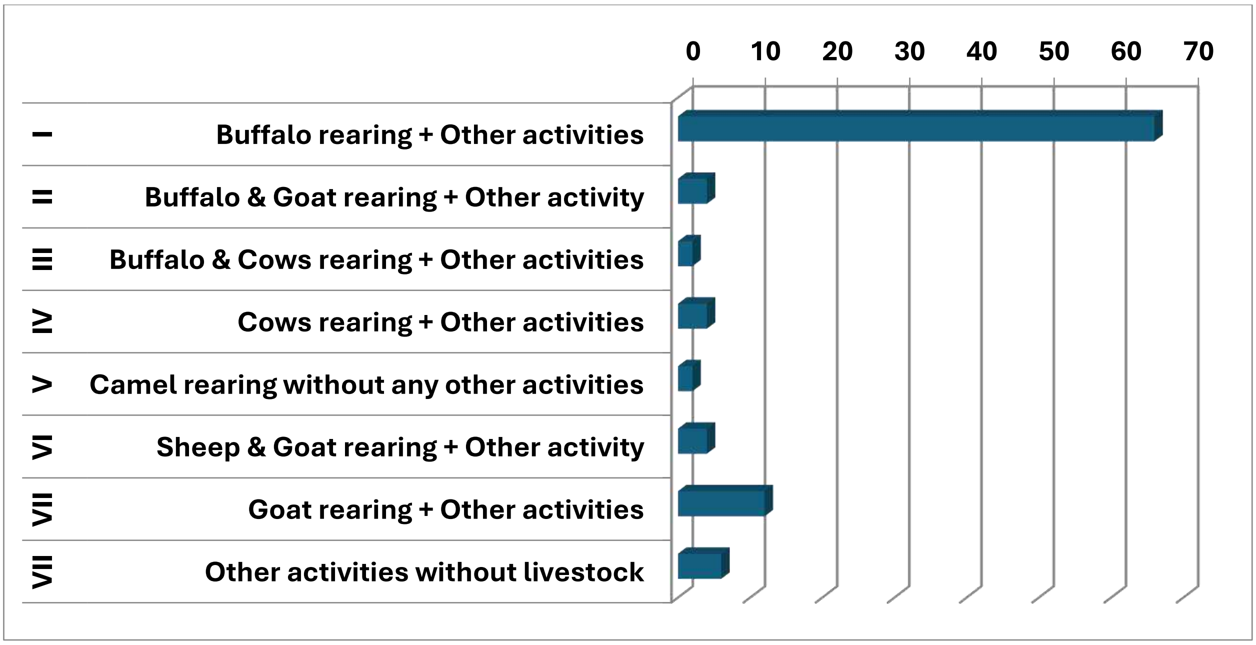

Figure 1: Household typologies and livelihood diversification adopted by pastoralists in Banni grasslands

Note: "Activities" indicate "income generating activities". The terms "income generating activities" and "livelihood options" are used interchangeably in the article.

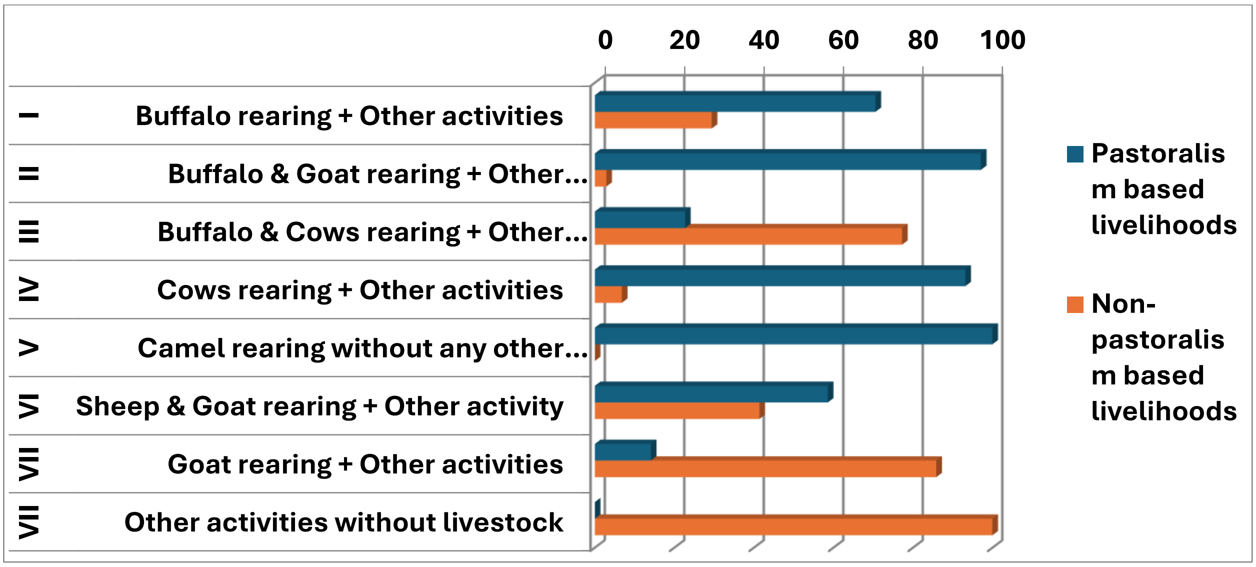

Figure 2: Share of pastoralism and non-pastoralism based livelihood options in average annual net income (%) for different household typologies in Banni grasslands

Discussion

Pastoralism/ animal husbandry as a remunerative and sustainable enterprise in *Banni* grassland is under severe pressure due to its degradation. The reduced carrying capacity has increased the cost of livestock rearing as the fodder shortage is being compensated by purchase of feed and fodder resources from market. Therefore, 98% pastoralist households have integrated non-pastoralism based livelihood options for income and livelihood security as an adaptation strategy. At the same time, the remunerative employment opportunities in secondary and tertiary sector are very limited in the region. Therefore, households shifting away from pastoralism are forced to opt for livelihood options which are less remunerative than the pastoralism/ animal husbandry itself.

Pastoralism in India is invisible in government policies and programmes since there is no authentic data available about the numbers, livestock and economic contribution of pastoralism. The 21st Livestock Census 2024, for the first time plans to include a separate enumeration of pastoral livestock which marks a significant step towards designing targeted interventions and public investment/schemes (Bhatti 2024). Grasslands are frequently ignored in sustainable development objectives. Adequate knowledge of how grassland degradation affects ecosystem services is essential for sustainable management and grassland ecological restoration (Dey et al. 2024). Ecological restoration of the grassland requires scientific management involving participation and engagement of the pastoral community and community based organizations at all levels of decision making. From 2019 to 2023, *P. juliflora* was uprooted with JCB earthmovers restoring 3000 hectares, thereby increasing vegetation species richness by 12% and tripling biomass productivity. Innovative income generation efforts such as sale of carbon credits generated from biochar production from *P. juliflora* were undertaken for sustainable management of the grasslands and economic stability of the pastoral communities (Pokar 2024).

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Enabling public access to South Australia's pastoral lands

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Key words: rangelands; public access; pastoral; South Australia

Abstract

South Australia's pastoral lands are a rich resource of unique landscapes and Aboriginal and European heritage, drawing visitors from across the world to experience these amazing locations alongside commercial pastoral businesses.

The Pastoral Land Management and Conservation Act 1989 (the Act) enables access to pastoral lands:

- the public can access any pastoral lands with consent from the pastoral leaseholder,
- Aboriginal people have the right to access pastoral land to carry out traditional practices, in accordance with non-exclusive Native Title, which exists over most pastoral leases,
- Public Access Routes enable public access to significant sites of high value without requiring leaseholder consent.

The Pastoral Board has established a network of 23 Public Access Routes (PARs) totalling more than 700km of tracks to National Parks or historic infrastructure which can only be accessed by passing through pastoral land. These tracks are largely unmonitored and require a 4WD for clearance and access. PARs were initially established in the late 1990s and early 2000s to encourage visitation into the pastoral lands and boost tourism, as well as to develop a remote road network to help connect pastoral lease holders with the broader community.

The SA Government is reviewing the long-term sustainable management of the PAR network to better enable public access to these valuable lands, while mitigating potential risks. This will include reviewing where PARs should be, trends in use, options for maintenance funding, and options for undertaking management of PARs including the role of lessees, government agencies and users. Stakeholders and the broader community will be closely involved during the review.

Introduction

The Pastoral Unit, which sits within the Department for Environment and Water (DEW), supports the Pastoral Board and the Minister for Climate, Environment and Water for the administration of the Act. The Pastoral Unit provides the following support:

- land condition assessments on pastoral land,
- lease condition matters including investigating compliance issues,
- lease tenure dealings (e.g. consents for transfers, mortgages, sub-leasing),
- maintaining operation of the Pastoral Board including communication to or from the board, and

- assistance and advice regarding access to pastoral leases (including public access routes and rights of access for Aboriginal persons).

The South Australian pastoral lands provide a valuable contribution to the economic prosperity of the state. There are 322 leases making up 220 stations over an area of 40 million hectares. This is approximately 40% of South Australia's landmass. Enabling access to these areas provides an opportunity for the public to experience and appreciate complex ecosystems, absorb Aboriginal and European heritage and visit historical infrastructure that helps shape the story of South Australia's transformation throughout time.

Striking the right balance between how, when and where to enable public access to the rangelands access is important. Getting this balance right helps maintain the health of the environment, ensure pastoral activities can be undertaken with minimal disturbance, while also promoting tourism opportunities to unique locations of both historical and conservation value.

There are legislative requirements in place to assist in ensuring access to the rangelands is safe for visitors, respectful for traditional owners, considerate of pastoral lessees and sustainable for the environment. Outside of legislation, the government needs to consider what the desired outcomes are for enabling access to the rangelands. This will help to proactively address possible risks associated with remoteness, isolation, and fragility of the landscape.

Discussion

Access to the rangelands can be achieved through several mechanisms. Each is in place to provide different outcomes for different people and visitors.

Traditional owner access

Aboriginal and Torres Strait Islander people have a deep connection with the land, which is central to their spiritual identity. This connection remains despite the many Aboriginal people who no longer live on their land. Aboriginal and Torres Strait Islander people describe the land as sustaining and comforting, fundamental to their health, their relationships and their culture and identity.

For Aboriginal and Torres Strait Islander people, their traditional Country and what it represents in terms of their history, survival, resilience and cultural and spiritual identity gives them much to take pride in. In the dominant Australian culture, land is thought of as a commodity to be used, enjoyed and owned, or as a place to build a home or grow food or develop a park. Aboriginal and Torres Strait Islander people consider the land differently. This is an important perspective for decision makers to understand to ensure all stakeholder views and beliefs are considered when access to the rangelands is being discussed.

There can be sensitivities around different land use property rights and cultural heritage that have the potential to cause conflicts between land holders and traditional owners if not consulted effectively. One mechanism that is also available to provide traditional owners assurance that they can access culturally significant land and undertake traditional practices is under Section 47(1) of the Act. This section outlines that Aboriginal people have the right to access pastoral land to carry out traditional practices, in accordance with non-exclusive Native Title (Native Title (South Australia) Act 1994), which exists over most pastoral leases. To help defuse possible privacy tensions with pastoralist, the Act prevents camping within a 1km radius of a dwelling or within 500m of a dam or water point.

General visitation

Should a member of the public wish to access part of the rangelands that forms part of a pastoral lease, they must gain consent from the lessee prior to accessing the land. Section 48(3) of the Act set outs the requirements for a person to seek consent of the lessee or the Minister prior to travelling across a pastoral lease, and outlines the penalty for non-compliance with this section of the Act.

This legislative compliance mechanism is an important inclusion to ensure respect of pastoral lessees and their operations are considered when accessing the rangelands, while also providing an opportunity for the public to visit and explore remote areas of the state.

Public access routes (PARs)

The Pastoral Board can gazette PARs under the Act, which provide delineated routes where the public can traverse leased land without needing permission of the lessee. The routes lead to sites of interest, like historical landmarks, infrastructure and National Parks. Before gazetting or revoking a PAR the Pastoral Board must consult with all pastoral lessees affected by the proposal, the relevant regional landscape board and any other interested organisations. No proposals for new PARs have been received since 2011.

The Pastoral Board has established a network of 23 Public Access Routes (PARs) totalling more than 700km of tracks to National Parks or historic infrastructure which can only be accessed by passing through pastoral land. These tracks are largely unmonitored and require a 4WD for clearance and access.

A lessee's rights cease over a PAR. The care, control and management of the routes are vested in the Minister of the Act. However, the Minister is not obliged to maintain the routes, recognising these tracks are in remote areas and there may be limitations in funding available for ongoing maintenance and management of the tracks. There is often a reliance on lessees, PAR users and Park Rangers to provide advice on track condition. PAR users are responsible for adhering to weather warnings and track closures to reduce risks while travelling along PARs. DEW installs signs to identify PARs and notable hazards on the track, and remind users of their responsibilities while on the PAR.

Upon the request of a lessee, tracks can be temporarily closed due to public safety reasons, facilitating stock management or conducting rehabilitation work on adjacent land. Closures are listed on publicly available websites, and the Pastoral Board can require a lessee to erect signs to highlight the temporary closure.

The SA Government is reviewing the long-term sustainable management of the PAR network to better enable public access to these valuable lands, while maintaining the safety of users, and at limited impost to the lessee. This will include reviewing where PARs should be, trends in use, options for maintenance funding, risk management, and options for undertaking management of PARs including the role of lessees, government agencies and users. Stakeholders and the broader community will be closely involved during the review.

Outback roads network

The Department of Infrastructure and Transport (DIT) manage and maintain over 10,000kms of unsealed, outback roads. These roads act as a gateway to the more remote areas of the rangelands, and are an important asset for pastoralism, tourism and other industries like mining and freight. These roads are graded regularly to ensure the network stays in safe condition for all road users. DIT are responsible for maintaining, repairing and upgrading outback unsealed roads to improve road surfaces. Capital works projects can be funded through a combination of South Australian government initiatives and federal funding.

Reasons for visiting the rangelands

Traditional owners may visit the rangelands for cultural reasons, while members of the public travel and visit for tourism purposes, or recreation and leisure activities like four-wheel driving. Some of South Australia's most impressive natural wonders can be found in the rangelands and are often cited as a reason for visiting. For example, Kati Thanda-Lake Eyre, Australia's largest salt lake, is located 770km north of Adelaide. This spectacle provides visitors with an opportunity to set up camp and appreciate the cultural significance this site has for the traditional owners, the Arabana people. Although usually dry, heavy rain events can see the lake come to life, with waterbirds and other wildlife descending into the area.

Rangeland access allows visitors to explore National and Desert Parks, some of which are home to World Heritage Nominated fossil sites, and world-renowned areas like the Flinders Ranges. Maintaining access to these locations encourages tourism, which can benefit state prosperity and growth, while also providing an opportunity to educate visitors on Aboriginal heritage and culture, and the important environmental value that these assets hold.

In more recent times, it has become increasingly evident that, as well as pastoralism, access to the rangelands is important for mining, commerce, and other business ventures, such as the emerging hydrogen and renewable energy industry. Most travel for such ventures is along outback roads, managed by DIT. In addition, some PARs are used as transit routes, which is beyond their scope of use and capacity. They vary in their condition and standard. As part of the current PAR review project, it will be important to explore how these routes can be made safer and more accessible if going to be frequently used for transit and thoroughfare purposes, while also maintaining environmental values. Consideration of an expansion of DITs outback road network could create transport efficiencies, improve economic growth while also increasing public safety.

Some land holders facilitate tourism operations and accommodation for visitors on their leased properties within the rangelands.

Limitations and risks

The South Australian rangelands are home to unique and beautiful landscapes. Care must be taken when travelling in isolated areas like these, as the remoteness and weather conditions can become hazardous quickly. DEW mitigates risks like these by closing the access to Desert Parks between December and March, to reduce the risk of travellers becoming stranded during the hotter months. The PARs that provide access to these sites of interest are also closed to help mitigate the risk. Closures to these areas can be disappointing for keen travellers. Clear communication for the reason for closures is an important part of rangeland access and management.

Given the expansiveness of the rangelands, and the multiple legislative frameworks that govern certain areas, it is sometimes difficult to ascertain the risk profile of an area. If an incident was to occur to a member the public visiting the rangelands, it can be case dependent for who has a duty of care and what personal responsibility the visitor has. Exploration into the minimum standard of the Minister's duty of care within the rangelands will be an important part of the PAR review to ensure PARs are maintained to an acceptable level, as well as ensuring sites of interests are actively monitored by the correct entity.

The remoteness of far north South Australia and lack of resources to monitor the movement of people through the rangelands is a risk that requires a multifaceted approach. Active communication between the Pastoral Unit, National Parks and Wildlife Service, DIT and lessees is a useful tool to gauge road condition and weather events. This can help determine if sites of interests or PARs must be closed, and it also assists DIT in developing their Outback Unsealed Roads Grading Program.

Conclusion

Enabling sustainable access to the rangelands promotes the value of their societal contribution, and provides benefits to a range of industries, including pastoralism and agriculture, tourism and the environment. Lessees, visitors and the government need to be aware of the connection traditional owners have with the land and work collaboratively to ensure positive outcomes for the rangelands are realised. It is important for the future health and prosperity of the rangelands that stakeholders engage and work together to identify suitable accessibility solutions, especially as land use and demographic changes emerge in these areas.

Improved accessibility could be achieved through increased funding for maintenance and management of PARs, the identification of a broader outback roads network to be maintained by DIT, and through a collaborative approach with traditional owners, lessees and DEW to identify important cultural heritage sites for tourism promotion. This promotion could leverage funding to improve the condition and accessibility of the sites, including signs for safety, a maintenance program for road condition, and any other infrastructure to protect to integrity of the sites of interest, like fencing.

Risks and responsibility associated with rangeland access must be determined prior to any change in policy or decision making that increases or decreases accessibility. This will help clearly identify the rights and responsibilities of stakeholders who are accessing, visiting or using the rangelands. In doing so, proactive risk mitigation strategies can be deployed, allowing people to safely and sustainably enjoy the landscape.

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The 'Drought Antidote' : An archaeology of artesian water management in NSW

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Key words: Great Artesian Basin; Pastoralism; Drought Proofing; Water Security; Archaeology

Abstract

The Great Artesian Basin covers a vast area of inland Australia, enabling dependable water supply across the rangelands. In New South Wales artesian bores were introduced to benefit the pastoral industry, established by the Department of Public Works under the *Artesian Wells Act, 1897* and the *Water and Drainage Act, 1902*, hereafter referred to as the Artesian Scheme. However, the focus of research has been on current environmental concerns and the rehabilitation of artesian bores, with limited attention to historical water management strategies associated with the scheme. Remains of environmental modification from the Artesian Scheme are extensive throughout pastoral landscapes, although this archaeological record is delicate and disappearing with inadequate research conducted. This paper explores the origins of the scheme and considers localised variation, implementation, and operation through investigation of a case study: Sherwood Bore, near Rowena in north-west NSW. Drawing upon historical documentation, oral history and archaeological interpretation of remnant infrastructure, this research revealed the Artesian Scheme represented socio-economic development by supporting pastoral settlement opportunities and pastoral growth.

Introduction

A large portion of New South Wales (NSW) is arid to semi-arid rangelands which experience low, irregular rainfall. Limited permanent water sources restricted pastoral development until the initial drilling of artesian water in 1878 (Powell *et al.*, 2015) and subsequent confirmation of the large extent of the Great Artesian Basin (GAB) in 1892 (DPW, 1893). This vast groundwater basin provided a dependable water supply and enabled large-scale expansion of pastoralism (Murray, 2018). The GAB underlies 22% of Australia, spanning 25% of NSW (DPIE, 2023), and large areas of Queensland, South Australia, and the Northern Territory (Figure 1).

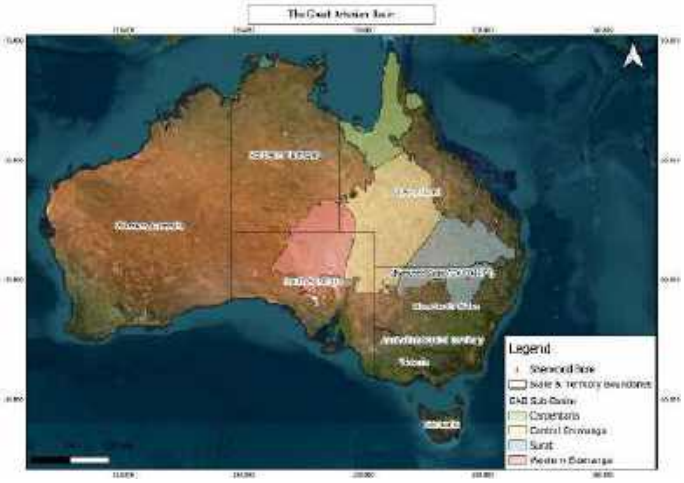

Figure 1: GAB Boundary (adapted from SEED layer "Water Sharing Plan – Groundwater Sources").

In the late nineteenth century economic, social, political, and environmental factors combined to encourage the initiation of one of the most ambitious modern schemes of deliberate environmental modification – the GAB Bore Scheme. From 1878, 8,000 bores were drilled across NSW as a means of providing permanent reliable water to landholders (DPIE, 2023), encouraging an expansion of European settlement into previously sparsely occupied areas, and significant growth of pastoral industries away from watercourses. In NSW, bores were sunk under the *Artesian Wells Act, 1897* and *Water and Drainage Act, 1902* for stock (sheep and cattle) and domestic applications, watering over 1,100,000ha (DPW, 1910, p. 9); hereafter referred to as the Artesian Scheme. These bores were governed by Bore Water Trusts, through elected Trustees, to oversee the maintenance through employing maintenance men, and operation of artesian water management (DPW, 1906). Associated water management infrastructure includes: *distribution tanks, divisors* (used to adjust the direction of flow), *bore-drains* (Figure 2a), and *water storage dams*. The Artesian Scheme represents unique rural engineering, governance, and employment in the context of a state development policy through expansion of the pastoral industry (DWE, 2009).


a)


b)

Figure 2: Sherwood Bore-drain (a) and Sherwood Bore (b), courtesy of D. Phelps, 2006.

The Artesian Scheme was successful in many of its aims, encouraging expanded pastoral settlement but also seeding its own demise. The early configuration of unregulated free-flowing bores led to significant problems with GAB water supply and the failure of much of the system. Since 1990 the *Cap and Pipe the Bores Program* (*CPBP*) has capped many bores and introduced reticulated systems of pipes, tanks, and troughs to reduce water loss through evaporation (DPIE, 2023). Consequently, in many areas the Artesian Scheme effectively finished more than 30 years ago, with prolonged deterioration, and operation is now almost out of living memory. Despite the significant impact on the development of European settlement in inland Australia and the pastoral industry (Godwin & L'Oste-Brown, 2012), the history at either a macro or micro scale is largely undocumented, with archaeological remains of the infrastructure vanishing or deteriorating.

This paper explores the history and archaeology of the Artesian Scheme in NSW. It aims to understand the archaeology of the scheme as an example of settler-induced anthropogenic change/environmental modification as a development strategy, as well as the industrial archaeology of the scheme and its operation. It will also examine regional implementation of the scheme, as well as micro-scale of a single bore's establishment, operation, and impacts upon adjacent properties, including the processes of maintenance of the bore and distribution system and its decline and modification over time. These aims are achieved through a case study focusing on Sherwood Bore (ID No. GW004471) (Figure 2b) which operated from 1907-2007, located near Rowena, NSW, on the property Glen Eden. This property has been owned and operated by the author's family since c.1902. Research explores historical documentation and generational oral history, combined with the archaeological record.

Methods

Investigation of the GAB was undertaken across multiple scales (state, regional, and local), which required an innovative combination of existing methodological approaches. Recognised methods were derived from previous studies and general literature to suitably combine interdisciplinary approaches to address the unique research topic. A multi-scalar approach was required to comprehensively understand such a large-scale management scheme, as there is interplay between levels where one informs the other, and which has not previously been undertaken for the historical period. Selected methods included the interpretation of historical sources, regional investigation, oral history, archaeological features, and artefact assemblages. The progression of the Artesian Scheme through macro and micro scales was achieved through the development of phases from the available evidence.

Results

Deliberation regarding the operation and implementation of such a large-scale water management scheme commenced in 1892 after a town bore was successfully sunk in Coonamble, which was previously considered outside the strata containing artesian water (DPW, 1893, p. 9). This success significantly increased the area of land with potential access to the GAB, prompting political discussion for future possibilities to supply permanent, reliable, water to regions periodically without water for the benefit of the pastoral industry. A subsequent design phase was characterised by experimentation and implementation of improved infrastructure and distribution approaches. By 1906 rapid implementation was underway to improve water security across an enormous pastoral landscape, "…which was formerly periodically denuded of stock by frequently-reoccurring droughts" (DPW, 1906, p. 5). In 1910, 48 Trust Bores were operational, supplying 1,102,695ha, with an additional 546,779ha proposed through future works (DPW, 1910, p. 9). Investigation of historical population change indicated no significant changes, suggesting the Artesian Scheme was intended to support economic growth, specifically for small pastoral enterprises to increase wool productivity. This also explains a concentration of Trusts within the semi-arid North-West, which had better potential to reach economic goals through reliable water supply, in comparison to the arid Western Division. The rapid geographic expansion of the large-scale Artesian Scheme was not reflected locally, and requires multi-scalar insight.

Localised progression represents the site-specific implementation of the Artesian Scheme through processes of construction and continuous maintenance to ensure dependable water supply. Archaeological survey introduced variation in management strategies and infrastructure, producing difficulties in comprehensively understanding the nature of this cultural landscape across numerous sites. Oral history revealed difficulties in the sinking of Sherwood Bore, and the effect individual agency from the maintenance men had on the archaeological record.

Discussion and Conclusion

Environmental archaeological studies of irrigation internationally have primarily focused on ancient management strategies (Shaw & Sutcliffe, 2001 & Konstantinov *et al.*, 2023), and advise a shift towards more sustainable modern practices. Guttman-Bond (2010) recommended sustainable ancient methods could be reintroduced, stating seven countries were successful, with further research underway. Reintroduction of knowledge was also proposed to combat aridification caused by climate change, noting methods may only be suitable across regions with similar climate conditions (Kaptijn, 2017). *Archaeology for Sustainable Agriculture* (2020, p. 420) suggested archaeology's strongest contributions were "…its ability to demonstrate that agricultural sustainability is historically contingent, and… its attention to outcomes, or completed cycles of agricultural development." This stressed the complexity and urgency for agriculture to improve sustainability, which would require on-going collaboration amongst diverse stakeholder groups (Fisher, 2020). This research highlights the ability for archaeology to enhance decision making, especially within water management and agricultural settings.

Large scale agriculture was also practiced in the Indus Valley in c.2600 BCE where an extensive network of canals was used for irrigation (Angelakis *et al.*, 2020). The use of bore-drain networks bares similarities in environmental modification to the Indus Valley, to supply water to extensive pastoralism, suggesting that the decision for distribution methods may have been influenced by previous approaches. However, unlike, ancient examples the Artesian Scheme was relatively short lived, spanning over 120 years, with initial implementation lasting only 19 years after discovery of water at Coonamble. The Artesian Scheme was also industrial, requiring less labour than the Indus Valley example, but rapidly causing dramatic change across a large landscape. Research into ancient water management indicates the longevity of environmental modification to improve water security for a variety of purposes. Research into management of the GAB could benefit understanding of ancient practices and can inform future approaches.

The use of artesian water was considered pivotal to pastoralism across arid and semi-arid regions in Queensland, NSW, and South Australia (Brake, 2020). Murray (2018) called for an archaeology of extensive pastoralism within the GAB, but did not outline a methodical approach, which this research has attempted to provide. Future directions could pursue variability through purposes of bores, landholder response, environmental variation, strategic differences in the Western Division, or a more detailed regional study through numerous case studies, especially of Florida Bore.

The Artesian Scheme was successful initially, substantially improving water security, especially during periodical droughts, but effectiveness varied, followed by early gradual decline. While historical water management was progressively phased out the Artesian Scheme endures, increasing the significance of understanding historical strategies to inform future decisions. Historical documents demonstrated the introduction of artesian water supply was intended to support pastoralism, enabling smaller enterprises to become viable – implemented following extensive pastoral sub-division. Interpretation of changing pastoral production in NSW revealed comparable stock populations, but improved resilience and industry response from periodical droughts, and supported increased productivity – this was reflected locally at Sherwood Bore through marginally improved stocking capabilities. This further suggests water security underpins production, while fodder insecurity and market dictate stocking responses. Review of regional population growth indicated no significant increase current to the introduction of artesian water, suggesting the Artesian Scheme was not intended to maximise population growth. Instead, the Artesian Scheme intended to maximise property number, settlement opportunities and economic growth through significantly improved water access and security enhancing wool productivity.

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Fate of yak herding in the highlands of Mustang, Nepal: A case of Namu Bhrapse Rangeland

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Key words: Livelihood; vegetation; tourism; climate change; employment.

Abstract

Rangelands are essential as they offer a range of ecosystem services that supports the livelihood of the people residing in the Himalayas. Yak herding is considered as one of the vital components of the rangeland ecosystem of Nepal. Yak farming tradition together with yak population are now facing an intensified decline mainly due to various reasons. Lack of palatable species, drying of water sources, lack of infrastructures and conflicts between local bodies and the government are some of the issues. While the earlier herders are getting old, it is difficult to entice the younger generations who are attracted towards lucrative business like agro tourism and cordyceps business that provides a great economic returns. As young people lack their interest in herding yaks, people from the neighbouring districts are paid to herd the yaks. Furthermore, climate change has led to worsen the scenario, with altered grazing pattern, lack of snowfall and rainfall and increasing temperature has depleted the vegetation quality and quantity in the rangelands. Unless there is an urgent intervention for sustainable management of rangelands from the government and local level, this culturally, economically, and ecologically important practice may disappear soon, leading to a serious repercussion on the communities and the environment they rely on. This study explains the scenario of rangeland of Mustang district namely Namu Bhrapsa Kharka which is a summer pastures for yak herding.

Introduction

Rangelands are a crucial part of Nepal's Himalayan ecosystem, covering 60% of the landscape and 22.6% of the country's total land area, including the mountains, hills, and Terai (Yi & Sharma, 2009; ICIMOD, 2012). These areas provide essential ecosystem services that support local livelihoods and environmental sustainability (ICIMOD, 2012). Mustang, located in the northern part of Nepal, is a dry region where yak herding, medicinal plant collection, and tourism are key sources of income for rural communities (Dong et al., 2009). Namu Bhrapse rangelands, at 3,700-3,800 meters above sea level, are a vital part of Mustang’s landscape, characterized by steep slopes and minimal precipitation (under 200 mm annually, mostly snow) (Pokharel, 2005). Agriculture and animal husbandry are the main economic activities, but productivity is limited by low rainfall, inadequate irrigation, and a short growing season (Chetri & Gurung, 2004). Despite their importance, Mustang's rangelands face anthropogenic pressures such as overgrazing, overexploitation of medicinal plants, and climate change impacts (Miller, 1996). Additionally, conflicts between human use and wildlife further stress the resources (Subedi et al., 2020). Effective rangeland management is crucial to improving livelihoods and income opportunities for herders. This study was conducted to examine the fates of the yak herding in the rangeland of Mustang to explore the socio-political aspects of sustainable rangeland resource management, contributing to the sustainability in Nepal's mountainous regions.

Methods

The study was conducted with five independent key informant interviews (KII) and two focus group discussions (FGDs) where yak herders, owners, *"Mukhiya"* (head of the village), head farmer and the technicians from the Municipality were interviewed to gather data on status of Namu Bhrapse rangeland in Gharapjhong Rural Municipality. Semi-structured questionnaires were used for the KII and FGD. Each FGDs consists of 10 yak herders and all were male. Additional data were collected through structured interviews, desk reviews, annual reports, workshop proceedings, and consultation at concerned municipalities and rangeland experts. Observations of Namu Bharapse rangeland included vegetation, yak herds, housing, and other infrastructure.

Results

During the FGD, eighty percent of the KII mentioned that yaks in Gharpojung Rural Municipality are basically reared for meat; yak meat and *"Sukuti*" (dried meat) is one of the key attractions to internal and external tourists to Mustang. In the past, yaks were used for meat only after their natural death, but now female yaks are culled in October as they age and lose their teeth, making them incapable of grazing or reproducing. Adult yaks are grazed in forests due to insufficient vegetation in the rangelands putting them at risk of snow leopard. Although the government offers 80% insurance for yak death due to accidents, disease, or predators, the protracted process often lead herders to prefer compensation through Annapurna Conservation Area Project (ACAP) said 92% of the herders. Eighty percent of the respondents stated that feeding is challenging in the rangeland because there is little vegetation and no additional supplement. Major grass species found in the Namu Bhrapse rangelands are *Cynanthus incanus, Herminium macrophylum, Bassecoia hookeri, Trogonella gracilis, Potentilla multifidi* etc, which are overgrazed. Recently, herders planted clover and rye grass, but the yaks overgrazed the lush greens, preventing their regrowth. Limited resources for reseeding led to the loss of germplasm. The government has installed some road tracks and water facilities, but they are insufficient for growing yak population. Herders, usually older males hired from other families' herd the yak of 2-4 families, are provided with food and salary for the year. However, the younger generation are lured towards international jobs/business, resulting in a shortage of herders, which is a serious challenge for yak rearing as reported by 95 percent of the respondents.

Discussion

The study gives valuable insights into the challenges of yak rearing in the Namu Bhrapse rangelands where the practice is closely tied to the economical, ecological, and cultural identity of this region but faces sustainability issue (Jing et al 2022). Yak rearing in Mustang is focussed on meat production however there is no legal provision for yak meat to boost tourism and local markets (Carter 2024). Insufficient vegetation and lack of support for provision of supplementary feeding complicate the practice (Kumagai et al. 2016). Grazing in forests exposes yaks to snow leopard predation, emphasizing the need for better predator management (du Chavoux 2020). Efforts to introduce grass species for restoration have failed due to overgrazing, indicating the need for better grazing management plans (Personal communication, 2024). Though the government has built roads and water facilities, they are insufficient for the growing yak population. High grazing taxes and limited rangeland support strain the economic viability of yak rearing. The reliance on older male herders and the younger generation's shift toward urban jobs presents a significant challenge to the practice (Banjade and Paudel 2008). To address these issues, government investment in sustainable systems, predator control, herder incentives, rangeland restoration and research on innovative practices and socio-economic solutions is essential.

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Agricultural developments on the rangelands of the Tibet Autonomous Region in China, with a special emphasis on the role of Tibetan women

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Abstract

Tibetan women play integral roles in agriculture on the rangelands of the high plateau of the Tibet Autonomous Region (TAR) in China. Agricultural development was the focus of ACIAR (Australian Centre for International Agricultural Research) funded projects in Tibet including capturing socioeconomic facets. Two projects that the authors worked on (2009-2012) provided the opportunity to explore firsthand livestock production systems in pastoral and crop-based areas of TAR. This paper aims to offer sociocultural insights, and to highlight the role of women in Tibet as enablers of change. For agricultural developments to proceed with greater success it will be important that women are included in changing practice.

Introduction

The Tibet Autonomous Region (TAR) spans 1.2 million km^2 (Tashi et al 2005). Livestock production is a predominant industry, where production systems (meat, milk and fibre) rely on long-established practices. Rapid changes brought about by increased industrialisation and urbanisation across TAR mean the traditional roles that Tibetan farmers and pastoralists once played are also changing. The Australian Centre for International Agricultural Research (ACIAR) has supported several projects in Tibet (e.g., Tashi et al. 2005; Rose 2011; Heath et al. 2012; Spiegel and Costa 2014) to aid the modernisation of agricultural practices so food and Tibetan livelihoods can be secured and poverty amongst Tibetan communities can be alleviated. A Tibetan researcher, the late Dr Nyima Tashi, was a strong advocate of agricultural developments in TAR, and actively established collaborative partnerships with ACIAR.

The following paper is based on the authors' combined firsthand research experiences during their time (2009 to 2012) working on agricultural development projects in TAR, written through the lens of an animal scientist (Spiegel) and an extension agronomist (Rose). Observational evidence, supported by project findings and literature, have allowed the authors to share their insights on pastoral and crop-based dairy systems in TAR, with a special emphasis on the role that women play in dairy production.

Background

TAR is made up of six prefectures and one municipal city of Lhasa situated at 3,656 m asl. Across the prefectures there are 74 counties, almost 900 townships and over 7,000 villages (Tashi et al. 2005). ACIAR funded research on the mineral nutritional status of Tibetan livestock and integrated crop and dairy systems. The former project identified many mineral insufficiencies and deficiencies (Tashi et al. 2005) and confirmed some alarmingly low, location-dependant, selenium levels in livestock (Spiegel et al. 2011). Two locations of particular interest included one crop-based township (Duopozhang) and one pastoral county (Jiali).

Selenium deficiency in livestock can result in reproductive disorders, but in humans, debilitating multifactorial diseases can occur, such as cardiomyopathy Keshan disease and osteoarthropathy Kashin-Beck disease. Both diseases are known to China, especially within areas of selenium deficient soil spanning from the northeast of China to the southwest to include parts of TAR (Yang et al. 2010; Yao et al. 2011).

Research efforts focussed on improving the nutritional status of Tibetan livestock involved authors spending extended periods in TAR: 5 months (Spiegel) and 3 to 4 weeks (Rose) each year from 2009 to 2012. Mineral surveys and mineral response trials were conducted across counties and production systems (see Spiegel and Costa 2014), and economic (Waldron et al. 2016) and attitudinal surveys (Rose 2011) conducted in the cropping zone of TAR. For the latter, adaptive research surveys, used to assess farm adoption opportunities and barriers, were conducted orally with farmers in Tibetan to avoid literacy issues and poor understanding of Mandarin. Impressions on the Chinese/Tibetan researchers' attitudes were made during presentations to scientific meetings and general discussions during data gathering.

The focus of this paper is on the two locations of Duopozhang and Jiali, representing respectively a crop-based and a pastoral-based livestock production system in TAR at risk from severe mineral deficiency.

Crop-based livestock system: pathways for agronomic practice change

This zone is characterised by traditional farming of intensive cropping and smallholder livestock production on valley floors (Fig. 1) and lower hill slopes with the average farm size of 0.8 ha (Heath et al. 2012) and altitudes ranging between 3,600 to 4,000 m asl. The township of Duopozhang in Naidong County (Shannan Prefecture) was especially of interest to the minerals project (Spiegel and Costa 2014) owing to the very low mineral selenium levels identified in dairy cattle – lower than any international previously published results – and severely low dietary energy and protein intakes of livestock, as seen by poor body condition. Research efforts were consequently concentrated here (e.g., see Waldron et al. 2016) and attitudinal surveys conducted with farmers in 2011 (see Rose 2011 & 2013).

During the authors' time spent in Duopozhang (starting in 2009), rapid changes were taking place. Investment in the expansion of this township by The Peoples Republic of China (supported by a range of International aid projects) meant roads were being developed, additional livestock (e.g., Boer goats and pigs) and new cattle genetics introduced, access and availability of water to households and for crop irrigation was being improved, Lucerne was being planted, methane digesters to supply energy for heating were being trialled, and extension efforts by local officials were starting. Research efforts by local organisations (TAAAS: Tibetan Academy of Agriculture and Animal Husbandry Sciences and the Tibet Poverty Alleviation Office), and international collaboration (TAAAS and ACIAR) were operating simultaneously for maximum impact and allowing for a test site that, if successful, could be used as a model for other crop-based villages in TAR.

During field research, we observed Tibetan sociocultural attributes, behaviours and traditions that underpinned, and were unique to, the production systems in question.

Firstly, it was apparent that Tibetan households were not only dependent on their livestock, but that their daily work, especially of women, largely involved managing livestock. Animals were kept in close quarters and fed with whatever was available, including household kitchen scraps. The dung from cattle was collected, dried and later used as fuel in the household for warming and cooking. Daily routines of Tibetan women also included feeding, watering and milking their cattle by hand twice daily, managing the calves to restrict suckling, letting cattle out of the house yard to graze available pasture (e.g., on the grazing common or tethered in cropping fields to graze weeds or crop residues), and collecting forage for their cattle (cut and carry practices of woody browse species). Secondly, the milk collected was churned by hand to make butter, the highly valued dairy product used to make Tibetan tea (traditional salty butter tea), with some butter spared for butter lamps in households for religious reasons. The use of butter as a form of topical cream to treat cracked teats in milking cattle was also disclosed by some of the households.

In terms of production, local dairy cows (as locally bred) are of small stature and low milk production. Traditional feeding includes very limited grazing, feeding of weeds, and in winter the use of straw as arable land is used for human consumption crops. As a result, animals have poor nutritional status, including low energy and protein intakes and restricted water intakes. Improving the mineral nutritional status of their livestock would have the benefit of boosting trace elements (such as selenium) in the human food chain. However, without correcting for under-nutrition, the full benefits of mineral supplementation and production responses would not be seen. Thus, overcoming protein and energy deficiencies in dairy cattle was priority. Adopting a focus on agronomic practices and cropping was required. As such, the attitudinal survey (Rose 2011 & 2013) sought to understand motivations for farming decisions and barriers to adoption of practice change such as practices of growing forage crops, double cropping, and supplementary feeding of stock.

The main motivation for increasing production was for a better life, with buying equipment a distant second. Lack of capital was a barrier to trying new ideas on farm, so opportunities to work off farm were considered important to provide the necessary cash flow. A major contradiction though, is that off farm work creates major labour shortages at peak times like harvest. Heath et al. (2012) discuss that strategies such as double cropping with fodder crops have the potential to increase production yet increase labour pressure at peak times. The survey also revealed a general reluctance of the older generation farmers to encourage succession to their younger generation. Observations of the women surveyed was the women did not identify themselves as the primary decision maker in farming decisions.

Delving into the adoption of improved production techniques, the farmers were willing if the practice was able to be done (e.g., new barley varieties / oats / vetch seed available), the up-front costs were not beyond their cash flow, and that the practice worked on their farms. While most projects supplied the early inputs to avoid the cash flow issues, the authors saw that while strategies such as growing maize were successful in the research phase, farmers said they were unlikely to adopt in the long term due to cost barriers. On the other hand, oats had survived beyond the research phase, as seed sales made it an economic option. Some resistance to lucerne had been overcome by the value of selling forage in the towns. Barriers to freely available water for dairy cows include access to flowing water, and the increased runniness of dung being associated with illness in the livestock and increased difficulty in fuel preparation.

Survey questions showed that little extension was done at their villages. Though farm schools were run, Chinese/Tibetan researchers lamented that farmers had to be paid to attend, and farmers felt that the schools were too hard to get to. While fertiliser and insecticides were widely used, there was little understanding of which ones to use or why they did or did not work, or even what the pests were. Herbicides were not popular as weeds are a fodder source for stock.

Fig. 1 Photo capture. Left and centre images: Tibetan farmer and Tibetan style home in Tibet's cropping area. Images on the right: Tibetan yak herders in pastoral Tibet. Photos courtesy of N. Spiegel.

Pastoral system: settlement and flow-on effects

This zone is characterised by treeless rangeland pasture, inhabited by Tibetan sheep, goats and yak and Tibetan nomads/herders (Fig. 1). Pastoral counties investigated by Spiegel and Costa (2014) included the yak and sheep production counties of Damxiong (4,200 m asl) and Naqu (4,500 m asl) and the yak production county of Jiali (4,500 m asl). For the latter, very low mineral selenium levels were detected (Spiegel et al. 2011).

The restructuring of TAR into production zones (Tashi et al. 2005) and the settlement of people into townships and villages has allowed for the provision of centralised services throughout TAR such as health care and schools, and the development of new housing. However, the restriction of movement of nomads as a result has led to unwanted consequences, such as the concentrated grazing pressure and increased parasitic infection in livestock grazing contaminated pasture observed by the minerals research project during their investigations, as well as degradation of the rangelands seen across different pastoral areas in TAR. Animal diseases and animal husbandry issues have negative flow-on effects for animal production and each household's ability to maximise food production. Although, having centralised services mean animal husbandry extension can be easily established within a county to service the local villages. The construction of a veterinary branch in Jiali County (Naqu Prefecture) for instance was taking place during the authors' time in TAR and could have an invaluable future role to play in disease control and prevention, stocking rate management and in extension and education. Two prevalent diseases affecting Jiali yak production observed by the minerals project included Warbles (Subcutaneous myiasis; caused by warble fly infestation) and brain parasites (Coenurosis; caused by the intermediate stage of the tapeworm *Taenia multiceps*) (Spiegel and Costa 2014).

Despite the rapid changes and modernisation that has been occurring in TAR, we observed traditional ways of life, such as Tibetan pastoralists still living in summer and winter tents. Pastoralists manage yaks for both milk and meat. Nomadic women churn yak milk into butter, an important part of the traditional diet. Other production includes the making of hard cheese, yogurt, yak blood sausages and dried yak meat. Some modern features observed included motorbikes, mobile phones, solar panels and electric appliances such as kitchen blenders. The collection of yak dung for fuel was still apparent at the time and no alternative heating or power for cooking was observed. The upkeep of a stupa (Buddhist shrine) in the township also meant locals could still openly practice religion and meditation, such as carrying out daily circumambulation (kora).

The practice of caterpillar fungus harvesting was encountered. This fungus (*Ophiocordyceps sinensis*), a unique medicinal fungus, is physically dug out and removed from the rangelands soil for trade. What was apparent through translated conversations was that nomadic households could boost annual earnings through harvesting and trading the highly priced *O. sinensis*. Some family members were carrying out annual spring harvesting and therefore spending extended periods occupied by this seasonal work activity rather than by daily livestock activities. The opposing effects for the household are apparent: good for cash flow, but reduced household capacity to tend to livestock. Wang et al (2018) identified other mixed flow on effects, such as low school attendance rates, possibly due to the lack of perceived benefits from education. In addition, there is concern over the overexploitation of *O. sinensis* contributing to the degradation of alpine and sub-alpine pastures (e.g., Hopping et al. 2018).

From extensive time spent in TAR, we observed pastoral women in contemporary Tibet fostering a strong connection and identity to their culture, including traditional dress worn in their homes, providing traditional hospitality, and conducting daily animal husbandry practices using traditional methods. During the field sampling of livestock, women were always present and playing an active role in sample collection. Dairy related tasks such as milking, yogurt and butter production were predominantly done by women. Women were handling their animals daily and a strong bond between handler and animal was evident. For instance, during jugular blood collections of yaks for mineral sampling, any yak that was not tolerating being restrained was quickly quietened and soothed by the presence and touch of their female herder. Animal handling techniques were also passed down to the next generation, with children exposed to animal husbandry or actively involved, for example decorative bags containing salt were carried by older children to lure yaks.

Discussion

Our observations suggest that Tibetan women play pivotal roles in shing-lay (Tibetan for agriculture) and are well placed as being integral to decision making for dairy production on the rangelands in TAR. Our experience from household visits and survey, showed most women do not identify themselves as the primary decision maker; but that may indicate women are more inclusive, rather than that men dominate the farming decisions. The trend towards reliance on off farm income, increasing the ratio of women to men managing the land, will only increase the role of women on the land. It is therefore pivotal that extension of agricultural research is tailored for both genders. For instance, participatory action learning for women would ideally focus on how production-related changes can interact with the household. Training at the village would be desirable, as women will be less likely to attend if training takes them away from their daily work and children. For men, the focus might be on production and could include training following adult learning principles, away from the village. Changing the perception of the low value of agriculture, to one of a valued profession, as well as increasing production from subsistence to trading, could help reverse the trend of discouraging the younger generation from farming. Part of this is the training of Tibetan farmers and herders to enable them to make informed decisions on inputs and outputs, rather than the top-down supply of information and inputs. Surveys identified, for instance, farmers applying nitrogen-based fertiliser to lucerne, as that was what they were supplied, and a very low knowledge of pests and diseases of both plants and animals. Research would also benefit from the two-way flow of information.

Other changes in a modernising economy may also have a major impact. For instance, in one village visited, methane digesters supplied energy for heating, making the collecting of dung for fuel redundant, and leading to dung being returned to the fields. In terms of optimising milk and meat production, breeding programs and the adoption of yak crosses and larger framed cattle in TAR (e.g., Holstein local cow crosses) run the risk of many adverse consequences, such as increased dystocia, exacerbation of protein and energy deficits, reduced butter fat content of milk, as well as loss of well-adapted native breeds and ecotypes.

Female Tibetan agricultural researchers also have a role to play to assist and promote agricultural developments, however they appear to experience dislocation from their roots due to extended education in ‘mainland’ China. Despite this, the female researchers assigned to survey work were willing to engage in the extension concept and showed empathy with the farmers. From the authors own observations during their time in Tibet, research was the primary focus and endeavour of many, with extension considered to be an early career job with low status. On a study tour to Australia, Tibetan / Chinese colleagues were amazed to meet highly respected extension specialists. This is a paradigm shift that research aid projects could aim to address.

The attitudinal survey work demonstrated the importance of embedding a strong social and extension component into research and development projects. For instance, the unexpected findings of Tibetan farmers using butter on cracked teats of dairy cattle or using nitrogen fertiliser on legumes offers a segway to exploring different methods for adoption to boost trace elements in the human food chain. For example, improved daily management of dairy cattle/yak udders could simply include an iodine-based (‘Iodophor’) teat dip disinfectant. The udder can absorb the iodine. For the application of fertilisers on crops, the option to use selenium fortified fertilisers on both fodder and cereal crops might be worth exploring to boost selenium levels in both animals and humans (G. Lyons, pers. comm.). All research and extension should, however, consider the risk of unintended negative consequences and remain flexible to alter direction.

The paper explored two different livestock production systems operating in TAR. The opportunity for future work to explore potential linkages and trade options between the two systems deserves research attention. With the potential to test new feeding systems and animal husbandry practices in the cropping zone of Tibet and to test and develop disease control in pastoral areas of Tibet. For example, there could be a natural exchange of knowledge and supply of feed concentrates across counties to bolster developments in agriculture on the Tibetan rangelands. Climate change and reduced isolation also leads to a need for further research as growing seasons lengthen and more pests and diseases emerge, and will change accepted management practices.

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THEME 2. CO-DESIGN, PARTNERSHIPS, AND INCORPORATING TRADITIONAL KNOWLEDGE FOR MORE ENDURING RANGELAND OUTCOMES

Bridging Perspectives – Indigenous, Non-Indigenous, and Traditional

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A comprehensive analysis of pastoral traditional knowledge functions

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Key words: Knowledge Functions, Pastoral Traditional Knowledge, Pastoralism, Traditional Ecological Knowledge

Abstract
Pastoral traditional knowledge is gaining recognition for its adaptability and role in enhancing the resilience of pastoral communities. To deepen our understanding of how this knowledge system demonstrates adaptive characteristics, we employ a functional lens to examine its dynamic nature in this systematic review. Our analysis, based on insights from 152 case studies worldwide, shows that this knowledge system has various domains and serves diverse functions, including ecological, economic, and socio-cultural functions, with further subfunctions. Ecologically, it primarily boosts climate resilience and adaptation; economically, it supports herd health and productivity; and socio-culturally, it preserves cultural identities and heritage. Furthermore, our findings highlight that each knowledge domain shows multifunctional characteristic. Our analysis also helps identify common functions across eight knowledge domains, each contributing to areas like sustainable resource management and climate adaptation, though to varying degrees.

Introduction
Pastoralist communities globally are confronting a myriad of challenges. Climate change is disrupting their traditional lifestyles through unpredictable weather, intensified droughts, land degradation, and poorer pasture quality (Ahmed et al. 2023). Socio-economic factors such as market dynamics and resource extraction are straining their adaptability (Galvin 2009). Additionally, land ownership policies and conflicts limit access to essential resources, compounding these pressures and threatening both the ecological balance and the cultural continuity of pastoral societies (Xie and Li 2012).

Despite these challenges, pastoral communities persistently employ and renew their traditional knowledge, continually learning from and adapting to changing environmental conditions and socio-economic landscapes. To dig deeper into how pastoral traditional knowledge (PTK) helps pastoralists adapt and thrive amid changing environmental and socio-economic pressures, we decided to apply a functional lens in this study. The function of knowledge, within this context, refers to the deliberate use of knowledge to achieve specific objectives as well as the actual impacts or outcomes of the knowledge. Specifically, we review the literature 1) to document the domains of PTK, 2) to explore the diversity of functions PTK serves in the lives of pastoralists, 3) to investigate whether a single PTK domain can serve multiple functions, and 4) to examine whether different PTK domains share common functions.

Methods

Our review used primary sources from peer-reviewed literature on PTK from the Web of Science and Scopus. The search string used was TS= ((traditional OR Indigenous OR local OR past OR old OR folk OR aborigin) AND (pastoral* OR nomad* OR herd* OR shepherd OR flock) AND (ecology* OR environment* OR rangeland OR grassland) AND (knowledge* OR practice* OR strategy*)) AND TS= (adapt* OR cop*). The initial search yielded 1076 documents (WoS = 432; Scopus = 644). After removing overlapping documents based on DOI, title, and abstract comparisons (n=318), we thoroughly screened 758 publications for relevance to our review, focusing on title, abstract, and methods. We included only peer-reviewed studies that provided empirical evidence of PTK and had a clear focus on PTK. Studies that only partially addressed PTK were included if the relevant section to PTK provided detailed insights. Publications were restricted to those available in English or Chinese. Ultimately, 149 papers met our criteria and were included in the review.

To investigate diverse domains and functions of PTK, we conducted qualitative thematic analysis and coded the verbatim statements referring to PTK, its applications and its outcomes in Nvivo. Additionally, we quantitatively assessed the distribution of the coded functions among different domains using the R program, specifically 'dplyr' for descriptive analysis and 'ggplot2' for data visualization. Using 'dplyr', we evaluated the distribution of different functions across various PTK domains and analyzed how these knowledge domains contribute to various functions by calculating the percentage distribution within each sub-functional group.

Results

Domains of PTK

Results from our analysis expand upon the initial framework proposed by Sharifian et al. (2022), who identified five key knowledge domains: livestock, forage/plant, landscape, climate/weather, and social-cultural knowledge by adding two new domains to this classification: herd mobility practice and herd diversification practice. The distribution of different knowledge domains across case studies shows a significant variation. More than half of the case studies (84, 55%) reported only one or two knowledge domains, while 39% (59 cases) documented three to four domains. Notably, only 9 cases (6%) documented a range of five to six knowledge domains. Among the knowledge domains documented, herd mobility is a practice most frequently reported, identified in 82% of cases (124 cases) across all climate zones. Climate and weather-related knowledge is the second highest cited knowledge domain, reported in 41% of the cases (n = 63). Knowledge domains relatively less often mentioned in the literature include landscape-related knowledge and herd diversification practice. Landscape-related knowledge was found in 33 cases (22%). Pastoralists routinely observe and learn about their surroundings while herding.

Diverse functions of PTK

Our analysis suggests that PTK covers different ecological, economic, and social-cultural functions in pastoral systems. Within the dataset analyzed, a total of 252 citations are applied to support ecological functions. PTK ecological functions include various subfunctions such as monitoring ecosystem health, preventing unsustainable resource use, predicting weather and climate variations, and maintaining biological diversity in the ecosystem. Upon examining the distribution of these citations among different knowledge domains, it is apparent that the domains of herd mobility practice (78 citations) and climate/weather-related knowledge (55citations) are prominently associated with ecological functions.

PTK's economic functions refer to PTK's role in enhancing the efficiency and sustainability of pastoralists' livelihoods. We identified three different subfunctions in this group: utilizing limited resources effectively, mitigating the impacts of natural disasters, and improving livestock productivity and health. Among all the recorded citations, there are 139 of them which play economic functions among pastoral communities. The domain of herd mobility (43%, 59 citations) emerges as the most prominent within this economic category. Although forage/plant-related knowledge is not prominently featured for its ecological function, this knowledge domain made up 18% (26 citations) of PTK economic functions. Livestock-related knowledge accounts for 11% (16 citations) of the economic functional group.

The social-cultural functions of PTK contribute to the maintenance of pastoral communities' cultural integrity and social structures. This functional characteristic stresses PTK's role in preserving traditional culture but also in enhancing the social bond of the community and promoting cooperation. Among the recorded citations, 59 citations are documented as fulfilling social-cultural functions. Social-cultural functions draw in social-cultural knowledge, which forms nearly half of this functional category (48%, 29 citations). However, it is interesting to note that livestock-related knowledge, accounting for 11% of all social-cultural functions, and landscape-related knowledge, representing 10%, also contribute meaningfully to the social-cultural fabric.

We further analyzed the data to better understand the weight of different subfunctions within the three main functions. The ecological functions of PTK stands out as the most common, with over half (58%) of the recorded subfunctions addressing four ecological functions: ecosystem monitoring, sustainable resource use, climate adaptation and resilience, and biodiversity conservation. Within ecological functions, climate adaptation and resilience is the most often cited subfunction, comprising 35% of all recorded citations. The subfunction of sustainable resource management represents 17% of the citations. Within economic functions, enhancing livestock productivity (14%) and livelihood support (12%) are two subfunctions most often cited. Overall, the social-cultural functions of PTK are the less often cited. Within those, cultural preservation (7%) is emphasized to a larger extent than some ecological and economic functions, including ecosystem monitoring and risk management.

Multifunctional characteristic of PTK domains

Our results also reveal that most domains are connected to distinct functions. For instance, social-cultural knowledge covers ten types of subfunctions, ranging from climate adaptation and resilience to social cohesion and community governance. Livestock-related knowledge, which one might expect to predominantly impact areas directly related to herd management, such as productivity, in fact, shows a diverse range of functions.

Common functions across PTK domains

In our comprehensive analysis of PTK, a pattern of common functions among various knowledge domains emerged. all the knowledge domains examined collectively contribute to sustainable resource management, and climate adaptation and resilience functions. In terms of knowledge domains contributing to economic subfunctions, all the knowledge domains were found to jointly contribute to improving livestock productivity. Furthermore, herd diversification and herd mobility practices were often intertwined in addressing risk management. Culturally, almost all the knowledge domains contributed to the preservation of cultural identity and heritage. Although social-cultural knowledge played a dominant function in improving social cohesion and community governance, some case studies reported that herd mobility could serve the same purpose.

Discussion

Our study reveals significant imbalances in the focus of existing case studies regarding knowledge domains. The fundamental knowledge of pastoralism globally, such as livestock-related (10% of the cases), forage/plant, and landscape-related knowledge are significantly underrepresented. Additionally, we found that more than half of the case studies (55%) investigated only one or two knowledge domains. This underrepresentation is problematic because it fails to capture the full complexity and interconnectedness of the pastoral knowledge system. Global research on traditional pastoral knowledge shows that pastoralists across diverse regions use a complex and common set of principles, including forage/plant, landscape, and livestock knowledge to manage resources efficiently and sustain their livelihoods (Sharifian et al. 2023). By focusing narrowly on certain aspects, research risks oversimplifying the holistic strategies that pastoralists employ. Pastoralists do not view these domains in isolation; rather, they integrate multiple domains to adapt to environmental uncertainties and ensure the sustainability of their resources. Thus, we argue that this narrow focus and fragmented approach risks presenting an incomplete or even distorted understanding of PTK. It fails to capture the holistic strategies pastoralists use to manage uncertainty and ensure the sustainability of their resources.

Moving from the specific domains of PTK to its broader implications, PTK exhibits diverse functions, playing ecological, economic, and socio-cultural roles. In our database, the most common ecological subfunction of

PTK is climate adaptation and resilience, which appears more frequently than the sum of the rest of the ecological subfunctions. This prominence likely stems from pastoralists' direct experience with climate variability, such as droughts, floods, and shifting seasonal patterns, underscoring their adeptness at navigating and mitigating the adverse effects of weather variability, and potentially of climate change. Regarding the economic aspect, PTK is mainly mentioned for enhancing herd productivity, and livelihood support and resource optimization. The findings show that forage/plant-related knowledge and mobility practice are the core for maintaining herd health and productivity. This aligns with the findings of Launchbaugh (2020), who highlighted that livestock could benefit from mobile grazing behavior by taking a variety of forage with different nutritional qualities. In terms of social-cultural functions, we found that livestock-related knowledge and landscape-related knowledge play significant roles in preserving the cultural identity and heritage of the pastoral communities. The landscapes that pastoralists inhabit and manage are imbued with cultural significance. Managing and preserving these landscapes, therefore, becomes an act of cultural heritage conservation. In certain communities, specific practices in landscape management, like controlled burning, are important parts of their culture (Fernández-Giménez 2015).

Building on the understanding of these varied subfunctions, our findings suggest that each domain of PTK serves multiple ecologic, economic, and socio-cultural functions. The significance of multifunctional characteristic within the knowledge system is profound. It enhances community stability by equipping them with a diverse set of strategies to deal with uncertainties and ensures that knowledge itself remains pertinent and flexible, capable of adjusting to evolving challenges. As some case studies show, even when a community is faced with constraints such as privatization, mobility adapts to fulfill other important functions, such as land preservation. This gives reason to believe that the multifunctional characteristic of traditional knowledge systems contributes to their continued relevance and transmission. Therefore, future studies could examine this relation more directly. Additionally, there is a significant opportunity for future studies to explore how these functions evolve and adapt over time, particularly whether knowledge domains develop new functions in response to environmental and social changes.

Expanding on the finding of multifunctional characteristic of each domain, another finding that deserves attention is the substantial common functions present across knowledge domains. The idea that communities utilize alternative knowledge to achieve similar outcomes due to various challenges is discussed in the existing literature. For instance, Gauer et al. (2021) explore how Indigenous communities adapt their knowledge in response to environmental changes, employing alternative strategies when certain knowledge becomes impractical or ineffective. Drawing on these findings, we propose that future studies could interpret this interplay and synergy as a mode of strengthening traditional knowledge systems. We hypothesize that the common functions identified across different PTK domains allow pastoral communities to approach challenges such as climate change from various angles, thereby increasing the likelihood of finding a more effective solution.

Given the diverse range and complex interplay of ecological, economic, and socio-cultural functions within PTK, there is a need for adopting an interdisciplinary approach. By incorporating perspectives from various fields, future studies can achieve a more holistic understanding of traditional knowledge systems and their functions. Additionally, there is a need for future studies to involve and collaborate directly with local communities. In this way, researchers can ensure that their work captures the full depth and interconnectedness of PTK while respecting and valuing the perspectives and lived experiences of these communities.

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Interdisciplinary investigations identify local knowledge important for pastoralist adaptation to climate change in Montesinho (Portugal)

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Key words: Rangelands; Mediterranean basin; local livestock breeds; co-participatory consultation.

Abstract

Pastoralists are among the most vulnerable groups to climate change and variability, as they depend on bioclimatic conditions for livestock forage biodiversity and production. In the complex socio-ecological system of the mountainous area of Montesinho Natural Park (north-east Portugal, Western Europe), traditional pastoralists are impacted by climate change in their rangelands (e.g. average monthly temperature increase, shifts in precipitation patterns) (Castro et al. 2021; Oliveira 2023).

To understand the adaptive responses of local pastoralists to environmental change, this interdisciplinary research applied a three-step method. Firstly, we performed walking ethnographies with shepherds for over two years and used dialogues and observations to identify perceptions and local adaptations. Secondly, adaptive practices from other pastoral groups that could be viable in the study area were identified from the literature. And thirdly, co-participatory consultation workshops with pastoralists and representatives of local and national entities were developed to discuss and assess the adaptive measures for its practicality and sustainability.

Shifts in precipitation patterns, drought and higher temperatures in the winter were identified as climate changes by local pastoralists, and several adaptive practices for water provision and conservation, additional fodder supply and livestock thermal comfort were listed by all local stakeholders involved in the project, as feasible solutions to overcome regional ecosystem shocks and trends.

Local knowledge and climate perceptions were important for the documentation of adaptations at the rangeland level. This integrative approach, which resulted in a good practices guide, promotes practitioners and decision-makers to identify and discuss measures that will contribute to the resilience of traditional mountain pastoralism in the protected area of Montesinho and similar agro-pastoral systems.

Introduction

Pastoralism is an ancient practice that requires flexibility and adaptability to respond to social, political and ecological landscape changes. Up to the 20th century, this practice was economically important in northern Mediterranean mountains and remains so in the Natural Park of Montesinho (PNM) in north-east Portugal, Western Europe. Here, traditional pastoralism contributes to landscape management, provides ecosystem services, is a source of animal protein in local diets, and represents cultural identity (Castro et al. 2021). Despite a significant reduction in the total number of animals and shepherds using the territory due to these historical changes, pastoralism remains an important activity in PNM. As with mountain pastoralists elsewhere, however, we are yet to understand how these groups will overcome contemporary climate challenges, or the social and ecological impacts of this practice collapsing.

Future north Mediterranean landscape projections include increased aridification and desertification as a result of climate change and current exploitation rates (Lazarev 2022). In the PNM region, recent investigations on climatic normals over the past 70 years, reveal reduced spring and increased autumn rainfall, alongside consistently increasing annual average temperatures (Oliveira 2023). Such events can deplete drinking water resources and induce heat stress in animals and plants, degrading animal health and decreasing palatable biomass, culminating in reduced livestock productivity and increased livelihoods risks (Kgosikoma et al. 2018).

Elucidating pastoralists climate change perceptions, significant impacts on activities and adaptive responses is therefore urgent. In such socio-ecological systems, as complex as PNM, an interdisciplinary approach integrating anthropological, ecological and climate knowledge is crucial for pastoralism resilience.

In this study we aim to (i) obtain insights into regional climate change perceptions amongst shepherds, (ii) identify the feasibility of climate adaptations to strengthen livelihood resilience, and (iii) provide technical oversight regarding adaptations suitability and sustainability. Project outputs will include a regional good practices guide.

Methods

The Natural Park of Montesinho (PNM) was established in 1979. The mountainous area (approximately 74,000 ha) has an elevation range between 445 and 1,487 m, average annual rainfall between 1262 and 806 mm, and average annual temperature range of 8.5 to 12.5°C (INMG 1991). The park is rich in plant and animal biodiversity mainly due to its climate, geology, and the transboundary river system with the neighbouring country, Spain. Just over 4500 people live within the park and livelihoods include both rural and non-rural activities. Pastoralism is a practice performed by fewer people than in the past, but the park still sustains herds with totals of 20,001 sheep and 687 goats across 35,296 ha of shrublands, woodlands, and cultivated areas. The low number of residents, particularly shepherds, reflects ongoing social and economic change.

To firstly identify climate change perceptions and other socio-economic-political changes affecting pastoralism in PNM, seasonal walks were undertaken between 2022 and 2023 with local sheep and goat herders. An ethnographical approach using conversations and observations yielded data, which was analysed qualitatively to identify perceptions and knowledge on specific themes: transformations in land use and pastoral activities (historical and contemporary), political and economic challenges, agrosilvopastoral resilience, pastoralists perceptions on climate change and adaptive responses. The list of adaptations identified was complemented with adaptations applied in other mountain regions globally, which could be viable under the PNM ecological, political and social conditions.

These adaptations were reviewed and discussed in co-participatory consultations held with regional pastoralists in two villages within the grazing territory of the project shepherds. The sessions comprised of presentation and discussion of project results grouped into (i) pastoralism in the past and in the present, (ii) climate change perceptions, and (iii) how to address the future as a pastoralist. The first and second parts were presented using photographs portraying life in the past and present and a summary of the descriptions and perceptions of pastoralism and climate changes provided during the ethnographic walks, which instigated open discussions among participants. The third part comprised of a comparison between two photographs depicting a current productive landscape and a future drier scenario. The adaptive responses identified during the walking ethnography and the literature review were presented to the participants in the form of smaller photographs, which were either selected or discarded according to its practicality, efficiency and applicability in the PNM, and prioritised based on the pastoralists needs. A final workshop involving local stakeholders engaged with the agrosilvopastoral system of the park (members of national associations of local breeds and governmental agencies) followed a similar structure. The participants were invited to contribute with their technical knowledge on discussions about the executability and enforcement requirements of each adaptation. Every person involved in this study was individually invited to participate, and informed about the research aims, outputs, and their rights to withdraw at any point.

Though this study aimed to present how PNM pastoralists are adapting to climate change, our work addressed a limited number of male only participants with a narrow age spectrum (50-69 years). Additionally, across the years, different researchers conducted the ethnographic walks which could have contributed to some bias as we did not follow an interview script. When conducting the co-participatory consultations, thinking of a future scenario with drastic water shortage and warmer periods was not always an easy task for some participants. Moreover, we believe some discussions among stakeholders were guided by their professional link to a regional/national entity.

Results

Walking ethnography yielded important insights on temporal changes in work organisation, dynamic agrosilvopastoral system resilience, and climate change perceptions. Furthermore, coping mechanisms were identified for the changing conditions pastoralists currently face. Climate change perceptions, suggest that seasons are less well defined compared to the past, winters are warmer, and there is less water in the soil (e.g. many springs and small streams have dried or have little water). Pastoralists further reported that rainfall no longer follows monthly patterns, frost and thunderstorms occur at unexpected times of the year, and snowfall frequency and quantity are lower. All these changes are believed to impact fodder productivity and drive higher resource and materials costs.

Adaptations implemented by PNM pastoralists and in other regions were reviewed by all parties (shepherds and stakeholders) involved in this traditional practice during the co-participatory consultations. The two consultations with local pastoralists resulted in the selection of 14 and 11 relevant adaptations, a difference most likely due to the edaphoclimatic characteristics of the west and east regions of the park where the shepherds graze their herds. We grouped the selected adaptations into three types: adaptations in the grazing territory, to the grazing of animals, and to the livestock production. Many of the response mechanisms were directed at providing water and forage for the animals, valuing and diversifying livestock products (e.g. added value product; production of cheese), and improving animal health. Priority among pastoralists was given to adaptations to be implemented by regional and national entities rather than by the shepherds themselves, probably due to the grazing territory being within a protected area with strong conservation enforcement and laws.

Discussion [Conclusions/Implications]

Pastoralists perspectives on precipitation and temperature variation, and other climatic hazards (e.g. lack of snow), reflect the changes taking place in PNM inferred from climatic data (Oliveira 2023). Moreover, they highlight the negative impact such events have mainly on water availability and crop productivity in PNM. As a response, all shepherds, regardless of their territories characteristics, apply coping mechanism frequently observed in other rangelands across the globe (Herrero et al, 2016): place water points in the territory, grow crops that are more drought resistant to feed animals in face of pasture shortage, adjust shepherding routes. Adaptations priority, however, appear to respond to the edaphoclimatic conditions of the grazing grounds. Planting trees and conserving pastures were top adaptations for pastoralists from the warmer and drier region of the PNM, while valuing livestock products more crucial for increasing pastoralism resilience among pastoralists from the colder region. The fact that most shepherding territory is located within a protected area that is under national administration could explain why in both consultations, priority was also given to large scale adaptations such as building water reservoirs, planting trees or implementing early weather warning systems. However, this result could also be due to individual strategies already being addressed and becoming less significant when compared to other major adaptations.

The stakeholders workshop confirmed some of the pastoralists perceptions on bureaucratic and legislative challenges to improve animal housing conditions or implementing water recovery systems. Though technology may benefit pastoral adaptations to climate change (Arjjumend 2018), in the PNM context, local protected area laws are somehow prohibitive. Moreover, other difficulties pointed out by stakeholders address the fact that many national strategies and policies are developed for pastoralism at a different scale than that of the PNM.

This investigation shows that pastoralists in PNM continue to adapt as they have done for decades, though we are unsure if these responses are enough to maintain the activity in times of accelerated and larger magnitude changes (Galvin, 2009). Indeed, worries emerged regarding the future of this traditional activity facing the impacts of a warmer and drier landscape, and political and social challenges (ex. unsuitable common agricultural policy, rural abandonment). Nevertheless, we hope that our research strategy of bringing together knowledge from pastoralists, stakeholders and scientists - "hybrid knowledge" (Dean et al. 2024) - will contribute to policy discussions at the regional and national levels on the complex Mediterranean pastoral systems and the need for climate change mitigation and coping strategies.

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Aboriginal and white pastoralist history — the positive stories

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Key words: Aboriginal people; Pastoralist; Race; Positive relationships; Nuanced history

Abstract
This paper examines the complex and often overlooked positive relationships between Aboriginal communities and white pastoralists in Australia. Narratives surrounding colonialism tend to focus on dispossession and conflict, yet there is a body of evidence that indicates some relationships were characterised by mutual respect, cooperation, and friendship. Using historical accounts, oral histories, and firsthand testimonies, this paper explores the diverse experiences of Aboriginal and white settler interactions, revealing a more nuanced history than is often presented.

The research highlights that while the overarching history of colonisation led to massive suffering for Aboriginal communities, the early pastoral era was marked by a variety of experiences, from oppression to collaboration. Through an examination of primary sources, this study contributes to a broader understanding of Aboriginal-settler relations, moving beyond simple binaries of conflict or harmony.

The importance of not simply accepting polarised positions about Australia's history is highlighted, as the reality of the situation was usually more complex. A deeper understanding comes from listening to alternative viewpoints about our shared history and discussing how we move forward together.

Introduction
The dominant narratives about Australian Aboriginal history since 1788 tend to emphasise dispossession, violence, and ongoing struggles for rights and recognition. While these stories are true and ubiquitous they can overshadow accounts of cooperation, friendships and nuanced relationships between Aboriginal people and white pastoralists. This paper seeks to highlight these positive perspectives, demonstrating that historical interactions were not uniformly antagonistic or destructive.

Historically, Aboriginal people's own oral histories reveal this dichotomy. Not all Aboriginal people working in the pastoral industry viewed white pastoralists as the enemy. Certain station managers and landowners are remembered with respect for their fairness, predictable treatment, or willingness to intervene on behalf of Aboriginal workers (Ross 1990; Ross and Bray 1989). Even today, many Aboriginal people want to talk about and acknowledge the pain of the past, and they also want to find a way forward.

This paper argues that Aboriginal-settler interactions in Australia cannot be reduced to a single narrative; relationships were not only shaped by the frontier wars, the disposition of land and discrimination. Dreadful events did happen, and the detrimental legacy lingers. Nonetheless, race relations need to be understood through a spectrum of experiences that reflect the diversity of individual relationships, shaped by time, geography, and personal attitudes. In the early days of settlement, and on stations today, enduring friendships and mutual respect does occur with some Aboriginal people and white pastoralists.

Methods

This study draws from four primary sources to examine historical relationships between Aboriginal people and white settlers. First, it draws on the writings of Alice Duncan-Kemp, whose detailed recollections, papers and books provide insight into her experiences growing up in the Channel Country alongside Aboriginal people and continuing to live most of her life in south-west Queensland rangelands (e.g. Duncan-Kemp 1961). The second data source is oral histories recorded by social scientist Helen Ross and a Warmun community member, Gija woman and language teacher Eileen Bray. These document Aboriginal perspectives on their interactions with white settlers in Kija country in the East Kimberley (Ross 1990; Ross and Bray 1989). Thirdly, this paper includes information from two interviews done by the author: Interview 1 with an Aboriginal woman and Interview 2 with a white descendant of a pastoralist. These offer personal accounts and reflections of family experiences in the rangelands and rural regions of eastern Australia. All these accounts support the premise that Aboriginal people and white pastoralists have had positive relationships with each other.

The qualitative data from these sources allows for an exploration of relationships across different regions and time periods. This paper does not claim to present a comprehensive review, but it highlights key themes that emerge from firsthand testimonies and recorded histories, which indicate that race relations are complex and nuanced.

Quotations used in this paper reflect the attitudes and language of settlers from the late 1800s and early 1900s, a period of pastoral expansion in Australia. This language, while confronting by today's standards, is retained here to provide an authentic representation of historical contexts.

Results

Despite the dominant narrative about dispossession of land and the enduring legacy of colonialism, positive relations did occur between Aboriginal people and early white settlers and pastoralists. These are largely unrecognised, especially in common parlance where the dialogue is often divisive.

Respect for Aboriginal culture

Some settlers respected Aboriginal people and their customs, even integrating these into their lives at times. In her book, *Our Channel Country*, Alice Duncan-Kemp explains that her parents taught her and her sisters to "*respect the Aborigines and insisted that we observe their laws and their rights to the vast area – their hunting-grounds and their only home – on which our stock depastured*" (Duncan-Kemp 1961 p232). She went on to describe that as children they '*were severely punished*' if they transgressed cultural boundaries (Duncan-Kemp 1961 p232). She had a deep understanding of Aboriginal people and their culture, as she spent considerable time wandering the country with Aboriginal people as a child, as she explains:

"We were placed under the care of Mary Ann, and Mother made her personally responsible for our welfare and safety. Mary Ann appreciated and vindicated the trust and confidence placed in her" (Duncan-Kemp 1961 p209).

George Debney of neighbouring Monkira Station was another settler who "treated and recognised the aboriginals as human, every black near and far loved Debney … 'Muluh-bu' they called him, 'the Very Wise One'" (Duncan-Kemp 1961 p137). Alice Duncan-Kemp recalled that he spoke 30 Aboriginal dialects, and "he could tell from a broken spearhead or the print of a bare foot what man has passed that way and to what tribe he belonged" (Duncan-Kemp 1961 p136).

Similarly, the Tamblyn family in central-west Queensland respected Aboriginal traditions by allowing corroborees to occur undisturbed. Elizabeth Tamblyn, William Lake Tamblyn's mother, ensured that white settlers stayed indoors during these ceremonies, recognising their cultural significance (Interview 2 2024).

Close friendships were not always desired, as explained by an Aboriginal woman (Interview 1 2024) about her father and grandfather who were Gunditjmara (south-western Victoria), living on their country:

“(The settlers) didn't talk to them much. But they were left alone … they had a good business in the timber industry; they made ends meet” (Interview 1 2024).

This aligns with what Duncan-Kemp said: “The aborigines did not intrude upon the European—the blacks never intrude. They only asked to be left alone (Duncan-Kemp 1961 p232).

Some Aboriginal knowledge and Law are considered private, sometimes it is ‘women’s business’ or ‘men’s business’; sometimes it is only for those who had reached a certain level of knowledge, of lore (Hicks 2020). As such, white people are not privy to many customs and knowledge.

Respect for Aboriginal customs, however, was not uniform. In the early days of establishing pastoral stations, many settlers disregarded traditional laws, often leading to conflict. “*Clashes with the blacks were a very real feature in the early pioneer days, but I have not mentioned anything of them because in my day such a thing was only a very remote possibility”* (Duncan-Kemp 1961 p232). However, those who respected Aboriginal culture and practices found ways to coexist more peacefully. Alice Duncan-Kemp's writings provide valuable insights into the cooperative relationships between settlers and Aboriginal people in early 20th-century Australia. She explains that keeping harmony meant adhering to customs, and that she:

> “owed so much to our parents training and the [Aboriginal women’s] finesse, and that to sit (at night by a fire) with the blacks a friendly distance away squatting over theirs, work being over, while the exchange of small talk, taking in the daily doings black and white, is the only sure way of keeping harmony and friendship” (Duncan-Kemp 1961 p116).

Such an understanding of Aboriginal culture and Debney’s ability to read country would have enhanced local Aboriginal people’s respect for him (Duncan-Kemp 1961). These accounts suggest that settlers and pastoralists who respected Aboriginal practices were able to coexist and foster cross-cultural exchanges, at least to some degree, but the depth of friendship is unknown.

Aboriginal Knowledge

Duncan-Kemp reflects on her appreciation for Aboriginal knowledge, noting that “I am grateful to the aborigines for what I learned from them of the good earth and its harvest, of human values and of dignity and decency —and reality” (Duncan-Kemp 1961 p236). She goes on to say explain that:

> “a very important side to Mary Ann’s activities … was the office of gdanaja or herbalist … Mary Ann possessed a great knowledge of the many divisions of the flower calendar and its intricate workings … some of this knowledge she passed on to her beloved ‘mississees’” (Duncan-Kemp 1961 p210-211).

Early settlers in Australia’s rangelands probably relied on Aboriginal knowledge to navigate and survive the harsh landscape more than is reported. Alice Duncan-Kemp acknowledged this in her writings, stating, “*The natives have been a wonderful asset to the settlers, without them, progress would have been impossible*” (Duncan-Kemp 1961 p233).

This perspective is reinforced by the descendant of Walter Lake Tamblyn, who was known to go walk-about with the Aboriginal people; sharing of food and reciprocity between ‘black’ and ‘white’ were a way of surviving in harsh environments and conditions, according to this interviewee. Such accounts challenge the simplistic notion that Aboriginal people were merely passive victims of colonial expansion. Instead, they actively shaped settler experiences and, in some cases, ensured their survival.

Aboriginal people's understanding of their land made them experts at navigation, finding food and water, forecasting seasonal conditions compared to white settlers who have arrived in Australia much more recently. While settlers often imposed their own European livestock practices, some came to appreciate the traditional knowledge of Aboriginal communities, particularly in relation to land use and resource management.

'Good Kartiya'

Oral histories collected by Ross and Bray reveal that Aboriginal people remembered certain white pastoralists as 'good kartiya' (good white people), individuals known for treating Aboriginal workers fairly and predictably, and in some cases, intervening on their behalf. Ross notes that "*the non-Aborigines who treated Aboriginal people well, and especially those who were willing to intervene on their behalf, are remembered with special affection*" (Ross and Bray 1989 p63). Among the earliest remembered were Sam and Arthur Muggleton, whom Aboriginal people recalled as encouraging settlement at Frog Hollow in north-western Australia as a refuge and providing meat, after 1905 (Jack Britten, 'Frog Hollow' in Ross and Bray 1989 p28-29).

Over time, the standards for what constituted 'good kartiya' and 'bad kartiya' evolved. As more pastoralists took active steps to intervene on behalf of Aboriginal workers, positive relationships like those at Frog Hollow became more common. Meanwhile, 'bad kartiya' remained, but their level of harshness gradually declined as expectations shifted (Ross and Bray 1989 p37). These comments indicate that perceptions change over time, adding to the complexity of race relations.

Nuanced Government Relations

The relationships between Aboriginal people and Government officials in the rangelands, had similarities to those between white settlers and Aboriginal people – they were far from uniform. Police behaviour varied more than is often acknowledged. The role of outback 'Native Police' force is documented in a harrowing account by David Marr (2023), who acknowledged the violent history of some of his forebears, with names, dates and crimes committed documented in early newspapers. Other accounts discuss the role of the Native Police in Queensland (e.g. Richards 2008; Roberts 2005; Walker *et al.* 2023), and elsewhere in Australia (e.g. Foster & Nettelbeck 2012; National Museum of Australia 2025). While many officers were complicit in violence, there were instances where police intervened to protect Aboriginal people. Ross and Bray (1989) outline several examples of positive relationships from the oral histories they collected, for example: Constable Flinders, who worked at Turkey Creek from 1914 to 1918 and intervened to prevent violence (Ross 1989 p37). Likewise, in the 1930s and 1940s, some pastoralists took active steps to defend Aboriginal employees. Jimmy Klein, manager of Texas Downs, stood up for Aboriginal workers and, in one account, saved a man from being shot by a white man after a fight (Bob Nyalcas, "Jimmy Klein" and "Violet Valley walkout" in Ross and Bray 1989 p63-64).

These examples illustrate that, while the broader colonial system was built on dispossession and control, and many massacres are documented, there were individual settlers and authorities who treated Aboriginal people humanely and even with kindness. The shifting expectations of fairness and respect over time also reflect the changing dynamics of Aboriginal-settler relations, as Aboriginal people increasingly asserted their rights and demanded better treatment.

Conclusions

Historical relationships between Aboriginal people and white pastoralists were complex and diverse. While the broader colonial project involved dispossession and violence, some individual relationships – especially after the initial dispossession phase - were marked by cooperation, mutual respect, and cultural exchange. Both parties appear to have been active in building the relationships, and the Aboriginal people had some agency in creating these relationships.

Recognising these nuanced histories does not negate the injustices faced by Aboriginal communities, but it does add depth to our understanding of Australia's colonial past. Having the difficult conversations about race relations, and about our history, helps us all understand the world from someone's perspective. Respecting our cultural differences is critical for society to move forward, and to bring harmony and build resilience in communities in the rangelands and beyond.

The challenge today is to integrate these perspectives into contemporary discussions on land rights and reconciliation, moving beyond simplistic narratives to acknowledge the full spectrum of historical experiences. Further research into personal diaries, oral histories, and archival materials will be essential in painting a more complete picture of Aboriginal-settler interactions.

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Key lessons learned when supporting Indigenous scholars and communities during co-creation of knowledge

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Key words: Co-production; co-generation; participatory; ethics

Abstract

This paper addresses the call, made by Indigenous scientists and knowledge keepers, for transformative change in western science by creating a new model of science based on relationships and reciprocity (Hird et al. 2023, David-Chavez et al. 2024). This transformation focuses on the rights of Indigenous communities and Nations when they co-create/co-generate/co-produce knowledge with non-Indigenous partners. Indigenous governance of research and practice includes development of relation-based scientific models, clear data sovereignty and governance, full inclusion of communities in all aspects of the research, cross-cultural learning, and development of safe spaces on science-community teams (Hird et al 2023, David-Chavez et al 2024). Here, I describe key lessons of doing this work, reflecting on western science and Indigenous approaches, using examples from pastoral lands in Africa and Asia and non-pastoral lands in the United States.

Introduction

Western scientists encounter many challenges when 'co-producing' knowledge with communities and other societal partners, attempting to blend western scientific knowledge with the broader knowledge of traditional knowledge keepers, Indigenous scientists, policy makers, practitioners and others in society (Chambers et al. 2021, Wyborn et al. 2019, Reid et al. 2016). Many co-production (often called co-generation or co-creation) initiatives face imbalances in power concerning whose knowledge or worldview counts, who generates knowledge and how, and who has access to that knowledge. In lands where colonial powers stole Indigenous land and forcibly assimilated Indigenous cultures (as in North America, Australia, New Zealand), these power imbalances are particularly acute when Indigenous and non-Indigenous participants attempt to blend their knowledge systems today. These power imbalances also appear in western scientific institutions and academia, where 'the colonial science paradigm' often devalues Indigenous knowledge, science and practice (David-Chavez et al. 2024). The objective of this paper is to describe lessons learned when blending Indigenous and non-Indigenous participants on teams who co-create knowledge about pastoral and non-pastoral peoples and their lands in Africa, Asia and North America.

Approach: Positionality and reflection on current practice

In this paper, my positionality matters. I am a female Caucasian, non-Indigenous social-ecological scientist from the land currently called the United States. This paper is based on my experience working for 25 years with Indigenous pastoral people in Kenya, Tanzania, and Mongolia. More recently, it is based on a decade working on mixed Indigenous and non-Indigenous teams of scholars and practitioners on coproduction/cogeneration in North America. Here, I summarize lessons learned from these experiences and refer to selected published works by Indigenous scholars and practitioners, codes of ethics, and international agreements. I organize the next section according to key core values and actionable methods described in Dominique David-Chavez and colleague's *relational science model for Indigenous research* (David-Chavez et al. 2024) and Coen Hird and colleague's 'recovery guide for settler-colonial scientists' (Hird et al. 2023). I then reflect on the practice of my research teams in relation to these Indigenous models, drawing out key lessons that would deepen our current practice. Due to text limitations here, I include some additional important quotes from Indigenous and non-Indigenous scholars and a few additional selected references in Table 1. See key papers cited here as a taste of the breadth and richness of current Indigenous scholarship.

Table 1. Key quotes from Indigenous scholars and Elders and selected additional references.

Key quotes from Indigenous scholars and Elders	
Hikuroa et al. 2011 (comparing Maori traditional knowledge and western science)	'Both mātauranga Māori and science are bodies of knowledge methodically created, contextualised within a world view…. While there are many similarities between mātauranga Māori and science, it is important that the tools of one are not used to analyse and understand the foundations of another (Hikuroa et al. 2011).'
Liboiron. 2021	'Every morning when I put on my lab coat, I have decisions to make. How will we do science today? How will we work against scientific premises that separate humans from Nature, that envision natural relations as universal, and that assume access to Indigenous Land, especially when so much of our scientific training has primed us to reproduce these things?'
Watego. 2021 in Hird et al (2024)	Watego (Mununjali, South Sea Islander) writes: 'We simply don't need more texts that teach whitefullas about us on their terms'.
Hird et al. 2023	• 'Academic knowledge systems….preserve a power imbalance with Indigenous ways of knowing and being, often by omitting, misinterpreting, extracting from and devaluing Indigenous knowledges' • 'Prioritising community collaborations, relationships and trust as indicators of researcher success, as well as working with and empowering Indigenous communities to make sure they are upholding community expectations, can increase ethical science among scholars (AIATSIS 2020)'. • '….when Indigenous scholars are 'forced into roles as 'harmonisers', 'facilitators' and 'translators' to accommodate the need to bring people with us to effectively disrupt colonial norms, Indigenous scholars can experience 'translation exhaustion.' • 'Settler-scholars should realise they work on occupied lands and move past land acknowledgements, instead asking what is required of them should they want to become 'proper guests' (Stewart-Ambo and Yang, 2021).' • **'Derridean flip…:** Did that recent 'scientific' finding really prove ancient knowledge was right?' • **'Columbusing knowledges :** Claiming scientific 'discovery' of concepts, practices, species, etc., while failing to credit or acknowledge long-standing Indigenous knowledge and understandings thereof.' • 'Interrogate how your work upholds settler-colonial capitalist institutions which exist and benefit off the continued oppression of Indigenous peoples and their lands.'
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A Call for Change and the Relational Science Model for Indigenous Research

The need for transformative and profound change in western science

While there are many calls to broaden science to include interdisciplinary and transdisciplinary approaches, calls from Indigenous scholars ask non-Indigenous scientists to dig much deeper (Hird et al. 2023). They ask that western scientists recognize that their science is a construct of Western European culture and thus is only one way to create knowledge. They ask us to challenge our assumptions about the superiority of western science by recognizing that Indigenous knowledge is often the basis of western science. More specifically, they ask that western scientists ask permission whenever we work on (often stolen) Indigenous lands, treat their more-than-human research subjects as relations not objects, stop attempting to extract or assimilate Indigenous knowledges, and give full credit to longstanding Indigenous understandings. They ask us to resolve power imbalances between our knowledge systems by building equitable partnerships and uncovering how our 'work upholds settler-colonial capitalist institutions which exist and benefit off the continued oppression of Indigenous peoples and their lands' (Hird et al. 2023, p. 3). Answering this call can unleash innovation and problem solving potential (David-Chavez et al. 2024).

Commit to change: Deep listening, study, and learning

Here, Hird and colleagues (2023, p. 3) say, 'Continue to educate yourself and others, participate, and commit to working with Indigenous peoples towards an anti-colonial and inclusive science paradigm. Centre Indigenous rights as a responsibility.' In our work in Africa and Mongolia (where colonial history is different than in North America), this meant constructing, learning and working on teams with equitable participation of local/Indigenous scientists and community members. These teams were led by foreign researchers with decades of experience working with local communities as individual scientists and then on large, interdisciplinary/transdisciplinary teams (Fernández-Giménez et al. 2019, Reid et al. 2021). In North America, the non-Indigenous scientists on our teams embarked on a continual practice of deepening our understanding of settler colonialism, Indigenous knowledge/philosophy, intergenerational trauma, and extractive relationships scientists still have with Indigenous peoples. Despite these efforts, we found that we will never 'know' or fully understand, but we are clear that it is our job to educate ourselves as deeply as possible.

Integrity: 'Honor ethical responsibilities to communities impacted by research'

The first core relational value of the relational science model of Indigenous research is *integrity*. Here, David-Chavez explains: 'By explicitly centering relational values, we are emphasizing the fundamental importance of building, nurturing, and sustaining relationships between researchers and community to enable more ethical and effective science research practice…'. This value asks all researchers to 'cause no harm' and follow more formal ethical protocols (David-Chavez et al. 2024). Ethical protocols are based on the UN Declaration of the

Rights of Indigenous Peoples which include rights to equality, self-determination, self-government, liberty, security of person, secure access to traditional lands and waters, and restitution for stolen lands (UNDRIP 2007). These protocols expand on the Belmont ethical principles for transdisciplinary research (justice, beneficence, respect for persons) to include appropriate representation, self-determination, reciprocity and deference, as well as beyond-human ethics (Wilmer et al. 2021). Actionable methods include understanding and abiding by the Indigenous rights, obtaining 'free, prior and informed consent' before embarking on research, following the CARE principles (Carroll et al. 2020) and Indigenous/customary data protocols, and working with tribal advisory councils. One formal ethics code is the Australian AIATSIS Code (AIATSIS 2020); see others in (David-Chavez et al. 2024).

When working in Africa and Asia, our teams did not encounter Indigenous communities with formalized ethical protocols, and thus followed Western European-dominated ethics in these cases. I wish we had known about much of the work described here, like the engagement in ethical spaces (Ermine 2007) and the expansion of the Belmont principles (Wilmer et al. 2021). More recently, working with Alaska Native communities, we adopted the Circumpolar Inuit Protocols for Equitable and Ethical Engagement (ICC 2022) in our sustainable harvest research (Heeringa et al. 2019). In our current work with global Indigenous mountain communities, we are following the guidelines laid out in David-Chavez et al. (2024).

Respect: 'Sustain or restore Indigenous governance of Indigenous research and data'

Next, David-Chavez and team (2024) lay the foundation for fundamental change in western science by emphasizing the value of *respect.* They suggest western scientists stop extracting and assimilating Indigenous knowledges, instead deferring to Indigenous knowledges and knowledge keepers. Western scientists need to ensure Indigenous Peoples control the research process and its outputs and benefit from its outcomes. Actionable methods include listening deeply to community needs, using classic participatory action methods, uncovering barriers to community leadership, and establishing formal research agreements. Our western science approaches to co-production were deeply built on this core value. However, we did not always establish community advisory bodies. We also found 'outcome mapping' to be particularly useful where outcomes desired by community members drive the research goals (Reid et al. 2016).

Humility: 'Support opportunities for shared learning'

Humility is a third core relational value that helps 'us to observe…and support dialogue between worlds, rather than holding one above the other' (Ermine 2007, David-Chavez et al. 2024). It allows deep social learning and capacity building among researchers and communities alike. Examples of actionable methods include adaptive experiential learning through discussions during field hikes, storywork through focus groups, critical reflexivity practice, and participatory mapping.

In our work, we encouraged our graduate students to use classic ethnographic techniques to learn how to adapt their research to community needs (see Pickering in (Reid et al. 2021)). Some students arrived in an Indigenous community with a research topic based on deep reading, but then recreated their research topic and methods after months of consultation and multiple seasons working with community members. Also, in my experience, this is the most exciting and rewarding part of flipping the classic western science model, where I have found the deepest learning and most profound innovation.

Reciprocity: 'Ensure research process, outputs and outcomes benefit community'

A fourth core relational value is *reciprocity*. David-Chavez and team (2024) describe how research can ensure Indigenous communities are primary beneficiaries of research process, outputs and outcomes. Key actionable methods here include developing formal community research governance roles (e.g., community advisory groups); sharing funding equitably; and adopting Indigenous methodologies including data governance protocols (which control the collection and application of data about Indigenous lands and peoples). They also involve engaging Indigenous youth who will be future stewards of the land (see (Pickering Sherman and Sherman 2010)); community review of raw data and discussions of interpretation; Indigenous authorship of outputs; providing accessible data and outputs that are desired by Indigenous communities; and partnership benefits like workshops with story sharing/focus group discussions and local presentations.

These approaches are where the western science model of co-production, when implemented fully, most resembles David-Chavez and team's model. In our work in Africa, we flipped the usual approach to western science so that it was not driven from the needs of the researcher's intellectual development or an outside institution, rather it was driven by the needs of the community our research sought to serve (Reid et al. 2016, Reid et al. 2021). Of course, this approach applies more broadly than work with Indigenous Peoples alone, and includes our approach with communities of fish or trees, policy makers or farmers, and others. From a western science perspective, this means developing the focus, questions, methods, protocols of the research, data visualization, interpretation and products with Indigenous communities. It means spending significant time in community before finalizing the research topic to have many community consultations to ensure that research outputs and outcomes benefit the community. It can also mean aiding Indigenous Peoples as they serve as guardians for our more-than-human relatives. We also collected information together with and under the advice of community members. We interpreted what we found and designed and co-authored outputs together (journal articles, films, policy briefs, stories, etc.). We also discussed and anticipated possible short- and long-term outcomes and impacts and planned for them. Our graduate students often focused their efforts on initial community consultations and then returning results in feedback workshops (Reid et al. 2021).

A last key lesson: Do the hard work of providing safety for all involved

Finally, one the of the most important actions for western scientists to take is to stand up when non-Indigenous scholars are offensive to Indigenous scholars. This is particularly important when speaking up is hard to do. In our work, we faced this need when a western scientist colleague lashed out when they were asked to listen and no longer dominate. It also occurred when a powerful scientific institution removed an Indigenous colleague from a national committee when they spoke out about inappropriate consultation with Native American tribes (Mervis and Ortega 2024). Doing so not only provides support to Indigenous colleagues and community members, but also relieves them of the burden of speaking out themselves. Our current team practice is to work with indigenous facilitators to ensure safe cross-cultural interactions among our scientific team and agree on and adhere to joint community values for all our work.

Conclusions/Implications

In my view, co-production/braiding of knowledge among different knowledge systems is a pathway to begin to repair past and current harms caused by our approach to western science. It also unlocks great problem solving potential. The deep trauma caused by colonization (and western science approaches) created the dire need to establish ethical standards for all interactions of non-Indigenous scholars with Indigenous scholars. These wise values and methods could be applied, in principle, to interactions with all Indigenous and local peoples, including pastoral peoples. As such, 'business-as-usual' in western science is now old thinking, thanks to the leadership of a new generation of Indigenous scholars and their supporting communities.

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International cooperation to improve forage supply in grasslands in Kenya and Tanzania

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Key words: international project; participatory strategies; livestock production; pasture management; Arid and Semiarid Lands.

Abstract:
Grasslands and savannas cover a significant area of the earth and are home to much biodiversity and livestock, including cows, goats, sheep, and other animals. Livestock production in these ecosystems is characterized by a low supply of forage mainly due to advanced erosion processes, overgrazing, shrub invasion, lack of availability of quality grass seeds and the concomitant decline of palatable species. The purpose of this paper is to describe the exchanges and highlight the potential for collaboration for the construction of knowledge, in science and technology, focused on livestock production in the arid and semi-arid zones (ASALs) of Kenya and Tanzania. Between 2017 and 2022, a bilateral technical cooperation project promoted by the Argentine Fund for International Cooperation (FO.AR) was carried out called: "Improvement of livestock production in arid and semi-arid areas of Kenya". The activities of this project focused on the participatory identification of the main constraints affecting smallholder livestock production. The project involved Kenyan researchers, extension workers, national and county government livestock officials, and livestock producers. Since 2020, different Tanzanian institutions (Ministries) have resumed their relationships with Argentine cooperation agencies to participate in several training proposals to improve the supply of forage for livestock systems in Kenya and Tanzania. During the project, six missions were carried out, four from Argentina to Kenya and two from Kenya to Argentina, in addition to participatory workshops for the identification of constraints and proposals for strategies to address these constraints. The German government, which has a presence in the two African countries, had shown interest in these activities and in 2022 a new project was approved: "Strengthening capacity building to improve smallholder farming livestock systems and contribute to agri-food sustainability in Kenya and Tanzania". This project is financed by Germany and is executed by the following institutions: Kenyan Ministry of Agriculture, Livestock, Fisheries and Cooperatives, Tanzania Ministry of Livestock and Fisheries, Argentine Agency for International Cooperation and White Helmets Humanitarian Assistance (National Directorate of International Cooperation), Ministry of Foreign Affairs, International Trade and Worship; Ministry of Agriculture, Livestock and Fisheries; the National Institute of Agricultural Technology (INTA), the Tanzania Livestock Research Institute (TALIRI) and the Kenya Agriculture and Livestock Research Organization (KALRO) and livestock producer organizations at provincial and/or municipal (county) levels.

Introduction
Savannas and grasslands occupy a fifth of the earth's land surface witha large human population, and livestock and wild herbivores inhabit these biomes. Grasslands are known as seedbeds for the ancestors of cereal crops and the domestication of cattle, donkeys, goats, and sheep. Grasslands have been largely considered as a carbon reserve (Curtin and Western, 2005) and are highly dynamic ecosystems because of variable rainfall, soil nutrient levels, fire and herbivory (Rutherford et al., 2012). Grassland states vary from sites with a range condition with ample herbaceous cover, perennial grasses and scattered trees to states with a poor cover of annual grasses, absence of perennial and palatable grasses, a high proportion of bare soil and/or often bush encroached (Rutherford et al., 2012).

In arid and semi-arid lands (ASALs), where the climate is less suitable for crops, pastoralism is the main livestock system and occurs in 40% of Africa's terrestrial area (ILRI, 2021). Pastoralism contributes between 10 and 44% of the gross domestic product (GDP) of African countries with approximately 1.3 billion people benefiting from the livestock value chain. Also, over 75% of cattle herds in Kenya and 90% in Tanzania are kept by pastoralists who supply the bulk of meat consumed in those countries (Nyariki and Amwata 2019). Cattle production of small farmers in ASALs in Kenya and Tanzania and Arid and Semiarid Chaco regions in Argentina present common production and social features, for example, the lack of forage, the loss of native palatable grasses and forbs, the increasing area of bare ground, and bush encroachment caused mainly by overgrazing, deforestation and rainfall variability (Mureithi et al.2015).

The trajectories of knowledge development, including tacit and scientific knowledge, when shared, allows an accelerated knowledge growth amongst all the actors involved, facilitating learning about strategies to overcome common constraints. The approach focuses on the "win-win" strategy, where everyone learns from each other's experience.

In 2017, an international cooperation strategy began with the aim of improving livestock production which includes two stages, a first that reached until 2023, linking Argentina and Kenya, in a project founded by the Argentinian Fund for International Cooperation, with the main objective of exchanging experiences in research and extension, technology transfer and training in grazing management and animal nutrition contributing to security and food sovereignty, while taking care of the available natural resources.

At the end of 2023, a second stage in cooperation began with the start of a second project, founded by the German International Cooperation Agency (GiZ), linking Argentina, Kenya and Tanzania, with the main objective of strengthening the technical capacity necessary to increase meat and milk production in livestock systems of smallholder farming.

Methods
The methodology consists of:

1) International missions where key people visited INTA Agricultural Experimental Stations (EEAs), research centrs of the Kenyan Agriculture and Livestock Research Organization (KALRO), research centres of the Tanzanian Livestock Research Organization (TALIRI), farms, companies producing fodder, pasture seeds, balanced feed and companies for the manufacture and maintenance of agricultural machinery and tools..

2) Face-to-face workshops with farmers, researchers, extensionists and public policy decision-makers, to identify constraints and challenges of livestock production systems and identify strategies to overcome them.

3) Virtual workshops with researchers and extension workers from the countries involved working cooperatively dealing with specific topics of livestock production of ASALs aimed at sharing technological proposals.

4) Meetings with public policy decision-makers in the field of livestock production of ASALs.

5) Implementation of demonstration plots with appropriate technologies for forage management.

Results

From 2017 to 2023, a first cooperative project was carried out between Argentina and Kenya, seven missions were carried out, four from Argentina to Kenya and three from Kenya to Argentina. Visits to KALRO, farms, machinery workshops and enterprises dedicated to produce balanced foods were made in Kenya. During the visits to Argentina, EEAs (spell out) and Research Institutes of INTA and private farms were visited. In addition, both during the visits to Kenya and Argentina, meetings were held with public officials from the livestock areas of the provinces and counties visited. These exchanges aimed to know and understand the challenges of the livestock producers of the ASALs, the technological developments of the science and technology institutions aimed at overcoming these challenges and the strategies developed by the private sector.

Two participatory workshops were held, the first in 2019 in Isiolo city in Kenya, to identify the main restrictions, opportunities and solutions that arise in livestock production in the ASALs of Kenya. Thirty-seven people participated and they identified the following restrictions: overgrazing, high stocking rate, bush encroachment, land degradation and land use change, non-implementation of grazing management plans, droughts and water scarcity, inadequate water harvesting structures, deforestation, weak connection between extension services and research activities, inadequate marketing information system, insecurity, competition for resources and poor intercounty linkages.

A second workshop was held in the frame of the GiZ founded project during November 2024 in Arusha city in Tanzania, to identify the main appropriate technologies to promote the improvement of the forage supply for pastoralists' and smallholders' livestock systems in the arid and semi-arid areas of Tanzania. Twenty-seven people participated. The methodology implemented was a foresight analysis and it was discussed that the main technologies should be oriented towards well defined land ownership by individuals, groups or company, developing of climate-smart approach technologies, effective invasive species strategy control, effective control of soil erosion, increased production of pasture seed and the development of water infrastructure for livestock.

Two virtual workshops were held with broad participation of researchers and extension workers discussing and analysing strategies to improve livestock systems in the ASALs of Kenya and in the Arid Chaco region of Argentina. Seven INTA research centres in Argentina in different provinces, three KALRO research centres in Kenya and the International Livestock Research Institute(ILRI) in Nairobi, and two Tanzanian Livestock Research Institutes in Tanzania were visited during the virtual workshops.

The design of two experimental-demonstration plots and its location were defined in the last mission made in November 2024 by the technical team of the three countries. The productivity (biomass) and seed production of 4 native species will be determined: Bush rye (*Enteropogon macrostachyus)*, Maasai love grass (*Eragrostis superba*), Horsetail grass (*Chloris roxburghiana*) and Foxtail grass (*Cenchrus ciliaris*). Also, an experiment to assess the effect of bush clearing by two methods was designed including 3 treatments: a) Control, without intervention: b) Manual bush removal and c) Mechanical treatment for shrubbing. The analysis of the investments, labour and administrative aspects were managed by the technicians with the support of personnel from GIZ. The plots were closedto domestic and wild animals, and have different areas.

Discussion

The characteristics of livestock farming in the ASALs of Kenya, Tanzania and the Arid Chaco of Argentina are similar, both from the natural conditions, the social actors involved, and the restrictions and challenges faced, although their historical trajectories are very different. Technological developments are similar, although with particularities in each country, which allow mutual learning by sharing experiences. While in the two African countries research and extension activities are separated between different institutions, in Argentina both are within the same institution, which favours dialogue and exchange. The exchange of experiences, discussion and analysis of strategies with practical learning in the visualization of the technological trajectories followed by each of the countries to achieve the resolution of common problems, is highly valued and tends to accelerate the process of development of technologies and its application in livestock systems.

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Collaborations for rangeland restoration and conservation

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Increasing rangeland resilience through collaborative, climate-adaptive, community-engaged rangeland restoration with the Ute Mountain Ute Tribe in Southwestern Colorado, USA

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Key words: community-based restoration; Indigenous peoples; ecological restoration; climate adaptation; seed-based restoration

Abstract
Seed-based restoration of degraded landscapes in dryland systems often fails to result in desired revegetation. Locally specific strategies are needed to overcome barriers to native plant establishment. To meet these challenges, we convened a collaborative team that emphasises relationship building, including scientists from the United States Geological Service (USGS), Colorado State University (CSU) and CSU Extension (CSUE) at the request of Ute Mountain Ute Chairman Heart to bring restoration research to Tribal lands in southwestern Colorado, USA. Our team has continued to focus on restoring ecosystem structure and function, improving productivity for grazing and ensuring access to cultural resources.

In 2020, collaboration with the Ute Mountain Ute Tribe (UMUT) began, and two experimental sites were established: a USGS RestoreNet (Field Trial Network for Dryland Restoration) plot and a culturally important location for hyperlocal seed-based restoration questions and treatments rooted in Indigenous knowledge systems. In the first phase, we explored local challenges and tested innovative approaches, informed by community input, Western scientific literature and traditional ecological knowledge. Using an intentionally scaled approach and rigorous scientific methods, the sites test climate-adaptive restoration treatments in 4-m^2 plots including ground modifications, seeding vs. outplanting seedlings, herbicide treatments to suppress invasive species, and others.

Preliminary results show effective restoration strategies include imprinting the landscape with pits, outplanted restoration islands and the importance of integrated invasive species management. Equally importantly, we have built relationships and met Tribal needs through education and outreach.

Since 2020, we have gained insight into the challenges and successes of working collaboratively across a land-grant university, tribal government, governmental institutions and other community groups. By honouring different perspectives and expertise, we are creating actionable science and building relationships essential to the restoration, future grazing and long-term health of arid systems on Tribal lands.

Introduction

Arid and semiarid (dryland) ecosystems cover roughly 40% of the earth's land surface, provide critical ecosystem services and are increasingly prone to degradation associated with climate change (Hoover et al. 2020). Following degradation, recruitment of native plants through natural recovery is often unsuccessful. Similarly, seed-based restoration in dryland systems often fails to result in desired revegetation (Shackelford et al. 2021). Barriers to native plant establishment from seed include water limitation, extreme temperatures, depleted soil and competition with invasive species (Shackelford et al. 2021). Acknowledging these challenges, we sought to explore reasonable treatments that could be applied at scale when attempting to restore lands in dryland ecosystems.

On Tribal lands, the challenges to restoration are exacerbated by the reduction of Indigenous peoples' sovereignty, land dispossession, ongoing displacement, oppression and heightened climate change vulnerabilities (Archuleta et al. 2015, Farrell et al. 2021). Recognising the multifaceted barriers to restoration, the team decided to investigate active restoration techniques on a small scale that could be practical and applied at the large scale needed for the region on rangelands. Locally specific, culturally informed and scientifically grounded strategies are needed to develop appropriate and effective restoration approaches (Wickham et al. 2022).

To meet these challenges, at the request of UMUT Chairman Heart to bring restoration research to Tribal lands in southwestern Colorado, we convened a collaborative team that emphasises relationship building, starting in 2021. This team includes staff from UMUT Environmental Programs, the Dryland Ecology and Management Lab at CSU, CSUE, and the United States Geological Survey (USGS) RestoreNet team. Building on the networked trials from the USGS RestoreNet team, we were able to install a RestoreNet research site incorporating treatments of interest to UMUT Environmental Programs staff to meet the needs of their restoration goals, that are appropriate for the environment and community cultural values (Laushman et al. 2022, Long et al. 2020). As we collaboratively developed potential treatments, we kept the goal of increasing forage for livestock grazing and the practical application of treatments in mind so successful treatments could be scaled in the future. Project collaborators were also able to openly communicate about the needs for staff funding and labour to make this project possible.

As the 10-year RestoreNet project continues, our team and projects have expanded beyond our initial rangeland restoration project. Building on RestoreNet, a second experiment site was established in 2022, at a culturally important location to test additional hyperlocal seed-based restoration questions and treatments rooted in Indigenous knowledge systems.

Methods

Frameworks and principles for collaborative restoration projects with Indigenous peoples

The collaborators in this project came with various levels of experience and expertise in working with traditional ecological knowledge, rangeland restoration, Land Grant Universities and/or Tribal Nations. We have looked to team members' experience as well as others who have demonstrated successful collaborations addressing ecological restoration and specifically collaborative projects with Tribal Nations (Wickham et al. 2022, Long et al. 2020). This project is one of many that are partnering U.S. academic institutions and government agencies, as well as their policies, protocols and scientific bodies of knowledge, to support the sovereignty and implementation of Indigenous knowledges. Throughout the project, the aim of researchers embedded in U.S. institutions is to provide resources and expertise while following the lead of the UMUT's community members and staff. By honouring and weaving these different ways of knowing, we work towards repairing relationships between human and ecological functions (Robinson et al. 2021).

Relationship building and goal setting

Building relationships and establishing new collaborative research projects has, in our experience, taken time and required consistency in the people and entities involved. CSU/CSUE staff's initial collaboration with the UMUT on rangeland restoration projects was due to chance meetings, planned organisational meetings, community listening sessions and persistence from both sides. These relationship-building efforts are what brought Chairman Heart to an online stakeholder meeting hosted by local, regional and on-campus CSU faculty introducing the idea and gauging community interest in a land restoration project. This meeting was followed by an in-person site tour and then a request to bring dryland restoration research to UMUT land (Laushman et al. 2022).

From ideas to implementation

Translating ideas to implementation would not have been possible without dedicated Tribal collaborators who continue to engage with this project and navigate Tribal approval processes. From the beginning, clear communication and expectations ensured we were able to meet each other's needs. Additionally, a data-sharing agreement to protect and describe when data could be shared or used between partners was a critical aspect of project development and ensuring findings from Tribal lands were shared in a manner that respects Tribal sovereignty.

Leveraging a regional restoration field trial network (RestoreNet) to meet local needs

First, in 2021, local, regional and on-campus faculty from CSU/CSUE and the Tribal staff collaborated with the USGS to establish a RestoreNet site (Havrilla et al. 2020, Laushman et al. 2022), a distributed dryland restoration field trial, on UMUT Tribal land to test restoration treatments of interest. Using an intentionally scaled approach and rigorous scientific methods, the sites test climate-adaptive restoration treatments in 4-m^2 plots including ground modifications, seeding vs. outplanting seedlings, and other locally identified treatments of interest including *Tamarisk sp.* (saltcedar, a common invasive tree in the area) mulch and polymer beads. As a large-scale networked restoration trial network RestoreNet, led by USGS in partnership with universities and a variety of research partners, tests consistent treatments across environmental gradients but also allows for additional local questions. A desire to ask additional hyperlocal questions outside the RestoreNet framework at a slightly more mesic site led to the establishment of a second experiment.

Place-based restoration trials at a culturally important site

Second, we established a separate field site for restoration research at a culturally important location to test additional hyperlocal seed-based restoration questions and treatments rooted in Indigenous knowledge systems. Treatments at this site included the use of locally available materials left over from cultural harvest practices, and low-tech rock structures rooted in Indigenous knowledge to slow and spread water (Martin et al. 2010). The strength of this project has been a focus on local placed-based treatments and culturally relevant practices valued by members of the team and the communities in which they live.

Results

RestoreNet

Preliminary results from the RestoreNet site demonstrate that imprinting pits (modelled after waffle gardens used by Indigenous peoples across the Southwest) and covering the soil with mulch have increased seed germination. These two techniques increase water retention and soil nutrient availability. Further, seedlings that were grown in a greenhouse, then outplanted to the site show promise, as a higher percentage of these seedlings have survived and flourished over the three years since the site was established than seeded species. This result indicates that restoration islands, a technique in which small groups of seedlings are planted, then self-seed to increase the native plant community, may be beneficial for restoration in the area (Davies et al. 2020).

Place-based restoration

While seeded species recruitment has been limited, this site has emphasised the need to consider integrated invasive species management as an essential aspect of restoration work at this location of cultural importance. Of the treatments tested, low-tech rock structures that slow and spread sheet water flows and coarse woody debris that creates favourable microclimates at the soil surface seem to be the most effective.

Meeting local needs

Through these projects, we have also gained insights on collaboration, building trust and respecting the many ways of knowing. We have learned that thoughtful consideration can make implementing new ideas more successful. Ensuring all partners are invited to participate throughout a process including in the planning process, implementation on site and to provide feedback as a plan is developed, ensures an investment and sense of ownership in the project's long-term success.

As a result of trust building, sharing and discussing results, we have also created interest in larger-scale studies and projects that can take what we have learnt and apply it at scale, leveraging what we have learnt about treatments and species success to be more successful with future restoration projects. Also, building relationships and discussing local needs led to the development of different types of collaboration to address further needs related to rangeland health and management. Through collaboratively organising educational workshops for ranchers or sourcing funding for rangeland monitoring, collaborations stemming from one rangeland research project have grown to include multiple projects to meet many different community-based goals.

Discussion

Since 2020, we have gained insight into the challenges and successes of working collaboratively across a land-grant university, Tribal government, governmental institutions and other community groups. By honouring different perspectives and expertise, we are creating actionable science and building relationships essential to the restoration, future grazing and long-term health of arid systems on tribal lands.

The continued efforts of many individuals led to effective working relationships. From this foundation, we can continue to further expand projects to meet the rangeland restoration needs of the Tribe. We can also reflect on our successes and struggles to continue to improve working relationships, community outreach and understanding the strengths that come from respecting many ways of knowing and the many ways we can understand, relate to and value rangelands.

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Knowledge co-production between herders and scientists for the better management of species-rich pastures

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Abstract
The substantial research gap between rangeland/livestock science and conservation biology/vegetation ecology has led to a shortage of evidence needed for grazing-related conservation management. Knowledge co-production and long-term knowledge partnerships between scientific and traditional knowledge could help fill this gap. We worked closely with traditional herders in Hungary (including co-design and co-publication) on understanding grazing behaviour of beef cattle on species-rich grasslands. We found that cattle grazing on species-rich pastures displayed at least 10 different behavioural elements as they encountered 117 forage species from highly desired (preferred) to rejected, with small discrimination error. Herders had broad knowledge of grazing desire and they consciously aimed to modify desire (modify selection behaviour, grazing preference) by slowing, stopping or redirecting the herd. Many of these have conservation benefits. We also prepared a global review on forage-related knowledge of herders based on scientific papers and video documentaries, and collaboratively discussed with traditional herders. We found 35 indicators used by herders to describe forage species. These indicators were used in context-specific management decisions, with a variety of objectives to optimize grazing.

Introduction
The substantial research gap between rangeland/livestock science and conservation biology/vegetation ecology has led to a shortage of evidence needed for grazing-related conservation management. Connecting scientific understanding with traditional ecological knowledge of local livestock keepers through knowledge co-production and knowledge partnership could help bridge research and knowledge gaps (see some example: Barani 2007, Biró et al. 2019, Reid et al. 2014, Schlecht et al. 2006).

An understanding of traditional ecological knowledge systems is increasingly acknowledged also as a means of helping to develop global, regional and national, but locally relevant policies (Sharifian et al. 2021, 2023). Pastoralists often use lands that are unsuitable for crops due to biophysical and climatic extremities and variabilities (Krätli and Schareika 2010, Manzano et al. 2021). Forage plants of pastures that are often unpredictable in availability (Molnár et al. 2020, Sharifian et al. 2023), are utilized by herding communities by applying locally relevant multigenerational knowledge. In this presentation we will show our study of the grazing behaviour (plant selection and avoidance) of beef cattle on species-rich lowland pastures in Central Europe (Molnár et al. 2020), and a global review of the forage-related knowledge of pastoralists and herders and how this knowledge is used in herd and pasture management (Sharifian et a. 2023).

Methods

We studied the grazing behaviour (plant selection and avoidance) of beef cattle (ca. 33 000 bites) on species-rich lowland pastures in Central Europe, as well as the related traditional herding practices. We also did >450 outdoor interviews with traditional herders about livestock behaviour, herders' decisions to modify grazing behaviour, and effects of modified grazing on pasture vegetation. The whole multi-year research was done in close collaboration with several key knowledgeable herders, starting with co-design of the research, doing data collection and data analysis and discussion together and finishing with co-publication (papers and conference presentations).

In the other study we analyzed the forage-related knowledge of pastoralists and herders by reviewing scientific papers (based on keyword search) and video documentaries (searching on the internet through keywords and directly contacting specialist researchers) with the original voices of herders on forage plants and indicators, their use in land management, and plant-livestock interactions. Semi-structured interviews were also conducted with key knowledge holders in Iran, Mongolia, Kenya, Poland and Hungary. The key results and conclusions were discussed again with two key knowledgeable herders before publication. We found 35 indicators used by herders to describe forage species and manage herds and pastures.

Results

We found that cattle grazing on species-rich pastures displayed at least 10 different behavioural elements as they encountered 117 forage species from highly desired (preferred) to rejected (Fig. 1., Molnár et al. 2020). The small discrimination error suggests that cattle recognize all listed plants 'by species'.

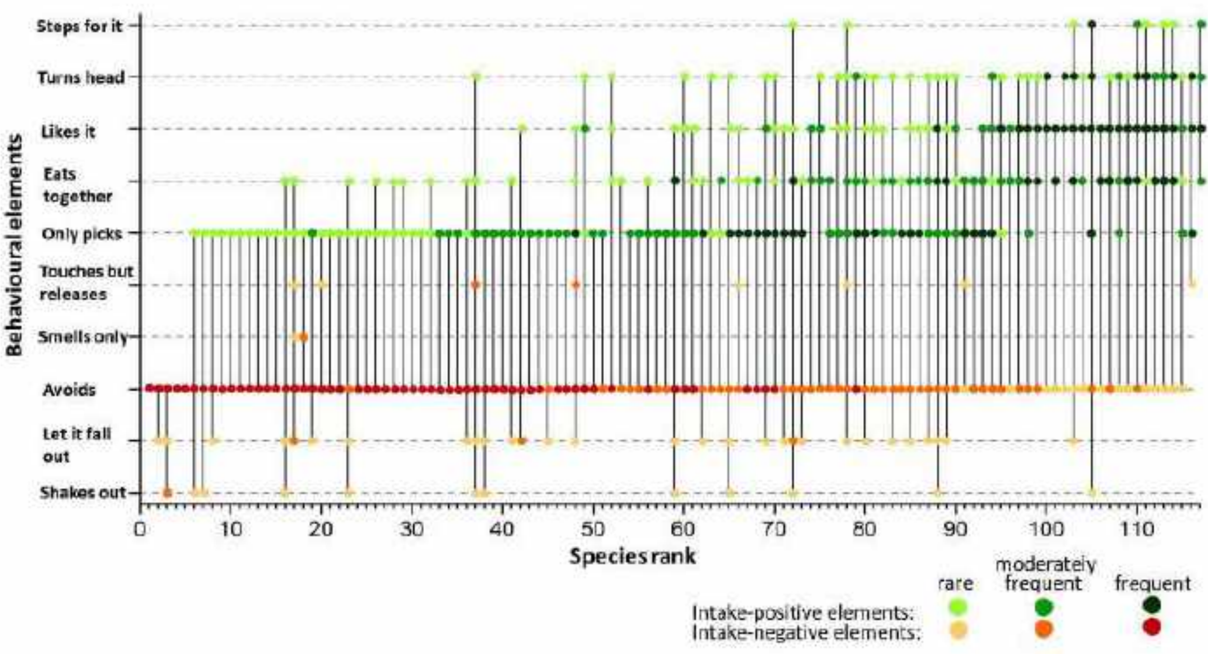

Fig. 1 Frequency of behavioural elements toward 117 plant species. Species were ordered from left to right according to their ranks based on their desirability index (proportion of intake-positive types, in %). Coloured dots indicate frequency of behavioural elements (from light (rare) to dark (frequent)). Dots of the same plant species are connected with a thin vertical line.

We also found that herders had broad knowledge of grazing desire and preference, and they consciously aimed to modify desire (selection behaviour on the short- and long-term) by slowing, stopping or redirecting the herd. Modifications were aimed at increasing grazing intensity in less desired patches and decreasing grazing selectivity in heterogenous swards. Many of these have significant conservation benefits (Table 1).

Table 1 Conservation relevant herding techniques of traditional herders in Central Europe used to control grazing behaviour, animal distribution, modify intake of livestock, change selectivity of grazing, and protect the forage resources on their pastures (frequency of application: ***: used often, *: used rarely).

Traditional herding techniques to control grazing behaviour	**Freq. of use**	**Conservation relevance of traditional herding techniques**
Attention to livestock, keep monitoring them for prompt and proper interventions with the least possible stress	***	Fine-tuned livestock-herder-pasture relation is the basis for proper management
Protecting the pasture from unnecessary disturbance and promoting regeneration after a grazing period	**	Herders consciously protect pasture vegetation according to their indicators
Designing daily 'menu' (sensu Meuret 1997, Meuret and Provenza 2015) along the grazing route (sequence of foods to maintain and boost appetite, and increase desirability of less preferred forage species)	**	Designed menus help utilize the pasture evenly, animals move less and fatten better (cf. profit) (leads to lower grazing pressure)
Letting them spread and graze calmly	***	Movement and trampling are decreased, smaller disturbance to breeding birds
Selecting an area to be grazed during its highest desirability status, depending on season and weather	**	Utilizes less preferred parts of pasture, often improving its forage quality
Block movement of the herd, or just slow them to get them satisfied with the less preferred forage of the patch, eat mixed forage	***	Less selective grazing results in more homogenous utilization and can prevent spread of pasture weeds
Targeted grazing of less-desired, less preferred forage species, improving pasture by grazing	***	Prevents accumulation of litter, and suppresses bushes and tall plants (like *Phragmites, Typha*)
Increasing willingness to graze less selectively and more intensively by shortening a meal from 4-5 to 1-1.5 hours	*	Less selective grazing (more homogenous utilization, and management of pasture weeds)
Move them faster (towards watering / resting places) to prevent excessive grazing trails	*	Too many grazing trails could cause degradation (spread of weeds)

In the second study we identified indicators herders use to understand the forage plant-livestock-herder relationship and to manage herds and pastures. The indicators of forage plants described botanical features, livestock behavior during grazing, and the impact of plants on livestock condition and health (Table 2). The indicators were used in context-specific management decisions, with a variety of objectives to optimize grazing. We identified ten global principles: 1) Livestock-centered perspective of forages; 2) Close monitoring and prediction of forage quantity and quality; 3) Use (targeted grazing) of plants with medicinal and good nutritional properties to improve livestock status and health; 4) Inner need for responsibility of the herder in modifying livestock's forage selection and intake; 5) The livestock is herded but to a certain degree it is allowed to play a decisive role in forage selection, place of grazing; 6) Using different livestock types to make use of various forage resources; 7) Making use of 'all' plant resources, through understanding and utilizing relative and changing palatability; 8-9) Adapting to changing forage availability by proper timing of grazing at multiple temporal, and at multiple spatial scales; and 10) Keep focusing on context-influenced change of forage preference and intake (Fig. 2).

Table 2 Indicators used by traditional herders and pastoralists to describe forage plants in different parts of the world, number of local indicators found, and number of countries where these indicators were documented (indicators were grouped, see bold categories).

Indicator	**No. of local indicators**	**No. of countries**
General valuation (good forage, bad forage)	590	12
Types of livestock that eats is	362	14
Nutritional value	244	17
Seasonal variation	187	12
Only parts are eaten	174	10
Human factors	127	6
Scarcity fodder	117	14
Availability	115	8
Animals like or dislike it	102	12
General	98	10
Prevents/cures disease	49	5
Appetite	41	4
Physiological stage	37	5
Sensitivity	35	6
Morphological characteristics	35	9
Method of preparation	33	2
Habitat	32	9
Population trends	23	4
Causes disease	19	7
Animal product quality	17	7
Stress	15	1
Plant herbage yield	13	2
Hay quality	13	3
Chemical content	10	9
Taste	10	7
Causes injury	9	7
Regrowth, resprouting	8	5
Plant size	8	5
Grazing behavior	5	5
Host to harmful species	5	4
Smell	4	2
Colour	3	5
Interannual variation	2	3
Feeding behavior	2	1
Plant gender	1	1

Fig. 2 A) Hungarian herders point out "*I see the grass through the mouths of my animals*" (Molnár, 2017) which is similar to the observation of a French shepherd as described by Despret and Meuret (2016), that "*his* [the shepherd's] *fingers know and anticipate what the sheep's mouths know*". Both statements, though from herders situated in different countries and herding regions, accentuate the fact that herders' knowledge is partially gained through the close monitoring of the relationship between their animals and the forage. B) Hungarian herders say "*Tippan* (small tussocky *Festuca pseudovina* grass) *is the soul of the Hortobágy steppe!*", which is very close to the observation made by Mongolian herders living 6000 kilometers away who perceive that "*Botjul* (small tussocky *Festuca lenensis* grass) is the best grass that my livestock can find to feed on in Mongolia" (Gantuya et al. 2019, 2021).

Discussion and Conclusions

The traditional herd management practices, presented here, have significant conservation benefits, such as avoiding under- and overgrazing, and targeted removal of pasture weeds, litter and encroaching bushes, tall competitive plants and invasive species (Molnár et al. 2020, Sharifian et al. 2023). We argue that knowledge co-production with traditional herders who belong to another knowledge system could help connect isolated scientific disciplines especially if ecologists and rangeland scientists work closely with traditional herders, co-designing research projects and working together in data collection, analysis and interpretation. Stronger links between these disciplines could help develop evidence-based, specific conservation management practices while herders could contribute with their practical experiences and with real world testing of new management techniques (Molnár et al. 2016, Török et al. 2016, Vadász et al. 2016).

Although pastoralists vary greatly across the globe, the character and use of their traditional forage-related knowledge do seem to follow strikingly similar principles. Understanding these may help the local-to-global-level understanding of these locally specific systems, support bottom-up pastoral initiatives and discussions on sustainable land management, and help to develop locally relevant global and national policies.

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Protection of sacred springs in South Australia's rangelands

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Key words: partnerships, First Nations, mound springs protection

Abstract

Bubbling up from Australia's Great Artesian Basin, mound springs are unique lifelines across the rangelands and are of great ecological and cultural significance. For the Arabana and Dieri people, mound springs are central to their culture, and have sustained life in South Australia's desert lands for thousands of years. In partnership with volunteer group Friends of Mound Springs, Brook Pastoral Company, Dieri Aboriginal Corporation, and the South Australian Arid Lands Landscape Board (SAAL Board) a joint project has had positive outcomes for the culturally important Reedy Springs and St Mary's Pool on Murnpeowie Station on the Strzelecki Track.

Early engagement with all groups in a genuine partnership approach included involvement from initial ideas to co-design, planned works, site visits, and on-ground works. A 2.45 km fence was installed to protect the 42-hectare spring group, expanded to protect the springs as well as new cultural sites identified by Dieri people during site visits. In addition, fencing was also installed to manage vehicle access to a nearby waterhole. Knowledge has been shared on cultural and ecological values of the springs and ongoing monitoring will continue using the same collaborative approach.

Kokatha Aboriginal Corporation were contracted to complete the fencing works, further supporting First Nations employment and participation outcomes and a rich cross-cultural exchange. The Board is working with Arabana Rangers and Arabana Elders, along with FOMS, on opportunities for springs projects on their Country and will consult with other First Nations groups for new projects.

Introduction

South Australia's rangelands contain around 5000 mound springs, which are natural outlets for water from the Great Artesian Basin (GAB), one of the world's largest underground aquifers (Lewis et al. 2013). The mound springs have high ecological value, supporting unique and endemic plant and animal species, while also being culturally significant for Aboriginal people (Beasley-Hall et al. 2024, Hercus & Sutton, 1985). In South Australia, native title groups whose country covers the mound springs includes Arabana, Adnyamathanha, Yankunytjatjara/Antakarinja, Dieri, Yandruwandha/Yawarrawarrka, Wangkangurru/Yarluyandi, and Kokatha (National Native Title Tribunal, 2024).

For more than 40,000 years the springs have been vital sources of water in the arid environment, supporting periodical occupation during suitable conditions, and are linked to cultural stories, trade routes, ceremonies and sites of cultural significance (Brake et al. 2019). For example, for Arabana people, kutha ngarrawa (mound springs) are a central theme in their culture and the stories that connect Arabana people to their Country (Government of South Australia, 2017, Nursey-Bray & Arabana Aboriginal Corporation, 2015). Arabana are concerned about maintaining Wadlhu Ngurrku-ku (Healthy Country) with kutha ngarrawa providing water and resources, as well as being sites of ceremony and trade routes (Government of South Australia, 2017).

Following pastoral settlement in South Australia, the location of the springs shaped key infrastructure routes, such as the Overland Telegraph line and the Ghan railway (Harris 2002). Across the GAB, springs are under threat from reduced artesian pressures as a result of excess water extraction and uncontrolled bores, and due to physical disturbance of spring structure and dependent ecosystems through grazing, trampling and increased nutrients (Keppel 2022). In the South Australian rangelands, efforts are underway to mitigate these impacts and improve conservation and management of the springs, but meaningful engagement with First Nations, pastoral land holders, volunteer group, industry and government is required if springs management is to be successful.

Methods

In 2022, the SA Arid Lands Landscape Board (SAAL Board) received funding from the Lake Eyre Basin (LEB) Program (a federal program with funding from all LEB jurisdictions), and in 2023 from BHP mining company, with stipulation to deliver projects involving the protection of sites of ecological or cultural importance within the Lake Eyre Basin, which include mound springs.

Site selection - The need for multi-stakeholder involvement for springs management was identified early. Given the large number of springs in South Australia, the SAAL Board first approached Friends of Mound Springs (FOMS) for assistance in identifying suitable springs for protecting. FOMS is a volunteer group with members who have extensive knowledge of South Australian springs, their management history and condition, and have established relationships with First Nations groups.

After FOMS identified potential sites on Dieri and Arabana Country, consultation commenced with pastoral land holders and Dieri and Arabana, to establish which springs might be viable based on all groups' agreeance. The engagement process followed the guidelines in the SAAL Board's Communication and Engagement Strategy (SAAL Board, April 2022). Landholders were approached to gauge interest in participating in springs management and involved a site visit to confirm current conditions and the potential management options. While numerous sites were identified, the complexity of the site for management options (where stock water points, long-term management and spring topography were considered) and landholder interest in the project within the funding timeframe, meant the number of springs as option for the project, were reduced.

Following discussions with Dieri and Arabana, the scope of the project was refined to sites where fencing was deemed a suitable method for springs protection. Two sites were identified in further consultation with pastoral lease owner Brook Pastoral on its lease, Murnpeowie Station, on Dieri Country: Reedy Springs and St Mary's Pool. It is worth noting, that land managers need to approve a potential project, especially for infrastructure, prior to the final agreeance with the respective First Nations group.

The aims of the project were to manage non-native herbivore impacts to springs (Reedy Springs) using exclusion fencing and to manage visitor access to a nearby waterhole (St Mary's Pool) with fencing to prevent vehicle access. Furthermore, in addition to the fencing of Reedy Springs the land managers required an alternate water point to be identified, to reduce pressure on the fence from stock seeking water. Consequently, the project included installation of a new tank and trough, to be fed by new pipework connected to a bore 10km away.

Cultural Surveys and fence design **-** The main spring vents at the Reedy Spring group are situated in an area of relatively flat topography meaning fence installation is relatively simple. FOMS provided advice on fencing design given their years of fencing experience, with a design that allows for both kangaroo access and restricting non-native herbivores, while also considering soil conditions of the area.

Dieri completed a cultural heritage survey in October 2023 and the fencing boundary was expanded (from initial project design) to incorporate and protect the cultural and archaeological sites Dieri identified during the cultural survey.

Dieri were also concerned about visitor impacts and vehicle management options were discussed at St Mary's Pool with fence locations planned accordingly. On receiving heritage clearance approval from Dieri, a formal agreement was put in place with Brook Pastoral outlining the scope of work and responsibilities for ongoing maintenance.

Fencing - Dieri did not have the resources for completing the fencing, however, recommended other First Nations companies who may have the capacity. Subsequently, Kokatha Aboriginal Corporation were awarded the contract. To ensure the project met the expectations of all involved, a final site visit in May 2024 was conducted ahead of fencing work and any necessary adjustments were made. Representatives from SAAL, FOMS, Dieri, Brook Pastoral, and Kokatha attended.

At the time of fencing a vegetation survey was completed and georeferenced photos were taken to allow for comparisons in the future. The project was completed in early June 2024.

Results

The completed project saw 2.45 km of fencing erected to protect a 42-hectare area around Reedy Springs. The final fence design was a four strand barb wire fence, with rust resistant steel posts every six metres plus intermediate spacers, a main access gate and a spear gate to allow a point of exit for wondering stock. During the cultural heritage survey, cultural and archaeological sites were identified, and consequently, the fencing perimeter was expanded to include these areas. At St Mary's Pool the installation included a short fence consisting of polyethylene coated timber posts and chain gate to manage vehicle access.

The project involved three First Nations groups, one volunteer group (FOMS), a pastoral landholder (Brook Pastoral), multi-government funding, industry funding and the SA Arid Lands Landscape Board as the project facilitator and manager. A monitoring program is now in place for the site which includes fence and ecological (vegetation and water quality) inspections.

Discussion

First Nations involvement and engagement

The engagement process SAAL applied is an established way of doing business between the organisation and First Nations groups (SAAL Board, April 2022). The engagement approach, which sits between 'Collaborate' and 'Empower' on the IAP2 Spectrum of Public Participation (IAP2 2024), has additional benefits that extend beyond the delivery of an infrastructure project. Cross-cultural sharing between SAAL water project staff, FOMS, First Nations and the pastoral enterprise was valued by all involved and allowed everyone to gain an improved understanding of each other's context. While the project has contributed to the protection of a spring group from non-native animal access, of greater importance is the project has enabled First Nations groups to reconnect with the cultural connection they have with springs and be included in the decision making for protection.

Sharing project updates between all groups and collective on Country site visits kept the project on track and ensured the different groups' expectations were understood. Re-negotiating aspects of the project and reporting back to First Nation's Board Members to keep them informed was crucial to the project's success.

The timeline pressures that occur with external funding obligations can mean there isn't enough time for First Nations aspirations to be fully realised and considered in project planning. This is a matter that needs to be raised with funding bodies early, with extra flexibility sought, to shape the project as it evolves. Without this, there is risk that relationships, particularly between government and First Nations are damaged and projects may not reach completion, putting future projects at risk.

Springs Fencing

Reedy Springs is now one of the few springs in South Australia fenced for management purposes and it is worth considering the impact fencing will have on spring condition. It has been observed at other mound springs in South Australian where fencing or stock exclusion has occurred, that *Phragmites australis* has proliferated at the expense of other native flora (Gotch 2013) or has caused a reduction in open water (Harris 2020, Lewis & Packer 2020). However, this has occurred at springs where *Phragmites* was present at the time of fencing (e.g. Billa Kalina springs, The Fountain, Big Cadna-owie; Lewis & Packer 2020). Within the fenced area of Reedy Springs, no *Phragmites* was identified during site visits or prior to fencing and instead, the Springs are dominated by *Cyperus laevigatus* ('bore-drain sedge'). The risk, therefore, of *Phragmites* proliferation, following fencing and removal of grazing pressure is considered lower than at other springs where the species is already present, however regular monitoring of Reedy Springs will document any changes in vegetation composition and extent.

This project at Reedy Springs and St Mary's Pool resulted in renewed focus on springs management in South Australia's rangelands and has already allowed for further collaborative review, with Dieri and Arabana, of other springs with environmental and cultural significance that may benefit from active management. Ultimately this project resulted in strengthened relationships between government, First Nations groups, volunteers and pastoralists and has established a methodology, including the engagement process, that can be applied to the protection of other springs, or land management projects in region. The improved engagement process includes government and First Nations partnership at the very start of a program helping to ensure Traditional Owner guidance and cultural heritage are considered at early-stage project development.

Acknowledgements

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XII INTERNATIONAL RANGELAND CONGRESS AUSTRALIA 2025

Great Plains Grassland Extension Project: Tackling big conservation challenges through collaboration and cooperation

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Key words: Woody encroachment; grassland ecosystem; collaborations

Abstract
Grassland biomes are often extensive, and challenges such as invasive species can span multiple jurisdictions and ownerships. How can conservation efforts be scaled up to make a meaningful difference on such a large landscape? When an entire biome is in distress, what can be done to address the conservation need? Woody encroachment is threatening the North American Great Plains ecosystem, replacing old-growth rangelands with a mix of undesirable brush and trees causing a loss of ecosystem services including habitat loss, soil hydrologic alterations, and drastic reductions in grazing capacity. Conservation efforts in the past have been fragmented between agencies and individual landowners without making impact at the needed scale and have failed to halt rangeland losses. New mapping tools allow more precise location of problem areas, and recent research provides a new approach to tackle the problem.

The Great Plains Grassland Extension Partnership offers an example of how conservation efforts can expand across a biome. Range management specialists within each state's Cooperative Extension System have united to coordinate outreach efforts to ranchers, share new management techniques, report success and challenges, and assist and coordinate other conservation agencies such as the Natural Resource Conservation Service and state wildlife agencies. A single message incorporating the urgent need and a new approach to tackling the woody encroachment problem at greater than the individual property size has provided hope for reversing the degradation of North American rangelands. The partnership allows each state to engage with local partners who can forward the same conservation message. Working together, there is hope for melting the "green glacier" of advancing woody encroachment covering the Great Plains (Engle et al. 2008).

Imperiled Biome
Grasslands cover up to 41% of the world's land area (Petermann and Buzhdygan, 2021) and support goods, services, and cultural values that to contribute to human well-being. Grasslands also provide food and fiber production and ecological and biological services including freshwater supply, biodiversity, cultural diversity, belowground carbon storage, and the regulation of natural hazards (Havstad et al., 2007).-Nearly half of global grasslands have been converted to other land cover types and remaining grasslands remain vulnerable to future loss.

The Great Plains of North America is among the largest temperate grasslands in the world. Woody plant encroachment is driving a biome-scale transition from grassland to woody dominance (Figure 1) (Briggs et al. 2005; Engle et al. 2008; Twidwell et al. 2022; Morford et al. 2022). Causes include a lack of prescribed fire (Twidwell et al. 2013), introduction of seed sources (Johnson 1923), small scale approachs to control (Fogarty et al. 2022), and a carbon-enriched atmosphere (Blair et al 2014). Woody encroachment includes both brush and tree species. Junipers, especially eastern redcedar (*Juniperus virginiana*), while native, have been continually planted where they were historically scarce (Ganguli et al., 2008; and have rapidly spread.

Woody encroachment in the Great Plains can lead to a potential 75% reduction in rangeland production and escalating costs of brush management that can easily exceed annual revenues generated from rangelands (Fuhlendorf et al. 2008; Natural Resources Conservation Service 2021). These losses are resulting in a decline in ecosystem function and services that benefit communities in the Great Plains and throughout North America (Twidwell et al. 2013).

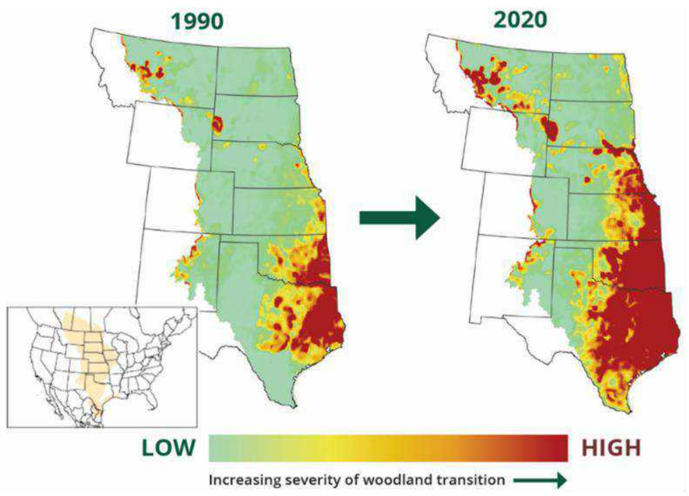

Figure 1. Woody plant encroachment is driving a large-scale transition from grassland (in green) to woody dominance (in red) in Great Plains grasslands from 1990-2020. Adapted from Fogarty et al. (2023).

Past efforts to control and reduce woody encroachment in the Great Plains have relied heavily on brush management and have been unable to halt the loss of grasslands at large scales (Archer et al. 2011; Rheinhardt et al. 2021). Several challenges have contributed to this outcome: 1) brush management is a reactive conservation practice that consists of woody plant removal in areas that have already experienced losses due to woody encroachment. An over reliance on this expensive practice has limited opportunities for more cost-effective and proactive approaches (Twidwell et al. 2021). 2) Follow-up management to address the rapid reinvasion of woody plants after mechanical removal is often lacking and results in short-lived management treatments (Fogarty et al., 2021; Scholtz et al. 2021). And 3) management treatments are often scattered across the landscape and lack spatial arrangement needed to benefit the broader landscape (Twidwell et al. 2021). There is a need for a more proactive and spatially targeted approach for reducing woody encroachment that addresses the underlying risks that drive woody encroachment (Twidwell et al. 2021).

New approaches for reducing woody encroachment

New approaches for reducing woody encroachment were designed to overcome key weaknesses of past approaches and better allow practitioners to scale up management over time (Twidwell et al. 2021). Management guidelines were built around a framework for reducing the risk of encroachment in grasslands. Management guidelines were then designed to 1) prevent risk from increasing in intact grasslands and 2) reduce the risk of encroachment by minimizing grassland exposure and/or sensitivity (Fogarty et al. 2023). For instance, prescribed fire can be used to manage the dispersal and recruitment stage of woody encroachment and prevent the loss of intact grasslands (Figure 2). In addition, restoration actions can be used to remove seed-producing woody plants, deplete the seedbank, and expand the extent of intact grasslands over time.

The workshop brought together scientists, extension specialists, and conservation practitioners from across the Great Plains region to improve the planning, design, and delivery of conservation investments. Ultimately, the workshop led to the development of an 85-page pocket guide (Fogarty et al. 2023) that serves as a resource for training the rangeland workforce on how to recognize and reduce grassland vulnerability to woody plant encroachment across a range of landscape contexts. With nearly 25,000 copies distributed in the first year of publication, the pocket guide has supported local field trainings across Great Plains states as part of efforts to scale up the implementation of new management guidelines (Figure 3).

The Great Plains Grasslands Extension Partnership offers an example of how regional partnerships in extension and outreach can be created to address large-scale threats. Next steps include the formalization of training and professional development opportunities through extension- and agency-sponsored education programs. The Extension Partnership has supported an unprecedented level of collaboration among scientists, extension specialists, and practitioners to address the biome threat of woody encroachment.

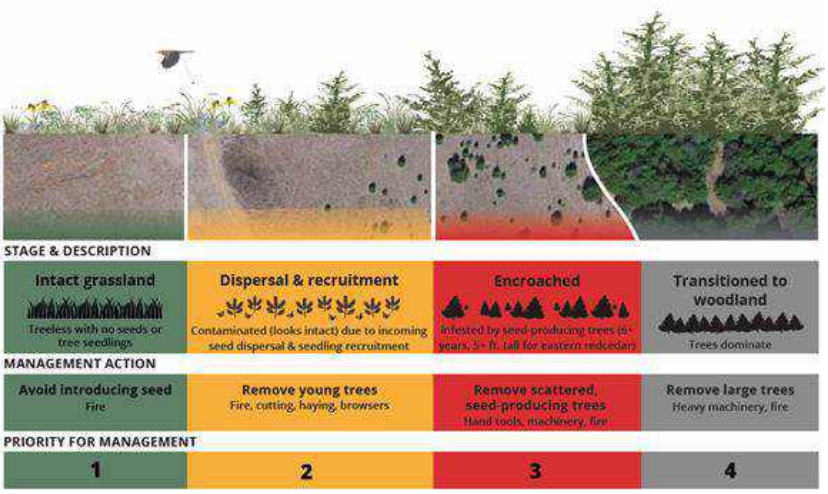

Figure 2. New management guidelines prioritize proactive management to prevent encroachment of intact grasslands and expand them over time through targeted management of encroached rangelands (Twidwell et al. 2021).

Figure 3. The Great Plains Grasslands Extension Partnership has supported a regional extension and outreach campaign to speed up the adoption of new management guidelines for reducing woody encroachment.

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Building public awareness for rangelands and pastoralists via social media and the FIFA World Cup 2026

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Key words: IYRP; soccer; digital platforms; outreach

Abstract

Overall, our global population has a very limited knowledge of rangeland ecosystems and the communities who most depend on them, despite the fact that rangelands comprise over half of the world's land area and supply vital ecosystem services such as food, fiber, and recreation. Therefore, how can we increase public understanding about rangeland systems to heighten awareness and improve rangeland policies and stewardship? The International Year of Rangelands and Pastoralists (IYRP) will occur in 2026 as approved by the United Nations General Assembly in 2022. Many events are planned to celebrate the IYRP, with a major emphasis on expanding global awareness. The FIFA World Cup is also happening in 2026, which after the Summer Olympics is one of the greatest world sporting events. This sporting event is held once every four years. The most recent FIFA World Cup was hosted by Qatar and was watched by over five billion people (61% of the global human population). For the first time in history, the 2026 FIFA World Cup will be hosted by multiple nations: the United States, Mexico, and Canada. Can the IYRP leverage attention for the 2026 FIFA World Cup to boost public appreciation for global rangelands and pastoralism? If so, how might this be achieved? Social media offers several tools and opportunities that could be useful to this end. In the lead-up to the games, for example, creative posts of rangeland residents playing soccer on unique, beautiful, and remote landscapes combined with targeted messaging could attract a large audience. This poster will explore various social media options, tentative frameworks or approaches, and the general feasibility for achieving impact. Partnerships with groups such as the IYRP Pastoralist Youth Working Group - distributed across 11 regions worldwide- could help provide raw material in the form of videos, photos, text, and artwork.

Introduction

According to the United Nations Environment Programme (UNEP) (2014), rangelands occupy 54% of all land on Earth, and at least 30% of land in the United States is rangelands (NRCS, 2024). Rangelands are home to an estimated 200 million people worldwide, which represent approximately 2.5% of the world population. Nevertheless, people often do not know or recognize the importance of rangelands in their lives. In North

America, rangelands are particularly important for livestock and fiber production, wildlife habitat, and recreational activities among other things. The mission of the International Year of Rangelands and Pastoralists (IYRP 2026) is to promote an understanding and appreciation of rangelands around the world, the people who manage them, and their contributions to all communities.

The objective of this project is to try to use social media as a platform to bring awareness to the general public as to what rangelands and pastoralists are. As of October 2024, 63.8% of the global population uses social media (DataReportal, 2024). Furthermore, 94.5% of the world's internet operators use social media at least once a month and the typical social user spends more than 2 hours per day on social media (Figure 1). These statistics show that social media could be a great way to reach a larger audience for the IYRP 2026. Our project will also take advantage of the FIFA World Cup 2026 happening in the United States, Canada and Mexico. The 2022 FIFA World Cup was able to engage over five billion people; which represents roughly 61% of the world population. Using this attractive event, which is watched and followed by a very large portion of the general public could be an effective way to talk about rangelands and pastoralists to people who might not be familiar with rangelands and the people working those lands.

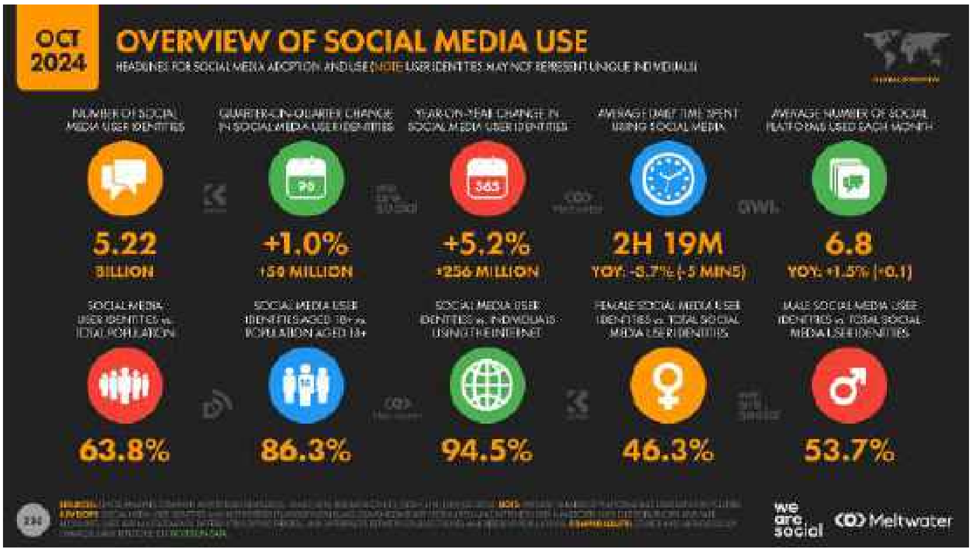

Figure 1: Overview of Social Media Use (DataReportal, 2024)

Methods

As of December 2024, our project is in the preliminary stage of development. Currently, the project has no funding. However, the core team is working on three main general ideas. The project was presented for the first time at the Society for Range Management (SRM) Annual Meeting in Spokane, Washington in February 2025. At this international meeting, we received feedback from rangeland scientists and professionals on our three main ideas to help us move forward with this project. The audience was very receptive and provided useful advice. We also used this opportunity to collect contact information of people who could provide photos and/or videos for our social media platforms. Our project is divided in two major components, namely: the FIFA World Cup Outreach and the Social Media Outreach.

There are 11 IYRP 2026 regions around the world (i.e. the Artic, Australia/Oceania, Central Asia & Mongolia, East Asia, Eastern & Southern Africa, Europe, North Africa & Middle East, North America, South America, South Asia, and West & Central Africa). Our plan is to represent and engage each region as much as we can. On our team, we have representants of the IYRP 2026 Pastoralist Youth Forum which will also help us engage youth in this outreach project.

FIFA World Cup Outreach

The final product for the 2026 FIFA World Cup Outreach may be about 10 videos (if possible) to be launched from March 2026 to July 2026 on social media. There will be two videos a month that will be viewed before the FIFA World Cup and during the sporting event. We will collect footage from all around the world of pastoralists playing soccer on rangelands. As a result, we will be able to have a diversity of footage which shows the variety of pastoralists and rangelands worldwide. Some of these videos will showcase traditional clothing worn by pastoralists around the world to illustrate material culture. In the videos, a soccer ball will roll through the different landscapes where pastoralists pass it to each other across the screen to establish connectivity among the different rangelands. For each video, there will be music, some text regarding facts about pastoralists and rangelands, and the IYRP 2026 logo and website. In order to simplify the editing work for this project as it is solely volunteer based, we have a demonstration production video to standardize approaches and illustrate filming recommendations. We will identify a network of people in the field who would be in charge of collecting footage for each IYRP region.

Social Media Outreach

For this part, we have two ideas. First, we will create monthly short videos based on the IYRP 2026 monthly themes (Figure 2). These short videos will be a photo montage of all of the 11 IYRP 2026 regions around the world. For each video, we will have photos, music, some text regarding facts about pastoralists and rangelands, and the IYRP 2026 logo and website. We will also have a rolling credit page at the end to thank each photographer for their contributions to the project. We plan to have the same structure for each video to provide a consistent message for the general public. Second, we will do a weekly "*Find the IYRP 2026 logo in this photo, and learn an interesting fact about rangelands and pastoralists around the world! #IYRP2026 #SRM*" on social media (Figure 3). This will allow us to share 52 photos over the year 2026 representing rangelands and pastoralists worldwide. We will post a photo on social media every Tuesday with a hidden IYRP 2026 logo, and on Fridays, we would announce where the logo was hidden and will give an explanation of what is shown in the photo. As we know, photos are a very powerful way of communicating! All of our social media outreach will be in English, Spanish and French.

Figure 2: IYRP Themes

Figure 3: Example of the Find the IYRP logo social media outreach idea

Timeline

The first half of 2025 will be focused on collecting footage (videos and photos) from partners and colleagues. The second half of 2025 will be focused on video and photo production. The year 2026 will be focused on distribution (Figure 4).

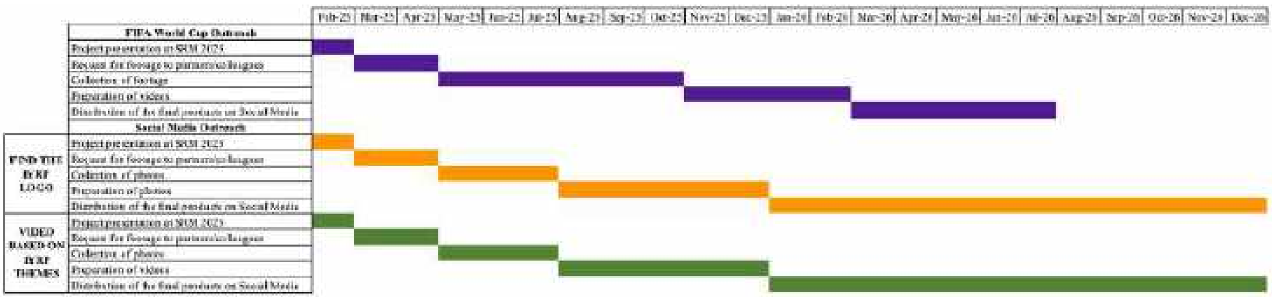

Figure 4: Outreach Projects Timeline

Overall, due to the statistics on the world's top social media platforms, our focus will be on Facebook, YouTube and Instagram (Figure 5; DataReportal, 2024)

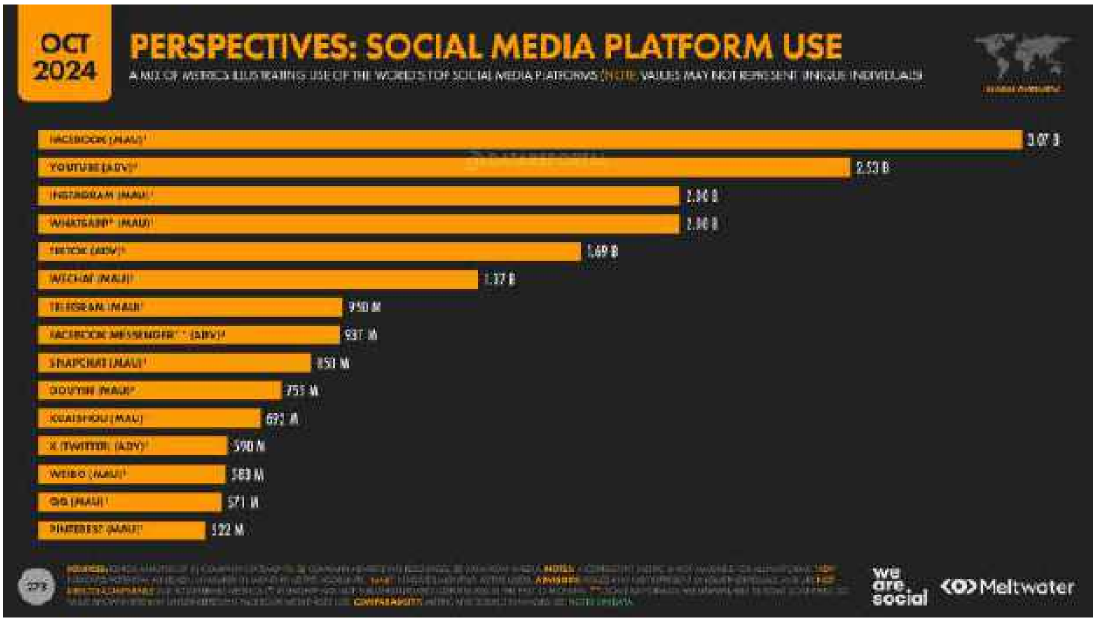

Figure 5: Social Media Platform Use (DataReportal, 2024)

Results

Because this project is still in a preliminary phase, we do not have any results to share yet. However, we plan to collect engagement data on the different social media platforms in order to learn more about the impacts of the outreach project. The data collected include, but are not limited to views, likes, comments, reactions, and shares.

Discussion/Conclusions/Implications

Because this project is still in a preliminary phase, we cannot yet discuss results or project impacts. However, our objective is to bring awareness about rangelands and pastoralists to the general public during the International Year of Rangelands and Pastoralists in 2026. We anticipate to achieve this with this project.

We received useful feedback on our ideas during the Society for Range Management Conference in February 2025. We submitted a funding request (pending) to the Society for Range Management to hire a professional editor for the videos related to the FIFA World Cup. We believe that our ideas will evolve with time and that new perspectives might emerge in the next few months. Other ideas are already emerging. For example, we may hold a mini-competition for the best soccer video with a soccer ball with the IYRP logo as a prize. This and other ideas may grow if funding sources are located.

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Collaborative approach to grazing management

Participatory rangeland management (PRM): from concept to continental scaling

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Key words: Participatory rangeland management, pastoralism, restoration, planning, community

Abstract

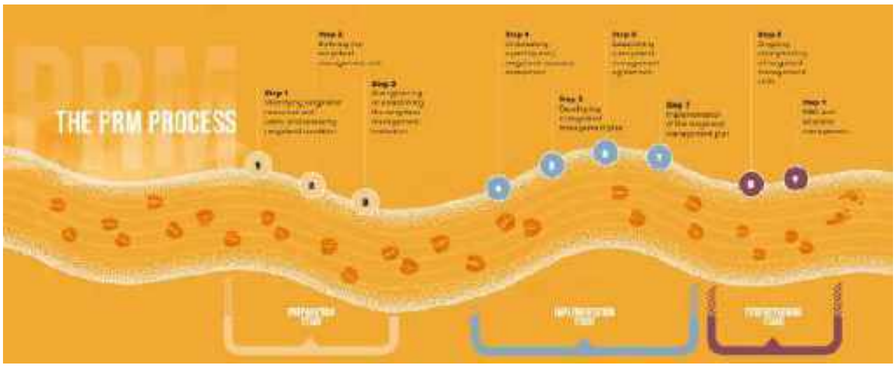
Participatory rangeland management (PRM) is a step-by-step process that builds the capacities of pastoralist communities to improve the management, governance and restoration of their land and resources. It seeks to address the challenges that pastoral communities across Africa face including a lack of tenure security with an increasingly degrading resource base as pressures on land grow. Introduced in 2010, it is now being implemented across more than 2 million hectares in East Africa. Three impact pathways were followed to reach this point – developing and piloting PRM, building capacities to implement PRM, and influencing a more enabling policy environment. However, though PRM in name can be easily scaled in terms of coverage, greater attention must be given to maintaining its core principles and deepening community engagement and capacities. It requires a significant investment from all involved including sufficient time and funding to move at a pace that allows for capacity building of communities to *lead* the process, co-develop solutions and support policy and legislation improvements.

Introduction

Pastoral communities across Africa face the ongoing challenge of a lack of tenure security with an increasingly degrading resource base as pressures on land grow. In 2010 n an attempt was made to reverse this situation; participatory rangeland management (PRM) was developed in Ethiopia drawing from the experiences of participatory *forest* management, adapted to a rangeland context (Flintan and Cullis 2010).

Following the introductory guidelines PRM was piloted at different scales (local/village and landscape) and later expanded across a million hectares. Evaluations highlighted its' initial impact and potential for strengthening good governance, improving rangeland health and productivity, reducing land use conflicts and benefiting local communities – both men and women (Flintan et al. 2019; Flintan and Eba 2023).

In 2019 PRM was introduced to Kenya and Tanzania by an EU-funded project implemented by local NGOs (namely RECONCILE, Tanzania Natural Resource Forum and KINNAPA) with technical support provided by ILRI. An independent assessment of this implementation highlighted important gains in rangeland management, livestock productivity and women's participation (Waweru et al 2021). More recently, ILRI and partners have supported its application in additional locations and as part of broader development processes such as within One Health and introducing gender transformation, climate security, peacebuilding, livelihood development, and rangeland restoration.



Today PRM is being implemented across more than 3 million hectares in Ethiopia, Kenya and Tanzania, with almost two-thirds of this being supported by ILRI (Flintan et al, 2025). A multistakeholder PRM scaling readiness workshop in Addis Ababa in mid-2024 set an ambitious target of all of Ethiopia's pastoral areas under PRM by 2034. Furthermore, the Intergovernmental Authority for Development (IGAD) Centre for Pastoral Areas and Livestock Development (ICPALD) and ILRI co-developed a manual on PRM (ICPALD 2024), with the aim of scaling across the IGAD region over the coming years. Additionally, ILRI is supporting the development and implementation of large-scale investments in PRM including an EU-funded Eastern/Horn of Africa project and a SDC-funded East Africa regional project.

There is a clear commitment to PRM in the East Africa region. There are also opportunities to expand to other countries e.g., Mali, Senegal (Flintan et al. 2022), Somalia (Flintan 2024) and Tunisia (Sghaier and Frija *forthcoming*). However, scaling PRM has challenges. This paper reflects on these, the impact pathways followed to reach this point, and what is being done to strengthen the approach and scale it.

Outcome impact pathways
i) Developing and piloting PRM

PRM is a process that can take many years to achieve and does not work well in short-lived project-oriented contexts. It requires long-term and consistent funding over at least five years as well as firm commitment from communities and supporting stakeholders. It has proved important to make this clear from the outset, and where possible offer shorter-term incentives such as livelihood-focused activities and learning visits alongside PRM establishment.

It has also proved important to develop and promote core PRM principles, which sets it aside from other community-based natural resource management approaches. First and foremost PRM is community-led. Having participatory rangeland resource mapping as the first step in the process has proved important for community leadership (Irwin et al 2015) Also PRM requires working at different scales – at the broader rangeland unit and at household cluster or village level with well-established linkages between.

Gender equity and social inclusion are also important principles. Though the community needs to be responsible for the rangeland management institution there is opportunity to influence its membership to be more inclusive (Bullock et al 2022). Gender transformative tools and approaches appropriate for collective societies to influence greater equity e.g. community conversations (Bullock 2024) and women's leadership forums (Dungumaro and Mkami 2019) can be introduced. PRM can be an important vehicle for building collectivity and such as peacebuilding – however, this has proved challenging and a recent study on the impact of PRM on collectivity showed little impact (Ng'ang'a et al 2024).

ii) Building capacities to implement PRM

Implementing PRM requires new skills and capacities as well as a change of mind-set i.e. that we 'outsiders' are facilitators of PRM and not drivers or leaders. The community also requires capacity building, and particularly where traditional institutions and practices have broken down. An institution capacity assessment is undertaken to understand needs.

New challenges may be faced that require co-developed solutions e.g. dealing with invasive species and restoring lands. Building up a toolbox of training resources targeting different stakeholders has taken time, particular as stakeholders work at different levels and with different priorities. In 2024 ILRI supported ICPALD to produce a manual on PRM for practitioners (ICPALD 2024).

iii) Influencing a more enabling policy environment

A process such as PRM requires an enabling policy environment and this has proved elusive. In Ethiopia the policy environment was neglected during initial piloting, and still there is no policy and legislation that supports PRM in same way policy and legislation on participatory forest management supports community rights to forests. However, steps have been made towards this through CARE Ethiopia establishing government-led regional PRM technical working groups, as well as the integration of PRM into government-led projects such as the Lowlands Livelihood Resilience Project Phase Two. And in Kenya working at county level (rather than national) has proved productive (Carleton and Flintan 2023).

Concluding remarks

Participatory rangeland management has significant potential for strengthening rangeland management and governance building on what communities are already doing, their knowledge and their institutions where functioning well. However, to be successful, it requires a significant investment from all involved including sufficient time and funding to move at a pace that allows for the capacity building of communities to lead the process and to build government support. The development and implementation of PRM by ILRI and partners has had positive results, however there is still much to improve and work on both in terms of deepening PRM implementation and getting scaling right.

Acknowledgements

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Diverse Adaptive Landscape-Livestock Interaction approach to beneficial grazing management in Canadian prairie rangeland production systems

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Keywords: Working landscape; societal benefits; temporal and spatial scale

Abstract

Rangelands can serve as nature-based solutions to climate and biodiversity crises by sequestering and storing carbon and providing habitat for multiple species. Since rangeland systems are complex, inherently variable, and are facing high rates of change, prescriptive or standardized management practices cannot reliably produce desired benefits. Since 2014, the South of the Divide Conservation Action Program Inc. (SODCAP) has collaborated with rangeland managers in Saskatchewan, Canada, employing a participatory, outcome-based approach to enhance ecosystem health and wildlife benefits in a livestock production context. SODCAP's ongoing Living Lab - Central Prairies (LL-CP) project engages agricultural land managers, researchers, and other stakeholders, using a producer centric approach, to identify characteristics of grazing management systems that can reliably produce needed benefits, including carbon storage and biodiversity. Work to date indicates that a Diverse Adaptive Landscape-Livestock Interaction (DALLI) approach to grazing management is used by local ranchers to ensure that desired benefits are produced over time. DALLI managers dynamically adjust grazing strategies and tools across spatial and temporal scales to distribute livestock impacts throughout landscapes, leveraging techniques like animal herding, strategic water and mineral placement, flexible fencing, and incorporation of diverse perennial and annual land use types within grazing systems. Management responds to and promotes ecosystem heterogeneity, producing a shifting mosaic of impacts, which supports system resilience and biodiversity. Interviews with ranchers who use this approach underscore how diverse factors, such as climate conditions, economic viability, and community well-being, shape management decisions and outcomes. LL-CP's ongoing data collection on soil carbon, greenhouse gas emissions, plant biomass, diversity, nutrient quality, and socioeconomic factors will help to quantify the benefits of DALLI grazing management. This work will help validate the potential of diverse, adaptive grazing strategies to promote sustainable rangeland management amidst dynamic environmental challenges.

Introduction

Rangelands can serve as nature-based solutions – helping curb both the climate and biodiversity crises – but are threatened by conversion, degradation, and climate change (UNCCD 2024). Commonly recommended management practices do not perform reliably in all contexts (Buma et al. 2024) and can negatively affect other important values, like species diversity (Grenke et al. 2020). To better ensure that rangelands provide needed benefits over the long term, solutions must reflect the inherent complexity of rangeland systems

(Walker 2020) and should be defined in collaboration with knowledgeable local rangeland managers (Teague and Kreuter 2020).

Rangelands are complex social-ecological systems, with unpredictable outcomes due to interactions and interdependence of their parts. Grazers interact with variable topography, soils, plants, and other ecosystem features, creating heterogeneity, which in turn influences other ecosystem processes (Fuhlendorf et al. 2017). Managers weigh diverse priorities and select different management approaches depending on their motivations and practical considerations. Conventional rangeland management has sought to reduce this complexity, prescribing practices that discourage or prevent selective grazing, to make ecosystems more efficient and predictable. This approach assumes that livestock production is the primary goal, and that uniform use of homogenized landscapes will maximize livestock production. However, the anticipated benefits do not always materialize (Briske et al. 2008), possibly because heterogeneity is important for the functioning of rangeland ecosystems (Adler et al. 2001).

Beneficial grazing management encompasses more than just production and should support healthy ecological functioning and long-term resilience of rangeland systems. To achieve this, management must be robust to extreme and highly variable climates, including excess moisture and drought; must address enduring impacts of historical land management; and must be capable of adapting to relevant environmental, economic and social changes, all while ensuring the production of multiple benefits. Operations should be financially viable, but short-term economic gains should not hurt long-term sustainability or involve trade-offs with crucial benefits such as biodiversity or carbon storage. Given that there are still many unknowns about the dynamics of rangeland systems, and increasing uncertainty about how these systems will function in the future, there is no one-size-fits-all definition of beneficial grazing management. Certainly, adaptive management is key. Briske (2017) further suggests that collaborative learning and collective action by diverse stakeholders is required to produce knowledge, increase adaptive capacity, and maintain resilience. Similarly, Teague and Kreuter (2020) advocate for researchers working directly with innovative rangeland managers to better understand, quantify and communicate how they secure beneficial outcomes.

In Canada, where most prairie ecosystems have been converted to annual cropland, rangelands are crucial reservoirs of diverse cultural, social and ecological benefits. Some prairie rangeland managers and institutions have been especially proactive in ensuring these benefits are produced, and that managers are recognized for their efforts. At the same time, policy makers are seeking input on what constitutes beneficial grazing management in various regions across Canada (Government of Canada 2024). This paper, utilizing the existing network of managers and researchers aims to describe a management approach.

Methods

The South of the Divide Conservation Action Program Inc. collaborates with rangeland managers in Canada's Prairie Ecozone, employing a participatory, outcome-based approach to enhance ecosystem health. Since 2014, we have formed dozens of land management agreements aimed at improving outcomes for wildlife, soils and vegetation within a livestock production context. Most agreements define target outcomes that managers aim to achieve, but do not prescribe methods by which to achieve them. In 2022, we engaged producers and other collaborators in a living lab project (McPhee et al. 2021), in which diverse participants work together to identify innovative pathways for creating agri-environmental benefits in working prairie agricultural landscapes. Living Lab – Central Prairies (LL-CP) has undertaken five formal co-development sessions focused on grazing management to date, with 39 producers engaging with researchers and other stakeholders through to facilitated sessions and iterative group discussions. Participants share and discuss observations and preliminary results concerning soil carbon, biodiversity, economics and more, and how these outcomes are affected by management. LL-CP researchers have also conducted semi-structured interviews with core participating producers (n=22) to better understand the practices managers undertake and why. These producers can all be considered rangeland managers.

The rangeland managers contributing to results operate diverse operation types – including ranches, farms, and community pastures – using management units that range from a few hundred hectares to 1000 hectares in size. Their operations are distributed across the three main soil zones of southern Saskatchewan (black, dark brown and brown chernozemic soils). This also represents a moisture gradient from mesic (black) to xeric (brown).

Observations

To address complex intertwined goals and desired outcomes, managers are utilizing a newly defined Diverse Adaptive Landscape-Livestock Interaction (DALLI) approach to grazing management. The approach is so named because managers dynamically adjust grazing strategies and tools across spatial and temporal scales to distribute livestock impacts throughout landscapes, taking advantage of animal behaviours interacting with natural variability to create heterogeneity. Managers monitor and respond to heterogeneous impacts in real time, leveraging diverse tools and techniques like animal herding, strategic water and mineral placement, flexible fencing, and incorporation of diverse perennial and annual land use types within their grazing systems,

Table 1: Comparison of characteristics of conventional grazing management approaches for the Northern Great Plains (NGP) region, Adaptive Multi-Paddock (AMP) and Diverse Adaptive Landscape-Livestock Interaction (DALLI).

Grazing management characteristics	Conventional approaches for NGP region	Adaptive Multi-Paddock (AMP)	Diverse Adaptive Landscape-Livestock Interaction (DALLI)
Paradigm	Homogeneity/ efficiency-based	Homogeneity/ efficiency-based	Heterogeneity/ system-based
Primary goal	Production without degradation of forage resources	Production with enhancement of soil health	Optimization of multiple social-ecological values
Mode of success	Prescribed practices	Prescribed practices	Defined outcomes
Rest periods	Incidental; in avoided areas	Prioritized; planned, post-disturbance (for recovery of desired species)	Prioritized, planned and *ad hoc*; pre- and post-disturbance (for stockpiling and plant community recovery)
Grazing periods	Long; planned based on expected forage supply	Short; planned based on expected forage supply, with some flexibility in response to actual supply	Variable; planned based on expected forage supply, with high flexibility in response to actual supply
Stocking rate	Low-Moderate	Moderate-High	Variable
Stock density	Low	High	Variable
Season of use and rest	Fixed	Fixed-Variable	Variable
Pattern of grazing impacts	Pasture-scale; fixed gradients of use, persisting and being reinforced over time	Operation-scale; uniform impacts, being reached sequentially, paddock by paddock	Patch- to landscape-scale; variable, shifting in space and time

Within the DALLI approach to grazing management, livestock interact with landscape features to create a shifting mosaic of disturbance that responds to, interacts with, and modifies preexisting variability in soil, water, vegetation, and other biotic and abiotic site characteristics, at multiple spatial and temporal scales. Managers desire to maintain actively growing and residual plant cover within an acceptable range of variability (which varies with site and vegetation characteristics) and to avoid livestock use of grazed patches and plant communities until adequate recovery has occurred. To ensure these outcomes are met, they carefully observe actual conditions, and adjust specific actions as required. A key element is rest, especially of native pastures, as a stockpile for future use and as a means of "drought proofing".

Iterative monitoring and adaptive management are utilized to meet desired management outcomes. Managers' attentiveness and flexibility allows them to layer new values and priorities on existing operational plans; to show leadership in how to achieve desired outcomes; and to seize new opportunities.

Achieving target outcomes often requires management to influence multiple responses – such as plant architecture, plant density, plant community composition – which may vary spatially and temporally, and which in turn influence multiple other ecosystem components (e.g., insect and bird communities; forage and livestock production).

Rangeland managers are spread over many differing landscapes and follow many different business models. As a result, there is no single solution to the desired multilayered environmental and socioeconomic outcomes. Interviews to identify key elements of DALLI with ranchers who use this approach underscore how diverse factors, such as climate conditions, economic viability, and community well-being, shape management decisions and outcomes. DALLI managers generally value long-term – often multi-generational – productivity of the working landscapes.

When compared to conventional approaches, and to Adaptive Multi-Paddock Grazing, a beneficial grazing management practice proposed by Teague et al. (2013), the DALLI management emphasizes heterogeneity and the prioritization of multiple social-ecological values (Table 1). DALLI management aims achieve defined outcomes, using variable grazing and rest periods, stocking rates, stock densities, and season of use to create a pattern of grazing impacts that shifts in space and time.

Discussion

The DALLI approach is a product of complex systems and is well-suited for undertaking management of rangeland systems characterized by high uncertainty. DALLI managers emphasize and enact adaptive management throughout their operations, dynamically adjusting grazing strategies and tools in response to emerging characteristics of the systems in which they operate. Managers are themselves a key component of the grazing system, with actions taken contributing and responding to emerging characteristics of the system. Specifically, management responds to and promotes ecosystem heterogeneity, producing a shifting mosaic of impacts, which supports system resilience and biodiversity. Since the DALLI approach inherently prioritizes multiple benefits, managers are well positioned to layer new values and priorities onto their operations, address challenges, and seize new opportunities when social and environmental conditions change. These features may make DALLI a particularly effective approach to beneficial grazing management in the Canadian prairies and beyond.

Ongoing data collection and analysis on soil carbon, greenhouse gas emissions, plant biomass, diversity, nutrient quality, and socioeconomic factors within the LL-CP project will help to quantify the benefits of DALLI grazing management. This work will help validate the potential of diverse, adaptive grazing strategies to promote sustainable rangeland management amidst dynamic environmental challenges. Together, biophysical and economic findings, qualitative analyses of social science interviews and ongoing co-development with participating rangeland managers will help explain how and why DALLI approaches can help ensure needed benefits are produced over the long term.

Conclusion

Around the world, rangeland managers are helping to ensure long-term productivity of these working landscapes, while recognizing and advocate for recognition of multiple values produced. They are a vital part of rangeland systems, and their attentiveness and flexible approaches are key to ensuring their success. As the production of social and ecological benefits from rangelands grows in profile and importance, and uncertainty about future conditions rises, we must continue to support, learn from, and communicate the successful approaches of knowledgeable and effective managers – including DALLI managers in the Canadian prairies – to understand and define locally appropriate approaches to beneficial grazing management.

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The Rangelands Living Skin project: lessons for co-designed, collaborative research in rangelands

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Key words: farmer-centric; collaboration; co-design; rangelands; producer-led research

Abstract

The value of conducting research with multidisciplinary and inter-disciplinary teams, involving both researchers and practitioners to develop problem-orientated and solution-focussed research is well recognised. 'Rangelands Living Skin' was a five-year project linking producers, scientists, education and extension agencies, commercial carbon companies and communications experts to evaluate cost-effective practices that focused on regenerating the New South Wales (NSW) rangelands in Australia, and supporting productive, profitable and sustainable businesses. The project brought together 12 project partners, plus additional expert consultants. The project aimed to create an evidence-base and build capacity for widespread adoption of practices that benefit soil, plants, animals and people – the living skin of the rangelands. Collaboration and co-design were at the core of the project, which took a farmer-centric approach. Producers from four grazing enterprises in western NSW were involved in all aspects of project design and delivery. An additional 26 producers were also signed up as 'observers', attending project events, collecting data across their own properties and creating a community of like-minded pastoralists in western NSW. Benefits of this approach included improving the breadth, robustness and relevance of the scientific research, bringing together diverse experience and perspectives, connecting stakeholders and increasing the project reach, producer engagement and participation. However, this approach was not without challenges, including increasing project complexity and scope creep, managing varying expectations of different partners, maintaining engagement and balancing the need for scientific design and rigor with practicalities of producer priorities and the environmental context. Key findings and recommendations from the Rangeland Living Skin project in undertaking collaborative, co-designed research for successful producer engagement, industry collaboration and adoption of research outcomes in rangeland grazing systems are discussed.

Introduction

The rangelands of New South Wales (NSW), Australia consist primarily of privately managed extensive grazing enterprises on native grass and shrublands that receive on average less than 500 mm rainfall per year. Historic overgrazing, uncontrolled total grazing pressure (TGP) and drought have collectively led to widespread soil degradation, erosion, loss of perennial grasses, poor landscape function and a loss of productivity across the region (McKeon et al. 2004). These drivers reduce community, business and landscape resilience, and as result, producers are looking for cost effective solutions to regenerate their resource base and remain viable into the future. Rangelands Living Skin (RLS) was a five-year project linking producers, scientists, education and extension agencies, commercial carbon companies and communications professionals to explore and evaluate cost-effective practices that focused on regenerating the NSW rangelands and provide support to enable livestock businesses to be productive, profitable and sustainable. The project aimed to create an evidence-base and build capacity for widespread adoption of practices that benefit soil, plants, animals and people – the living skin of the rangelands.

The value of conducting co-designed collaborative research, involving both research and practitioners to develop problem-orientated and solution-focussed research is well recognised (Mauser et al. 2013, Moser 2016). It has been a successful approach in projects in Australia (e.g., Price & Hacker 2009, Bridle & Price 2009) and internationally (e.g., Wilmer et al. 2022), increasing stakeholder engagement and connecting a diverse network of stakeholders to achieve a common objective, although the challenges of this approach are also recognised (Wilmer et al. 2022, Bridle & Price 2009). This paper outlines the co-design approach of the RLS project, the key outcomes of the project and provides recommendations in undertaking collaborative, co-designed research for successful producer engagement, industry collaboration and adoption of research outcomes in rangeland grazing systems.

Co-design approach and review method

The RLS project was co-designed, with project objectives, activities, deliverables, methods and data collection developed in consultation with 12 project partners. This approach was intended to ensure relevance and practicality of project objectives and deliverables and maximise adoption of learnings by producers in Western NSW rangelands. At the centre of the project was the involvement of four 'core' producers who approached the researchers and/or were identified through project partners with a common goal of achieving environmental, business and productivity outcomes across their properties. The producers collaborated with the project team to identify, implement and monitor practices they decided would be beneficial to achieving the goals they set for their property. Methods to monitor and evaluate the success of management interventions and practices were developed to ensure outcomes of interest to producers were measured and reported on. Where possible, the core producers were involved in the establishment of trials, collection of data and photo points following trial installation, and in communication of trial results through field days, newsletters, scientific publications, case studies, project milestone reports and the final project report. Other project partners included Resource Consulting Services, Western Local Land Services, Australian National University, CarbonLink, Select Carbon, Soils for Life and Meat and Livestock Australia. The project engaged producers from an additional 26 livestock production businesses in western NSW to build their capacity and support their decision-making regarding adoption of practice change on up to 1M ha of grazing land in western NSW. These producers were involved through data collection and monitoring across their own properties, training, online discussions with subject matter experts and field days.

Research trials were established to investigate effects of management interventions identified as areas of interest by the producers for their context and goals, with support of the project team. Interventions included water ponding, deep ripping, intensive short-duration animal impact, gypsum, soil biological stimulants, hard-seeded annual legumes and mixed-species cropping. Additional monitoring investigated the effects of planned grazing management on ground cover, soil carbon dynamics and relationships in rangeland grazing systems, soil chemistry constraints in NSW rangelands, ground cover trends across NSW rangeland grazing systems, rangeland grazing business profitability, and greenhouse gas emissions from rangeland livestock enterprises.

Over the life of the project, the project hosted 17 in-person field days and workshops on a variety of topics relevant to the project theme, including soil carbon, soil biology, soil monitoring, ground cover, grazing management and natural capital. Additional online workshops, webinars and recorded videos were hosted through the project on a broad range of topics and further extension to a broader audience was achieved via fact sheets, newsletter and media articles, presentations and social media.

Towards the end of the project, a survey to all project partners was distributed to collect feedback on the key successes, challenges and recommendations going forward of the collaborative, co-design approach and the outcomes of the project. 14 responses from 10 of the project partners were received. The findings were further discussed through three focus meetings with the project partners to refine this feedback into key learnings and recommendations, with all project partners provided the opportunity to provide further review and input via email and shared online documents. During this review and from trial and learnings throughout the life of the project, project partners documented key factors for engaging producers in research, development and extension activities in NSW rangelands.

Outcomes and learnings from RLS for collaborative research

Overwhelmingly, project partners considered the RLS a success and identified value in structured and meaningful producer collaboration throughout the project, from inception to delivery, as well as the broad skillset provided through partner organisations. Benefits of this approach included improving the breadth, robustness and relevance of the scientific research, bringing together diverse experience and perspectives, connecting stakeholders and increasing the project reach, producer engagement and participation. Key outcomes of the RLS project included:

- Enhanced producer awareness and capacity building related to management and monitoring of soil, pastures, biodiversity, landscape function, productivity and profitability in rangeland grazing systems
- Improved collaboration and knowledge exchange between producers, researchers and industry stakeholders in the NSW rangelands
- Scientific evidence demonstrating the efficacy of management practices and enhanced understanding of relationships between carbon and environmental variables in data-poor rangeland areas
- Demonstration of environmental, productivity and profitability outcomes of management practices in NSW rangeland grazing systems

Project partners also identified learnings, considerations and challenges of this expansive project team and producer-centric approach, including: 1) an ambitious project scope designed to be multi-disciplinary but which at times led to a lack of clarity and accountability, and was constrained by time and financial resources; 2) at times, limited producer engagement and participation in project activities due to competing events, long distances, low populations, and workload priorities; 3) external factors such as COVID-19 or floods which challenged momentum of the project; and 4) managing expectations of a large and diverse project team, at times with participants pulling in different directions in regards to the delivery of project activities and communication of project outputs. Key to overcoming these challenges was regular, open and respectful communication, recognising the skills and knowledge that stakeholders bring to the project team and taking a participatory approach to all project activities, including in the planning of events and development of project outputs.

Key 'success' factors in fostering producer engagement

Due to the large areas of land managed by producers, and the low population density in this extensive environment, it is critical that rangelands research, development and extension (R, D & E) actively, intentionally, and successfully engages producers to optimise value and potential adoption. At the conclusion of the RLS Project, the following recommendations were developed by the project team which includes the core producers to outline key strategies to foster meaningful engagement with producers, thereby enhancing the overall impact and value of collaborative projects.

→ **Set realistic and achievable R, D & E objectives** and priorities with both producers and industry
→ **Co-design** R & D projects with producers and industry stakeholders to ensure activities are relevant, practical and of interest to target audience and end users of information
→ Outline a **clear value proposition** for producers, including the project outcomes that will be of value to them and their business, now and in the future
→ **Engage producers in all aspects of project**, encouraging active participation and contribution and practical feedback (including project development, monitoring, hosting events, presenting results, reviewing project outputs)
→ **Incorporate producer knowledge** and feedback into project design, activities and outputs

- → **Value the time, expertise and contribution** of producers in the project team, including payment for time and services, ensuring equal partnership and ownership and clear accountability
- → Establish research and demonstration sites '**on the ground'**
- → **Encourage producer-led initiatives** and peer-peer learning. Where possible, have producers present and talk to the experience and results of projects on their property
- → **Highlight success stories, make the research accessible and showcase** R, D & E findings via multiple avenues including field days, workshops, media articles, case studies, podcasts and webinars, to increase reach and engagement
- → **Work with existing producer-led groups** or establish enduring producer networks that collaborate on multiple initiatives to ensure longevity beyond short-term projects
- → **Time events** to avoid 'busy' periods in the production calendar, avoid conflicts with other events, and plan ahead to 'save the date'
- → **Personal connection** is important – ensure regular one-on-one communication between the project team, industry and producers
- → **Provide opportunities for connection** between producers and with industry experts
- → **Provide summary of research or project results** and project data to producers in a timely manner and meaningful and practical format

Conclusion

The Rangelands Living Skin project demonstrated the potential for and application of co-designed, collaborative research and extension to understand and promote management practices that can achieve ecosystem sustainability, productive landscapes and profitable businesses in a semi-arid rangeland environment. The project highlighted the value of producer involvement in all aspects of project design and delivery, alongside a diverse team of stakeholders, and their role in promoting and communicating project findings to support wider adoption beyond the project participants. Engaging producers is critical in maximising the impact of research. Producer participation in R, D & E can be encouraged by ensuring there is a clear value proposition and the project outcomes are relevant to producer needs, valuing the time, knowledge and services provided by producers in the project team, supporting producer-led initiatives and ensuring local support and research activities.

Developing and delivering collaborative R, D & E is not without challenges; however, projects will be more successful if they have a clear project scope and deliverables that are developed collaboratively with all project partners, with regular open communication, flexibility in the delivery of project activities and ensuring sufficient time and budget to achieve project objectives. As political and industry R, D & E priorities and associated funding avenues change, there is an increasing need for a strong value proposition and co-investment by stakeholders to support continued R, D & E in the rangelands. New work will need to consider and facilitate links to First Nations people and would benefit from incorporation of indigenous knowledge and management. Furthermore, future R, D & E would benefit from connecting rangeland regions (across borders, e.g., NSW, QLD, SA, WA), bringing together investment under unified programs of work and sharing information and learnings across broader networks with similarities in production systems. Rangeland grazing systems are a unique and valuable asset for both livestock production and natural capital in Australia. By fostering strong, collaborative relationships among producers and other stakeholders for R, D & E and striving to meet the key principles and strategies for collaborative R, D & E we can drive meaningful progress towards a collective rangelands vision.

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Collaborative Adaptive Rangeland Management: Lessons learned and opportunities awaiting from the first decade

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Key words: collaborative; co-production; grazing management; participatory research; semiarid rangeland

Abstract

In the semiarid, shortgrass steppe of North America, the Collaborative Adaptive Rangeland Management (CARM) project engaged an 11-member stakeholder group composed of ranchers, non-governmental conservation organization representatives, and state/federal agency personnel since 2012. The stakeholder and research team collaboratively implemented adaptive, multi-paddock (AMP) rotational grazing management, and compared multiple outcomes to those from traditional management of season-long grazing at the same stocking rate during the growing season (mid-May to October). The transdisciplinary scientific team collected and provided to the stakeholders monitoring data about vegetation, livestock, and wildlife habitat, including cattle foraging behaviour and movement dynamics, diet quality, distribution of grazing animals, remotely sensed standing biomass, grassland bird populations, animal weight gains, financial returns, soil health and carbon, and vegetation production, composition, structure, and diversity. A collaborative learning objective was added for co-production of new knowledge and its application to new areas, and increasing trust, respect, and understanding among participants. Iterative decision-making and learning within and across years have been documented through revised objectives, key triggers for drought planning and flexible stocking, and enhanced dashboards for tracking precipitation, soil moisture, forage conditions, and livestock diet quality. A key lesson learned is the importance of open and transparent communications through sustained engagement of stakeholders, leading to increased trust. Research results highlight that higher stocking density with AMP grazing consistently reduces animal weight gains and consequently financial returns in non-drought years through altering foraging behaviour and reducing diet quality. At the same time, vegetation heterogeneity across paddocks is enhanced with AMP grazing, providing a wider range of grassland bird habitat. Future directions include application of new technologies for precision livestock management (e.g., on-animal sensors, near-real-time remote sensing) for flexibility in within-season stocking density to address improvement of livestock performance and profitability, low- and high-vegetation structure for numerous ecosystem services, and greater drought resilience.

Introduction

Born out of the key recommendation to have ranch-scale management-partnerships to address the production-conservation interfaces in rangeland management (Briske et al. 2011), the Collaborative Adaptive Rangeland Management (CARM) project began in 2012 by engaging with a 11-member stakeholder group comprised of private ranchers (n=4, associated with the local grazing association, Crow Valley Livestock Cooperative, Inc.), non-governmental conservation organizations (n=3, The Nature Conservancy, Environmental Defense Fund, and Bird Conservancy of the Rockies) and public land management personnel (n=4, USDA Natural Resource Conservation Service, USDA Forest Service, Colorado State University Extension, and Colorado State Land Board). This resulted in co-produced objectives on vegetation, profitable ranching (including livestock weight gains), and wildlife habitat that formed the basis for the transdisciplinary science team to develop monitoring methods to collect baseline data in 2013 and apply experimental treatments (2014-2023, Augustine et al. 2024). Social learning objectives were added in 2015 (Wilmer et al. 2022).

The overarching goal was to examine how science can be conducted at ranch-level scales with manager involvement to evaluate the effectiveness of adaptive multi-paddock (AMP) grazing management for both production and conservation goals. In particular, we sought to examine an approach to rangeland management that responds to current and changing rangeland conditions, incorporates active learning, and makes decisions based on quantitative, repeatable measurements collected at multiple spatial and temporal scales.

Methods

At the USDA–Agricultural Research Service's Central Plains Experimental Range in northeastern Colorado, USA, a semiarid, shortgrass steppe rangeland ecosystem, and a site in the Long-Term Agroecosystem Research (LTAR) network, we compared CARM, designed to incorporate AMP principles, to traditional rangeland management which is a season-long (mid-May to early October) grazing approach widely used in the region (TRM, Bement 1969). Each treatment was implemented on 130-ha paddocks paired by soils, topography, and plant communities (n=10 pairs). For the first 5 years of the experiment (2014-2018, CARM 1.0), yearling steers in the CARM treatment were managed as a single herd using AMP grazing with rotational movement of steers among the paddocks with planned year-long rest in 20% of the paddocks (i.e., 2 of the 10). In the second 5 years (2019-2023, CARM 2.0), CARM steers were managed as 2 herds using AMP grazing to reduce negative effects of stocking density on livestock weight gains (Augustine et al. 2020) with the same planned year-long rest in 20% of the paddocks. For the TRM treatment, each of the 10 paddocks were grazed by a separate, small herd such that both treatments were grazed by the same total number of steers each year, thereby controlling for annual stocking rate. The stakeholder group was given full agency in deciding how to collaboratively and adaptively manage the yearling steers in the CARM paddocks. See the following papers for additional methodological details regarding vegetation (Augustine et al. 2020), livestock diet quality (Jorns et al. 2024), livestock weight gains (Augustine et al. 2020, Derner et al. 2021), foraging behaviour (Augustine et al. 2022, 2023), grassland birds (Davis et al. 2020, 2021), tiller defoliation (Porensky et al. 2021) remote sensing (Kearney et al. 2022a,b), social learning (Wilmer et al. 2018, 2022, Fernandez-Gimenez et al. 2019), economics (Windh et al. 2019, 2020, Baldwin et al. 2022), and rangeland modelling (Cheng et al. 2021, 2022).

Results

Vegetation: Biomass production did not differ between grazing treatments (Augustine et al. 2020). Ground data collected in the CARM experiment was used to calibrate a new model that predicts daily standing herbaceous biomass at a 30-m pixel resolution from satellite imagery (Kearney et al. 2022a). We observed that frequencies of grazing on a palatable, cool-season grass (western wheatgrass, *Pascopyrum smithii*) were more sensitive to stocking rate than grazing treatments, as roughly two-thirds of tillers remained ungrazed annually indicating that season-long rest is present in both CARM and TRM. Frequencies of tiller regrazing were low (5−15%) and similar between treatments. Although defoliation patterns were similar between treatments at the whole-ranch scale, CARM enhanced spatial and temporal heterogeneity in defoliation frequencies among individual paddocks, as those grazed earlier in the season or for longer experienced more defoliation (Porensky et al 2021). The Agricultural Policy/Environmental eXtender (APEX) model simulated forage production across years and among soil types (Cheng et al. 2021).

Profitable Ranching: Livestock weight gains were consistently lower (11%–16%) in CARM than TRM, except when forage availability and quality were very low due to drought, or exceptionally high due to a very wet year (Augustine et al. 2022). Reduced weight gains in CARM were attributed to the higher stocking density of steers which altered foraging behaviour (more linear grazing pathways) and spatial grazing distribution (Augustine et al. 2023), and reduced diet quality (Jorns et al. 2024). We quantified the contribution of adaptive grazing management (i.e., the stakeholder group' selection of paddock sequence and grazing rotation indicators) to cattle weight gains using a third herd of steers rotated in a randomly determined sequence (i.e., without adaptive management). This comparison indicated that weight gains of adaptively managed cattle were about 25% greater than gains expected under purely random rotational grazing management (Derner et al. 2021). Satellite time series were used to estimate forage quality (Irisarri et al. 2022), which in combination with estimated standing biomass (Kearney et al. 2022a) can provide reliable estimates of yearling cattle growth rates (Kearney et al. 2022b). Daily weight gain was adequately simulated using the APEX model, with dry matter intake, total digestible nutrients, and temporal distribution of dry matter intake the primary influencers of livestock performance (Cheng et al. 2022). Economic evaluations revealed substantially greater costs for fencing and water infrastructure, and for labour in the multi-paddock CARM compared to TRM (Windh et al. 2019). Economic analyses that included long-term market conditions and fluctuations in cattle prices during the seasonal cycle showed that net returns were highly variable between CARM and TRM (Windh et al. 2020).

Wildlife: Relative to TRM, CARM enhanced heterogeneity in vegetation structure across the landscape, benefiting some grassland bird species (Augustine et al. 2024). Resting paddocks for a full year can generate grassbanks that benefit grassland birds that prefer taller/denser vegetation structure such as Grasshopper Sparrow (Ammodramus savannarum), whereas intentional heavier grazing can benefit grassland bird species preferring shorter/sparser vegetation like the Thick-billed Longspur (Rhynchophanes mccownii) (Davis et al. 2020, 2021). These results helped the stakeholder group understand the spatial specificity of managing for grassland bird species and led to refinement in the wildlife habitat objective by accounting for site fidelity of certain grassland birds and trade-offs between suitable bird habitat and vegetation/plant community objectives.

Social Learning: Evidence of shared learning included the individual stakeholders and researchers acknowledging and examining one another's worldviews (Fernandez-Gimenez et al. 2019). We also observed an increase in sister projects implementing lessons from CARM, including Barta Brothers Ranch at the University of Nebraska, and the US Sheep Station initiating a Sheep Collaboratory project. Following the experiment's first major drought in 2020, the stakeholder group and science team co-revised the grazing management plan to more explicitly address drought using precipitation and soil moisture gauges to monitor the amount of precipitation received to date relative to the long-term mean. Stakeholders and researchers have collaborated to organize numerous field tours, develop a symposium on the CARM project at the 2018 Society for Range Management meeting, and produce a video (USDA-ARS CARM video) and a series of fact sheets about shortgrass bird responses to rangeland management, and the CARM project was used as a case study in a report on Agroecosystem Living Laboratories presented to the G20 Chief Scientists in 2019.

Conclusions/Implications

Stakeholders and researchers successfully implemented a participatory, collaborative adaptive management method to co-develop new knowledge about social, economic, and ecological questions in semiarid shortgrass rangelands. This process was often complex and challenging, but those challenges helped inspire learning and developed strong working relationships. Respect, trust, and shared understanding were essential for the collaborative processes and were enhanced by commitment and time for meaningful discussion, debate, and group reflection. This experiment has quantified relationships among adaptive management decisions, cattle grazing distribution, weather variability, and ecosystem services.

To address improvement of livestock performance and profitability, low- and high-vegetation structure for numerous ecosystem services, and greater drought resilience, CARM 3.0 (2025-2029) will have 6 larger paddocks, with 3 replicate pairs of short- and tall-statured vegetation paddocks (383-728 ha, total of 3388 ha), while the TRM treatment will be maintained as 10 paddocks of 130 ha (1300 ha total), each grazed by a separate herd. Stocking rate will remain the same in both treatments within a year, and adjusted annually as decided collaboratively by the stakeholder group. Each of the 3 pairs of CARM paddocks will be grazed by a group of cattle managed adaptively as either 1 or 2 herds depending on weather conditions. Under non-drought conditions, short-statured vegetation paddocks will be stocked at ~50% above the TRM level and tall-statured paddocks at 50% below the TRM level. This will create both a grass bank and more vegetation structure for wildlife habitat in the tall-statured paddocks, while maintaining low structure wildlife habitat and high livestock production in short-statured paddocks. Movements of steers between the short- and tall-structure pairs of paddocks in CARM will be based on near-real time remote sensing tools (Kearney et al. 2022a) to provide the stakeholder group with maps of vegetation biomass and greenness, combined with demand from recent cattle distribution data via on-animal sensors (GPS and accelerometers).

In addition to the larger scale of paddocks in CARM 3.0, the stakeholder group and science team are currently revising the study objectives, which are incorporating the small mammal black-tailed prairie dogs (*Cynomys ludovicianus*) explicitly into the experiment (they were intentionally not included in CARM 1.0 and 2.0), spatially-explicit zones of management within paddocks for some key wildlife species, a shortened grazing season (ending in early September rather than early October) due to economic benefits (Baldwin et al. 2022), and inclusion of an Amplifier Team for more input regarding public needs and concerns, and strengthening messaging of findings from the project to the public for application, impact, and policy.

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12 years of grassland board in Uruguay

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Key words: Grassland, livestock, governance, board

Abstract

Pampas are the only biome in Uruguay, occupying about 60% of the territory and are the main forage resource for cattle and sheep production. Despite this, its value, its resilience to climate change and its provision of ecosystem services are generally underestimated. Almost all of these Pampas, and therefore their conservation, depend on the livestock farmers who own them. In this context, the Grassland Board (GB) was created in 2012, a formal environment within the Ministry of Livestock, Agriculture and Fisheries (MGAP) to improve inter-institutional articulation in pampas, promote the development of technological proposals to increase production in a sustainable way and less vulnerable to climate change, and preserve natural resources. Bringing together 19 public, private, research, extension and farmer institutions and organisations, it is chaired by the Institute Plan Agropecuario (IPA) and operates within the MGAP, which provides the technical-administrative secretariat. The creation of the GB and its experience of institutional articulation in the agricultural sector is an innovative experience that is highly valued by Uruguayan agricultural institutions. Technical proposals such as "Options for the Sustainable Intensification of Livestock Production in Uruguay's Natural Landscapes" have been approved, the "National Day of the Pampas " has been proclaimed by Law No. 20.088, and advice has been provided to decision-makers and to the most important national projects on grassland livestock production. Several high-quality products have been produced, such as publications and awareness-raising events, including the prestigious "The Gold Paspalum" awards. Finally, and after 12 years of intermittent action, the GB has achieved greater articulation between institutions, achieving consensual collective projects and messages. A formal and strong channel of dialogue has been established with the executive and legislative branches.

Introduction

Pampas in Uruguay is the only biome, occupies approximately 60% of the territory and is the main nutritional resource for livestock, most of these are in the hands of private producers and therefore their conservation depends on them. Despite this, their value, their resilience to climate change, and their provision of ecosystem services have generally been underestimated (MGCN, 2019).

In this context, in 2012, the Grassland Board (GB) was created as a formal environment within the Ministry of Livestock, Agriculture and Fisheries (MGAP) to improve interinstitutional articulation in rangelands, promote the development of technological proposals to increase production in a sustainable way that is less vulnerable to climate change and conserve natural resources (MGAP, 2012).

Methods

In this article we will develop how these 12 years of operation have been and their importance for livestock and Uruguayan pampas, we base this work on minutes, publications and interviews with delegates.

Results and Discussion

The GB is composed of 19 public and private institutions and organizations, is presided over by the Institute Plan Agropecuario (IPA) and operates under the auspices of the MGAP, which provides the technical-administrative secretary. The creation of this ambit and its experience of institutional articulation in the agricultural sector represent an innovative experience, highly valued by Uruguayan agricultural institutions (Cáceres and Caballero, 2020). This space brings together government institutions such as: MGAP, the Ministry of the Environment and the National Meat Institute; extension institutions such as: IPA and the Uruguayan Wool Secretariat; Research institutions such as: the National Institute of Agricultural Research, the Faculties of Agronomy and Science of the University of the Republic; producers such as: the National Commission for Rural Development, Federated Agricultural Cooperatives, Rural Association of Uruguay, CREA Groups, Rural Federation, Uruguayan Association of Grasslands Farmers, Uruguayan Society of Rational Grazing, Uruguayan Society of Silvopastoralism and Pampeanas Regenerativas Orientales; regional institutions such as: the Alianza del Pastizal and the Inter American Institute for Cooperation on Agriculture completed their integration.

This integration provides the GB with different points of view and interests, from academia to farmers associations, including the organizations responsible for management and extension. The monthly meeting of representatives of society who directly develop productive activities on pampas with those who generate knowledge and develop technologies, decision makers and articulators, who carry out knowledge transfer, generated an ideal environment for the identification of problems and solutions. The uninterrupted work during 12 years has allowed the consolidation of the area as a recognized and valued space. The good relationship between delegates from different institutions has facilitated the operation and discussion of policies.

Within this framework, the GB has managed to consolidate itself as a space for consultation in livestock farming on the natural environment, advising the Ministries of Agriculture and Environment and other institutions on the main projects on the subject: Family Farmers and Climate Change (2013-2019), Improving the Sustainability of Family Livestock of Family Livestock in Uruguay (2016-2018), Participatory Assessment of Land Degradation and Sustainable Land Management in Grassland and Pastoral Systems (2017-2021); Livestock and Climate project (2019-2023); Grass Management project (2020-2025), to name the main ones. In addition, the GB has shown a great capacity to respond to the different demands posed by the authorities, such as the systematization in less than a month of all the projects related to livestock and campos in Uruguay (MGCN & DGRN, 2020).

In recent years, the GB has set three objectives in its strategic plan:

1. To conserve our country's biome, the Pampas.

2. Improve the economic, environmental and social results of livestock farming on the Pampas.

3. To promote the recognition and valuation by society of the Pampas and its ecosystem services.

With respect to the first objective, the GB managed to put the issue on the agenda, thanks to the exchange with the legislative power it was possible to establish with Law number 20.088 the “National Day of the Uruguayan Pampas” and also has been working on different legislative proposals to improve its conservation (Figure 1), it also provided technical elements for the characterization of grasslands (Stainano and Paruelo, 2017).

Fig. 1. Meeting at the National Parliament between Legislators, authorities and delegates of the GB.

Regarding the second objective, technical proposals such as “A New Paradigm of Intensification for the Campos of Southern South America to Increase Economic and Environmental” (Jaurena, et al. 2021) were agreed upon (Figure 2), and the creation of the Livestock Farming Observatory on Natural Grasslands, which seeks to generate a public good that improves the management of the country's natural resources, facilitating the contribution of information generated and its access and interpretation by actors responsible for their management and administration, ensuring the continuity of the products already generated from the Science and Technique system (MGCN, 2021).

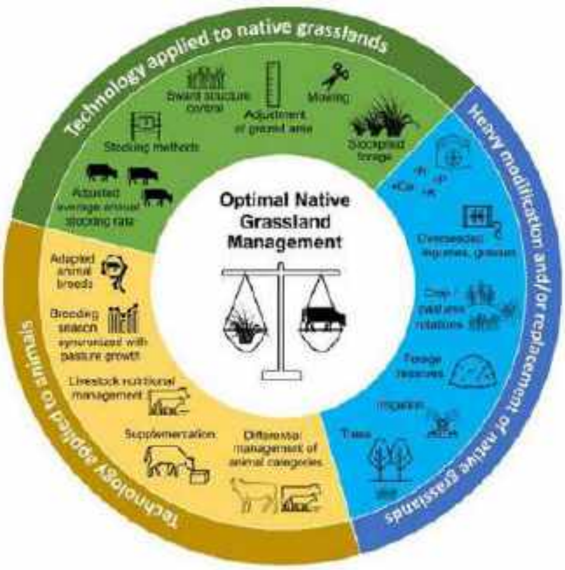

Fig. 2. A new model for livestock sustainable intensification that describes the role of technology applied to livestock management (orange), to modified or replaced native grasslands (blue), and to native grasslands (green) to achieve optimal native grassland management (Jaurena, et al. 2021).

The third objective seeks to promote the recognition of rangelands by the Uruguayan Society, in this sense, several high-quality products have been produced, such as publications, courses for producers and technicians, a traveling photographic exhibition and awareness-raising events such as the recognized “The Gold Paspalum” acknowledgments (Figure 3), which seek to highlight those who have contributed significantly to livestock farming in the Uruguayan Pampas.

Fig. 3. Presentation of "The Gold Paspalum" acknowledgments 2020 (left) and 2024 (right).

Additionally, the GB has achieved a real knowledge and articulation among its member institutions and organizations, materializing this in different extension, research and education projects, executed jointly (MGCN & DGRN, 2020). Furthermore, common messages have been generated, such as "the need for farms to work with higher pasture height", a simple premise that implies an improvement in the productivity and sustainability of Uruguayan cattle ranches.

Conclusions

In its first 12 years, the GB has consolidated and positioned itself as a relevant actor of consultation on rangeland and livestock issues in Uruguay. In addition to making concrete products, the GB goal has always been to "make things happen" regardless of which organization or institution

Acknowledgements

To all the delegates of the organizations and institutions that have been part of this area and whose work has consolidated and strengthened submits it.

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WAARC, a state government funding initiative to catalyse agricultural research in northern Western Australia

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Key words: collaboration; agricultural research; governance; northern Australian agriculture

Abstract
There is broad agreement that research and development is an investment in the future viability and success of an industry. This view has underpinned the establishment of the Western Australian Agricultural Research Collaboration (WAARC). This Western Australian (WA) state government initiative is designed to foster collaboration among WA's participating research organisations (DPIRD, CSIRO, Grower Group Alliance and the universities of Curtin, Murdoch and WA to support WA-centric new projects and research capacity building. WAARC is seeking to support longer-horizon research developing and integrating new areas of science with potential for industry application and to enhance early-career development opportunities for researchers. Its creation is a response to the diminution of a consolidated research capacity in WA. The WAARC initiative currently comprises six program of work, all of which are potentially relevant to the sustainable intensification of agricultural production in northern Australia. Of these, the Northern Agriculture program focuses exclusively on developing research and research capacity in this region. The objective of the program is to increase the Gross Value of Production through intensification of agriculture by 2030 focusing on sustainable growth of irrigated agriculture and the northern beef industry. A key priority in the Northern Agriculture program is the integration of irrigated agriculture and beef production. Growth in agriculture in northern WA focuses on intensifying the cattle industry and optimising irrigated agriculture, ensuring that this is achieved in a way that is environmentally and socially responsible. A related key priority is capturing economic benefit of growth by First Nations' pastoral and related enterprises.

Introduction
In the north of Western Australia (WA), there is strong potential for further development of the agricultural sector, particularly through capitalising on existing resources for irrigated agriculture near Kununurra in the eastern Kimberley region. This region has a geographic advantage for trade with south-east Asia, but its remoteness, climate extremes and low population density have proved challenging for sustaining the workforce required to deliver the research. The WAARC Northern Agriculture program, launched as part of the WAARC initiative by the WA Government, focuses on supporting longer-horizon research projects and fostering collaboration across WAARC's research partner organisations; DPIRD, CSIRO, the Grower Group Alliance and the universities of Curtin, Murdoch and WA. The Northern Agriculture program is developing new opportunities for investment in new projects and capability-building activities to support the agricultural

industry in northern Australia. The program aims to support irrigated agriculture and beef production in northern WA to achieve sustainable growth while ensuring environmental and social responsibility. It is envisaged that this will be achieved through the strategic development of projects with research partners and industry, and by providing leverage to extend other research activities. An emphasis on benefiting First Nation enterprises through economic empowerment and knowledge sharing further underscores the program's inclusive vision. WAARC is developing its governance structure, which has ongoing financial support through funding from each of the partner organisations.

Methods

The review paper draws on insights from secondary data sources, including project reports, official documentation and published literature, as well as contributions from individuals currently involved in the WAARC initiative. It also incorporates case studies of similar initiatives in comparable regions. The review further considers research on agricultural research collaboration and governance models. The aim of the review was to consider the opportunities, challenges and governance issues in agricultural research when implementing a collaborative model for research in northern WA, with a focus on identifying best practices and actionable recommendations.

Results and discussion

Benefits of collaboration

Cross-organisational collaboration is a foundational characteristic of the WAARC initiative, and WAARC encourages a collaborative culture by having a minimum of three partner organisations participating in its funded research activities. A key aim of WAARC is to develop the next generation of researchers, based and focussed in WA, in a way that builds connections with the agricultural industry so that they are better prepared to identify and address emerging challenges. Enabling early-career researchers to develop relationships through projects that link universities with more industry-facing organisations and producers is expected to result in more solution-focused and impactful research (Strycharz et al. 2022). Inter-organisational collaboration is needed to address complex challenges facing agriculture through integrating multidisciplinary expertise, sharing resources, fostering innovation and focusing on industry issues. If coordinated well, research collaboration will enhance the scalability and impact of research outputs, improve funding opportunities and prevent duplication of efforts, thereby increasing efficiency (Jones et al. 2021). Collaborative efforts support knowledge exchange, capacity building and stakeholder engagement, and ensure that research aligns with farmers' needs, industry demands and policy priorities. By fostering collaboration between research institutions and industry, WAARC aims to build capacity and projects with a higher level of collaboration, thereby delivering actionable solutions to agricultural challenges facing WA.

Collaborative research in northern WA

Applying a collaborative research model in northern WA to build research capacity and invest in novel areas of research (e.g. precision agriculture, water-efficient irrigation and sustainable livestock systems) provides significant opportunities to increase sustainable agricultural production. However, human capital and expertise are a significant limitation in northern WA, as it is for most of rural Australia. Conducting research activities in this region also presents additional unique and significant challenges, including harsh climatic conditions, which can be favourable to pests and disease, water scarcity during the dry season, and limitations in soil fertility and pasture quality. The working conditions in this region also present unique health and safety considerations that further complicate experimental work and data collection. Additionally, balancing profitability with sustainability, especially for First Nation enterprises, requires nuanced approaches to ensure economic and social viability. Under these conditions, investing in research tends to entail higher operational costs, longer development timelines and less certain outcomes.

There have been several previous, but ultimately fruitless, efforts to develop collaborative research initiatives to meet the needs of the northern WA agricultural sector. These efforts were initiated in various iterations across the organisations represented in WAARC but lacked the resources to break away from business-as-usual research structures to generate broad collaboration and longevity. However, these proposals contributed to the foundations and momentum for the current WAARC and its Northern Agriculture program. At a national level, supporting agriculture in the north of Australia across WA, Northern Territory (NT) and Queensland has been a central mission of the Cooperative Research Centres for Northern Agriculture (CRCNA). Running from 2017–2027, the CRCNA has been responsible for the establishment of a broad range of research projects across Australia's north, including WA regions, in particular, the Pilbara and Western and Eastern Kimberley.

Having agricultural researchers regionally located in the north of WA (and Australia generally) is important to expedite research activities into industry adoption. Locally based researchers experience greater immersion in local contexts, allowing for deeper engagement with communities, stakeholders and ecosystems. This proximity can foster trust with local groups, including First Nations, and enable more responsive, adaptive research methodologies tailored to the region's unique challenges, allowing quicker uptake by local industry as barriers to adoption are identified through co-design and local networks/relationships. A fly-in fly-out (FIFO) model can reduce long-term costs and allow researchers access to peers, mentors, expertise as well as specialised research facilities and broader resources based in urban centres.

The FIFO model has been widely adopted in other industries of the WA economy in the north and other regions to ensure the supply of highly specialised and credentialled experts through to low-skilled workforce (McKenzie & Hoath 2017). The resources sector has the economic capacity to fund both well-organised FIFO logistical process as well as offer attractive financial compensation for the more unorthodox work roster. Public institutional employment models and conditions, however, are often neither flexible enough nor resourced sufficiently to enable the FIFO model to operate from the major city centres. The challenges are similar for rural-based staff to work for parts of the year in the region during the field season and another region/office in the off-season, despite primary producers and other parts of the industry moving to this model. For example, many of the current generation of broadacre farmers are now opting for a Drive-in Drive-out (DIDO) lifestyle with many working between large city centres on the coast and their inland rural properties, while those in the north of WA do the same over the wet season. Nevertheless, these FIFO/DIDO approaches risk limited continuity and weaker relationships with local stakeholders, are higher in cost, and may contribute to a less nuanced understanding of regional dynamics, which could undermine the effectiveness and relevance of research outcomes. Balancing these models requires careful consideration of the project's objectives, regional needs and resource allocation, with no clear preferred model due to the substantive pros and cons for each (McKenzie & Hoath 2017).

WAARC is expecting to play a key role in supporting targeted research activities and recruiting and providing ongoing support to early-career researchers over and above traditional pathways and funding. Providing additional funding for industry-facing PhDs and supporting appointment and retention of early-career research positions will help to alleviate some staffing shortages in northern WA and foster industry engagement with postgraduate researchers through its PhD research scholarship program, a key objective of WAARC. This program helps to engage early-career researchers who wish to align their research with the Northern Agriculture program goals and potentially build relationships with local industry and remote regions that may not have been available otherwise. WAARC also provides the network of WA-based mid- and late-career researchers, and national connections via CSIRO, who can provide mentoring and support for these WAARC early-career researchers irrespective of the lead partner organisation. The WAARC model (including an 'Agricultural Technologies' program) is seeking to expedite new technologies, such as augmented reality, providing novel solutions for remote research capacity.

Developing governance models

Effective governance underpins successful collaboration. The WAARC management team includes representation from participating organisations and processes such as workshops to ensure broad participation among collaborating partners. In the Northern Agriculture program, the small scale of agricultural research in northern Australia, particularly in the cattle industry, means that the pool of potential research participants is quite small. The WAARC governance structure assists across a range of areas including agreeing on priorities, communication, contracting and an equitable distribution of resources. Australia's Cooperative Research

Centres (CRCs) have a long history of enabling research, and their experiences are valuable in designing and improving WAARC's governance framework.

WAARC currently operates via a memorandum of understanding and a Steering Committee, which meets regularly to review proposed research activities and to provide strategic guidance. These committees are a common feature of joint venture-style structures in WA. The longer-term organisational structure of WAARC is being reviewed and will likely change to a more suitable model for the organisation in the long term. The investment governance structure for WAARC should incorporate a robust framework with clear investment policies, risk management protocols, and accountability mechanisms to safeguard the fund's sustainability and optimise returns for innovative projects and capacity-building initiatives. It must also align with WAARC's funding priorities to support high-level innovative projects and strategic research areas, maximising the impact of the fund's investments. To be successful, WAARC must seamlessly integrate capacity-building initiatives to enhance research capabilities and develop human capital within its organisation and partner entities, as previously outlined. The current structure is designed to support agile decision-making, particularly in fund allocation, while embedding long-term sustainability measures such as financial stewardship, performance evaluations, and strategies to replenish the investment fund. Flexibility is a critical aspect of this framework, allowing WAARC to pivot as needed to address emerging agricultural priorities. For example, recent investments by WAARC in polyphagous species (e.g. shot-hole borer beetle) research have aimed to mitigate damage caused by this insect pest to urban and agricultural trees.

WAARC also plays a pivotal role in future preparedness, ensuring research capabilities are ready to support rapid responses to escalating challenges in northern WA, such as biosecurity threats, environmental concerns or trade market disruptions. However, administrative coordination across the initiative presents unavoidable complexities, which has occasionally slowed contracting and project initiation. Specialist staff have been instrumental in managing these constraints, and further administrative improvements are anticipated as the WAARC initiative continues to mature.

Conclusion

The WAARC Northern Agriculture program exemplifies a strategic approach to addressing regional agricultural challenges through research collaboration. While opportunities abound, addressing the unique challenges of northern WA requires robust partnerships, governance and flexibility. Institutional flexibility to enable work-life balance and the ability to work part-time in the north during favourable parts of the year and in other regions for other parts and/or via a FIFO model need to be considered. The program's focus on integrating irrigated agriculture with beef production demonstrates the potential for scalable and sustainable agricultural models. However, leveraging these opportunities will depend on overcoming logistical barriers, including developing a locally based skilled workforce, and ensuring that First Nations' communities are integral co-beneficiaries.

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Valuing traditional and Indigenous knowledge: evolution, threats and opportunities

Mongolian herders' plant knowledge: intergenerational transfer and change

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Key words: Traditional Ecological Knowledge; rangeland, plant, Mongolia

Abstract
Traditional Ecological Knowledge (TEK) is increasingly recognized as an important component of biocultural diversity and a potentially valuable resource for adaptation to future changes. TEK is a vibrant knowledge system held by geographically and socially defined communities in relation to their day-to-day interactions and relationships with their environment and is transmitted between generations. With the socioeconomic changes in the last 30 years in Mongolia, many young herders have moved to cities for jobs and education and many elder herders have followed them, to help care for grandchildren and to avoid the increasing harshness of livestock herding caused by climate change and rangeland degradation. With these demographic and social changes, some fear that TEK is being lost. Therefore, we sought to document herders' current plant knowledge, and to compare the knowledge of younger and older herders, and those living in remote rural and settled areas. We asked 30 herders in four subdistricts in Arkhangai province, Mongolia to list all the plants they know that grow in their community and to discuss their uses. Knowledge of plants and their uses did not vary between rural and settled areas, likely because many older participants had moved to the province center, taking a lifetime of herding knowledge with them. Plant knowledge did vary with age. Younger herders didn't mention certain species that have declined in the local environment, likely due to environmental changes. To support conservation and intergenerational transfer of plant TEK, we are working with rural herders, schoolteachers and the district cultural center to develop school curricula and museum exhibits featuring local plant TEK.

Introduction
Traditional ecological knowledge (TEK) is increasingly recognized as an important component of biocultural diversity and a potentially valuable resource for adaptation to future changes. TEK is a vibrant knowledge system held by local place-based communities in relation to their day-to-day observations, interactions and relationships with their environment (Berkes 1999, Fernandez-Gimenez and Fillat 2012). TEK is accumulated, practiced and transferred from generation-to-generation and it holds place-based values and belief systems (Berkes et al. 2000). The connection between cultural and biological diversity as known as biocultural diversity emphasizes the coupling of environment/nature and culture (Loh and Harmon 2005; Seele et al. 2019). Plant biodiversity indicates the richness of the rangeland resources and their health, on which herders' dependent on plant resources for livestock forage, food, medicines, firewood, construction of dwellings as well as ritual and cultural practices. Cultural diversity is manifested from individual ideas to entire community and culture (Loh and Harmon 2005).

Many TEK studies warn about potential loss of these knowledge systems due to social-ecological and political changes (Fernandez-Gimenez et al,. 2017) and some recent studies also emphasize the importance of TEK application for adaptation to future changes considering of dynamic nature of the TEK (Peter et al. 2024). Therefore, providing means for younger generations to access TEK is critical contribution to preserve, practice and use TEK for adaptive management in a changing world. Mongolia is one of the few countries practicing mobile herding on its vast open native rangelands (Fernandez-Gimenez 2000, Honey church 2010). However, overgrazing and climate change are degrading Mongolia's rangelands (Liu et al. 2013, Zhao et al. 2015), and at same time herding culture is fading due to socio-economic changes (Fernandez-Gimenez et al,. 2017). In Mongolia, TEK is transmitted between generations, elders sharing knowledge with children and grandchildren within families during day-to-day activities, and with young herders of communities when they meet and exchange information on the pasture (Peter et al. 2024). Current, ecological and socio-economic changes are thought to weaken and alter access to, transfer and, practice of TEK in Mongolia in two main ways. First, many young herders have moved to cities for jobs and education and many elder herders have followed them, to help care for grandchildren and to avoid the increasing harshness of livestock herding caused by climate change and rangeland degradation. Second, introduced techniques (herding via car and motorbike) and technologies (mobile phone, satellite collar) reduce workloads and save time for herders, but also limit the practice of TEK and weaken herders' close interactions with and observations of their environment (Seele et al. 2019). In light of these changes, we sought to document herders' current plant knowledge, and to compare plant knowledge across herders of different genders, ages and living in remote rural areas versus settlements. We expected women and men both to know many plants, but we expected that the types of plants they emphasized might differ. For example, we thought that women might mention more plants used for food and human medicine and that men might mention more forage plants. We expected older herders to hold more knowledge about specific plants and their uses. We expected herders in more remote rural areas to maintain more traditional practices and therefore to hold more knowledge of plants, in terms of number of plants and their uses.

Methods

We conducted our study in four different subdistricts (baghs) of two districts (soums), Ikh Tamir and Undur Ulaan, of the Arkhangai province. Arkhangai lies 500 km to the northwest of Ulaanbaatar, the capital city of Mongolia. These four baghs include Azarga bagh of the Undur Ulaan soum which is distant from the soum and aimag centers, Bayangol bagh of the Undur Ulaan soum which is very close to the soum center, Khan Undur bagh of the Ikh Tamir soum is close to the soum and aimag centers, and lastly, Tsetserleg VII bagh which is very close to the aimag center. Arkhangai aimag is in the mountain and forest region, where forests, rivers and lush vegetation support four types of livestock, horse, cattle, yak, sheep, and goat.

We interviewed herders during the spring, early summer, and fall of 2022. We recruited interview participants using a snowball method and sought to include herders of all ages and herding experiences across these four baghs. All interviews were conducted in Mongolian and participants were asked to list all the plants they know and that grow in their homeland (*nutag*). After a participant named all the plants they knew, we asked about each plant's use either as medicine, food, and/or livestock forage. Finally, we asked them to share their observations about increasing or decreasing trends in abundance of each plant. Data collection was conducted with participants' free, prior and informed consent and conducted under the Purdue University Institutional Review Board (IRB) protocol (# 2021-1083). All interviewees read and signed the consent form before we started our interview. In total, we interviewed 30 herders, of which 24 were men, and 6 were women. Seven of the interviewees are from Azarga bagh, six are from Bayangol, eight are from Khan Undur bagh and nine are from Tsetserleg. Seven of the 30 interviewees are people aged above 61 years old, 15 are aged between 41 and 60 years old and 8 are people under 40 years old. The average age of the participants was 50, and the oldest and youngest participants were 81 and 25 years old. Interviews were audio recorded and transcribed for analysis. We entered free lists of plants in the local and scientific names into Excel, calculated descriptive statistics and a cognitive salience index (Sutrop 2001) from free list data. Only plants appearing on two or more lists are included in this calculation. We used one-way ANOVA to test if lists generated by four baghs and three age groups differ from each other and t-test to assess gender differences.

Results

By gender: Men listed more plants than women (t=2.236, df=26.16, p=0.034). Women generated 56 plants' list. Ten of the listed by women are good livestock forage plants, 15 are medicinal plants, 18 are for human food use such as for making tea, jam and juice, other uses such as firewood, hair washing, carpentry. Of the women listed plants, 11 plants are decreasing, and two plants are increasing. Plants with greater CSI listed by women are *Pulsatila ambigua* (*khukh yargui*), *Urtica* species, and *Artemisia frigida* (*agi*), *Pulsatila flavescens* (*shar yargui*), *Gentiana azura* (*khukh degd*) and *Thymus gobicus* (*ganga*).

Men listed a total of 125 plants, including 47 livestock forage species, 42 medicinal plants, and 32 plants used for human food and other purposes, such as firewood and carpentry. Of the total listed, 33 plants are decreasing, and 10 are increasing. Plants with higher CSI listed by men include livestock forage species such as *Elumus chinensis* (khiag), *Stipa species* (nariin uvs), *Pulsatila ambigua* (khukh yargui), *Artemisia frigida* (agi), *Gentiana azura* (khukh degd), and *Allium scheonoprasum* (khumkheel), all of which are decreasing.

By age: There was no significant difference in the average number of plants listed by three different age groups (p=0.13). However, younger herders listed fewer plants, while older herders listed more.

Young herders (below 40) identified 24 forage, 20 medicinal, and 12 human-use plants out of a total of 69 plants listed. They observed the growth trends of 11 plants, with seven decreasing (2-livestock forage, 2-medicinal, 3-human use), three increasing, and one plant showing differing growth trends according to two herders. Plants with greater CSI are *Stipa species* (nariin uvs), *Elumus chinensis* (*khiag*), *Pulsatila ambigua* (*khukh yargui*), *Gentiana azura* (*khukh degd*), *Artemisia macrocephala* (*Tsarvan*) and *Gentiana algida* (*Vanjingarav*), *Allium scheonoprasum* (*khumkheel*), *Artemisia frigida* (*agi*).

Middle-aged herders (41-60 years) listed 46 forage, 27 medicinal, and 28 human-use plants out of a total of 94 plants. They observed the growth trends of 34 plants, all of which 26 plants (15-livestock forage, 9-medicinal, 2-human use) are decreasing, six are (3-are livestock use, 2-medicinal, 1-human use) increasing and two plants showing differing growth trends according to four herders. Plants with greater CSI listed by this age group are *Pulsatila ambigua* (*khukh yargui*), *Pulsatila flavescens* (*shar yargui*), *Gentiana azura* (*khukh degd*), *Allium scheonoprasum* (*khumkheel)*, *Sanguisorba officinalis* (*Sud uvs*), *Oxytropis myriophilla* (*tagsh*), *Elumus chinensis* (*khiag*) and *stipa* species (*nariin uvs*).

Older herders (61+ years) listed a total of 97 plants, including 21 forage species, 31 medicinal plants, and 15 human-use plants. They observed the growth trends of 24 plants, with 21 decreasing and 3 increasing. Plants with higher CSI listed by this age group include *Artemisia frigida* (agi), *Festuca lenensis* (Botuuli), *Elumus chinensis* (khiag), *Allium scheonoprasum* (khumkheel), *Stipa species* (nariin uvs), *Urtica species* (Khalgai), *Gentiana azura* (khukh *degd*), and *Rheum species* (*Gishuune/Tsoorgono*).

By location/lifeway. There was no significant difference (p value=0.39) in the number of plant listing among herders in the four baghs. Herders in Tsetserleg (aimag center) listed more plants (99 plants) than those in the other three baghs followed by Khan Undur (81 plants) and Azarga (75 plants) baghs. Herders in Bayangol bagh listed fewer plants (62 plants) than those in the other three baghs. Common livestock forage plants listed by herders in all four locations include *Stipa* species, *Elumus chinensis* (khiag), *Gentiana azura* (khukh degd), *Pulsatila ambigua*, and *Artemisia frigida* (agi). Plants with greater CSI listed by herders of the four baghs are shown in the table 2.

Herders in the Tsetserleg emphasized that 9 of the totals listed of 97 plants are livestock forage plants, 33 are medicinal, 12 are for human use. Participants in this bagh observed the growth trend of the only 25 plants and 16 (4 plants-livestock forage, 6 plants-medicinal, 10 plants-human used) of these plants are decreasing and 9 are increasing. Herders in Khan Undur listed as 39 livestock forage plants, 25 medicinal, 22 plants for human use out of 81 plants. They also observed the growth trend of the 19 plants, of which 13 (5 plants-livestock forage, 7 plants-medicinal, 1plant-human use) are decreasing, 6 are increasing. Herders in Azarga bagh listed

27 plants as livestock forage, 19 medicinal, 16 plants for human use out of 75 plants. They also observed the growth trend of the 17 plants (8 plants-livestock forage, 5-medicinal, 2-human used), of which 15 are decreasing, 2 are increasing. Herders in Bayangol bagh listed 18 plants as livestock forage, 8 medicinal, 10 plants for human use out of 62 plants. They also observed the growth trend of the 10 plants, of which 9 (5 plants-livestock forage, 3plants-medicinal, 1 plant-humanuse) are decreasing, one is increasing.

Discussion [Conclusions/Implications

Overall, plant knowledge did not vary by age or location but differed by gender. Women have more knowledge of plants used for human purposes, reporting that 32% of the listed plants are for food or other uses, 27% for medicine, and 18% for livestock forage. In contrast, men reported that 38% are livestock forage, 34% are medicinal, and 26% are for human use. Men noted a decline in forage plants like *Festuca lenensis* (Botuuli) and *Allium scheonoprasum* (khumkheel), while women observed plants used for human purposes, such as *Thymus gobicus* (ganga), used for washing hair and burning as incense. Both men and women noted an increase in *Artemisia dracunculus*, along with other weedy species such as *Artemisia macrocephala*, *Chenopodium album*, *Urtica species*, and drought-tolerant *Stipa krylovii* (shivee) which observed by men. Our findings suggest that women are more likely to mention food and medicinal plants, while men focus more on forage plants. Men typically manage livestock grazing, while women handle domestic chores like child and elder care, food preparation, and dairy processing, reflected in their responses. Due to an unbalanced sample (men = 24, women = 6), our conclusions are preliminary.

There was no significant difference in the number of plants listed by the three age groups ($p = 0.13$). However, younger herders listed fewer plants than older groups. Younger herders did not mention plants like *Festuca* (botuuli), *Oxytropis myriophilla* (tagsh), and *Rheum species* (gishuune/tsoorgono), which older herders listed. These plants, important for livestock forage, are declining due to climate change and overgrazing (Khishigbayar et al., 2014; Gantuya et al. 2021). Young herders, traveling by car or motorbike, have less opportunity to gather plant knowledge and observe the environment. They noted growth trends for only 16% of the listed plants, while middle-aged herders (41-60 years) observed 36%, especially more forage plants. Older herders listed more plants but observed fewer growth trends, likely due to moving to soum and aimag centers, limiting their ability to track environmental changes.

Common livestock forage plants listed by herders in all four locations include *Stipa* species, *Elumus chinensis* (khiag), *Gentiana azura* (khukh degd), *Pulsatila ambigua*, and *Artemisia frigida* (agi). We expected herders in remote areas to have more detailed plant knowledge. While Tsetserleg (urban) herders listed more plants overall, they mentioned fewer forage plants and more medicinal plants than other baghs. Herders in Tsetserleg observed a greater decline in plants used for human purposes (e.g., pine nuts, willows, wild berries) compared to forage and medicinal plants. Many older participants had moved to the aimag center (Tsetserleg), taking their herding knowledge with them. Contrary to expectations, living in the aimag center didn't equate to a lack of experience, but this knowledge isn't being applied or passed on to younger generations (Peter et al,. 2024). In contrast, herders in Azarga and Khan Undur listed more forage plants, with herders in Azarga and Bayangol observing a decline in forage plants, where livestock population increased 3 times over the last twenty years. while those in Khan Undur noted a decline in medicinal plants.

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Pastoral traditional knowledge in East Ujimchin Banner, Inner Mongolia

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Key words: herd breeding; herd sharing; mobile grazing; resilience; traditional ecological knowledge

Abstract

In the face of significant socio-economic and environmental challenges, traditional ecological knowledge (TEK) systems globally have shown remarkable resilience. This study investigates the resilience of traditional ecological knowledge by analysing three pastoral practices—mobile grazing, herd breeding and herd sharing—in East Ujimchin Banner, Inner Mongolia, China. Using interviews, participatory mapping and surveys, we delve into the dynamic nature of these practices, noting both changes and continuities. Our findings reveal that, while some elements of these three practices have changed, many others have persisted and remain active. For instance, in the context of mobile grazing, despite the changes in moving distance and frequency, herders still practise strategic seasonal movements within the limited pastures they have available. Another important finding is that each of the practices analysed serves diverse functions, such as restoring herd productivity, maintaining ecological balance and adapting to changing climate. Furthermore, the practices under study also have overlapping functions, aiding each other in aspects like climate adaptation. For instance, mobile grazing facilitates access to better pastures in harsh weather conditions, while herd sharing offers a collective approach to managing risks.

Introduction

A large body of research demonstrates the critical role traditional knowledge systems play in maintaining the resilience and sustainability of socio-ecological systems. These systems impact on environmental conservation, agriculture, health and community governance (Berkes et al. 2000, Molnár et al. 2023). Despite these advances, a hierarchical separation persists between scientific and traditional ways of knowing, rooted in colonial legacies and compounded by educational systems, policies, market economies, urbanisation and globalisation. These factors, alongside environmental and socio-ecological changes, challenge local traditional communities' ability to perceive, function and sustain themselves as their ancestors did. This challenge is reflected in extensive literature that often reports the loss or erosion of traditional knowledge systems (Fernández-Llamazares et al. 2023). Reporting on this loss can highlight vulnerabilities and mobilise global support to protect these cultural legacies. However, viewing these knowledge systems solely as fading risks their 'museumification', reducing them to static knowledge from the past rather than recognising them as dynamic and adapting entities (Berkes et al. 2000, Reyes-García et al. 2014).

This study examines the resilience of the TEK system among pastoral herders in East Ujimchin Banner, Inner Mongolia, China, focusing on the intrinsic resilience mechanisms within TEK. We analyse three traditional herding practices—mobile grazing, herd breeding and herd sharing—to see how these practices have historically enabled herders to adapt to past environmental changes and how they may continue to support adaptation to contemporary socio-environmental challenges.

Methods

This study is based on nine months of fieldwork in East Ujimchin Banner, Inner Mongolia, China. Three villages were selected as study sites. We combined both qualitative (semi-structured interviews and participatory mapping workshops) and quantitative methods (survey) for data collection. To gain a comprehensive understanding of traditional practices in the area, the study began with interviewing three key participants. Through these interviews, we identified mobile grazing, herd breeding and herd sharing as the practices that contributed the most to adapting to climate variability. To delve deeper into the details of these practices, semi-structured interviews were conducted with other elders (n=40). We also conducted three participatory mapping workshops in each village with 12 local elders to document historical mobile grazing practices. To collect data on current application of the three practices, we used data from semi-structured interviews to design both individual and household survey. Additionally, we organised household participatory mapping workshops with 30 randomly selected households to understand current mobile grazing practices. For data analysis, a mix of qualitative and quantitative methods was used.

Results

Mobile grazing practice

Regarding the motivations, according to interview responses, mobile grazing was core to maintaining livestock health and productivity, ecological balance and climate adaptation. Comments made during household mapping of current movements show that nowadays herders continue practising mobile grazing primarily to rest and regenerate pastures (93%). Seven participants cited the improvement in livestock health through varied pastures as their motivation, while two participants noted the importance of maintaining tradition.

Traditionally, mobile grazing in the area was characterised by frequent movement, careful selection of seasonal pasture locations, strategic timing of movements and long-distance mobility during extreme weather events. Regarding when to move, participants mentioned that changes in temperature, pasture quality or productivity of grazing areas determined the timing of seasonal movements. Participants also reported that, in the past, East Ujimchin herders also employed long-distance mobility to cope with severe winter events that severely restricted access to pastures.

Since 1984, mobile grazing has experienced significant changes, characterised by reduced movement frequency, fewer seasonal pastures and diminished long-distance grazing. Despite these changes, a key element of mobile grazing has persisted: seasonal utilisation of pastures. Data from 30 participatory household mapping sessions show that households with over 1333 ha of land typically have three seasonal pastures. The households managing pasture areas ranging between 667 and 1333 ha have two seasonal pastures. Among participants with less than 667 ha, micro-mobility is the predominant strategy. As in the past, the type and number of seasonal pastures continue to be influenced by the available pasture area and landscape characteristics.

Herd breeding practice

In terms of the motivations, participants reported traditional breeding traits for selecting male livestock helped ensure that the livestock are productive, well suited to the local climate and reflective of cultural values. According to the survey data, a large majority of participants, 94% (n=213), believe that, in general, breeding practice now significantly contributes to restoring herd productivity. Moreover, 78% (n=178) of participants view breeding as crucial for enhancing their livestock's resistance to winter disasters. Similarly, most participants agree on the ability of breeding to enhance livestock resistance to drought (76%, n=173). When considering the importance of breeding to increase resilience to pasture shortage, levels of agreement were more varied, but still most informants agreed (62%, n=141).

Through interviews, we identified 19 traits across the five types of livestock, each serving different functions, including enhancing productivity, improving climate resistance and preserving cultural values. Regarding the functions of identified breeding traits, high productivity is particularly emphasised, with six key traits across different livestock types specifically valued to maintain productivity. Climate resistance traits are also considered crucial to ensure that livestock can withstand harsh weather conditions. Beyond their practical functions, the participants noted the physical traits of livestock also embody unique cultural identities and beliefs.

Parallel to changes observed in mobile grazing, breeding practices in East Ujimchin have also undergone significant transformations since 1984. Certain selection traits, such as 'single-colour selection' of stallions and bulls and 'born in the middle of lambing season' of rams have a noticeable shift in awareness and use. Moreover, bucks and bulls are now preferred without horns. Despite these changes, 30 traditional traits continue to be sought, although their use varies. For selecting a ram, most participants follow four traditional breeding traits: selecting animals with big and even tails (84% of survey participants), long and straight backs (84%), wide hips (84%) and the (82%). Stallion selection continues to value traits such as lineage (86%), square hip (71%) and long back (70%). In the case of bulls, traits such as lineage (72%), thick body skin (69%) and balanced and even horns (48%) remain important.

Herd sharing practice

As participants reported, traditionally, this practice contributed to fostering societal equality. During the collective era, it was also practised to maintain herd-pasture balance, address labour shortages, minimise climatic risks, sustain herd growth, and help herders with few or no animals to increase their herd size. Household survey results show that the primary reason for engaging in herd sharing now is to mitigate land shortages, cited by 38% of households. Other significant reasons include helping families in need and addressing labour shortages (18% each). Additionally, 15% of households use herd sharing to increase their herd numbers, and 7% of participants use it as a strategy to adapt to severe climatic events. A smaller portion, 3%, view herd sharing as an important tradition that should be preserved.

In the past, families with larger herds would share some of their livestock with families with fewer or no livestock. In return, the sharing families paid the labour of caring for the livestock by offering some of their livestock, along with meat and dairy products, to the host families. Later during the 1950s, when a family wanted to share part of its herd, there was a requirement that 60–70% of the herd be female, with 30–40% of the newborn offspring belonging to the host family after one year.

Survey data show that most households (81%) know about the herd-sharing practice, and 25% of the households either have shared their livestock with other families or received livestock from others. Compared to past practice, now it is more common to receive/pay money rather than take/give back offspring. Overall, based on survey data, herd sharing is perceived positively for its ability to address several critical challenges faced by herders. A significant portion of households (82%) believes that herd sharing can help herders manage land shortages; 73% of households also recognise its role in dealing with current labour shortages. Additionally, 70% of households perceive herd sharing as an effective strategy to combat land degradation, and more than half of them (52%) reported it helpful in mitigating severe climatic events.

Discussion

One of the main findings from our work is that, while various elements of all three practices have changed, many others have persisted and remain active. In the context of mobile grazing in East Ujimchin, despite the changes in moving distance and frequency, herders still practise strategic seasonal movements within the limited pastures they have available. They do so by careful observation of the subtle signs in the pastures, the landscape and changes in vegetation. For families with insufficient pasture area to support distinct seasonal grazing, micro-mobility is adopted. Aligning with these findings, despite the sedentary or semi-sedentary reality of many pastoralists globally, it is crucial to remember that mobility remains an integral component of herding life (Varga et al. 2020, Na et al. 2018).

Another important finding from our study is that each of the practices analysed serves various functions. Historically, these practices have been multifunctional, addressing the past needs. Currently, as environmental and socio-economic conditions evolve, new functions are also emerging, allowing these practices to adapt and respond effectively to contemporary challenges. If we imagine East Ujimchin pastoral knowledge as an ecosystem, then different types of knowledge can be understood as organisms within this ecosystem. Just as species populations in an ecosystem perform diverse roles—from nutrient cycling to climate regulation—also different types of traditional knowledge perform multiple functions. Research suggests that ecosystems with greater functional diversity are more resilient to disturbances and changes, as this diversity enables multiple adaptive responses to environmental fluctuations, thereby maintaining ecosystem stability and facilitating recovery after disturbances (Días & Cabido 2001). Similarly, we argue that the diverse functions of TEK may contribute to the resilience of the knowledge system itself, ensuring it remains dynamic and capable of withstanding socio-environmental shifts.

Another finding is that the studied practices play common functions together. TEK systems are inherently holistic and complex; within them, diverse knowledge and practices work synergistically to adapt to and manage the natural environment effectively (Iaccarino 2003). For example, in adapting to climate variability, herders do not simply rely on weather forecasts, but also emphasise strategic herd breeding to select traits that improve livestock's drought tolerance and productivity. In East Ujimchin, the three practices also complement each other in terms of climate adaptation. Mobile grazing is crucial during severe weather events, allowing herders to move their livestock to more suitable pastures. Breeding is vital for climate adaptation, focusing on traits that improve weather resilience. Herd sharing offers a community-based approach to managing climate risks. This functional complementarity of knowledge allows pastoral communities to approach challenges from various angles. But more importantly, we argue that the interplay and synergy among functions may contribute to the resilience of the knowledge systems through maintaining the essential ecological, economic and socio-cultural functions of these systems.

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Use of ethnoveterinary practices among transhumant/pastoral farmers in hilly areas of Jammu and Kashmir, India

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Key words: transhumance; *Trachyspermum ammi; Curcuma longa*; herbal medicine**;** Gujjars

Introduction

Transhumance is a unique phenomenon of seasonal migration of families along with livestock, mostly to higher altitude in summers and returning to the lower plains in the winter. The vertical migration follows the climatic pattern suitable for growth of livestock and is driven by the availability of sufficient grasslands or rangelands (Photograph 1). Jammu and Kashmir has a large transhumant population (0.6 million people) which is more than the total population of countries like Maldives, Iceland, Luxemburg, Brunei and many more. The livestock economy is the backbone of transhumant families, in fact the only mode of sustenance. The entire socio-cultural-economic model of transhumance revolves around the core of livestock rearing, mainly goat/sheep husbandry and dairying. Traditional and household ethnoveterinary treatment is prevalent in these hilly areas and forms the first line of defence for treatment of livestock (Ishtiyak & Hussain 2017, Tali et al. 2019, Mir et al. 2022). Herbal and plant-based ethnoveterinary medications form the major part of livestock treatment in these areas (Sharma et al. 1989). These traditional herbal remedies are cost effective, easily available and less technical, which makes them more popular than Western medications. The reliance on ethnoveterinary medication among the tribal population of Reasi and Udhampur Districts inspired the current study with following main goals:

1) To identify and document the different traditional plant-based treatments used by tribal people
2) To document the type of diseases being treated with these plants and their byproducts
3) To investigate the level of trust by tribal people in these traditional remedies.

Photograph 1: Transhumant migration in search of grassland

Methods

The main study areas were the remote villages of Reasi and Udhampur Districts of Jammu and Kashmir with a high density of tribal/transhumant population, mainly Gujjar and Bakarwal. Reasi and Udhampur are predominantly hilly districts with variable climatic conditions, ranging from subtropical to semi-temperate. These districts mainly can be divided into 'hilly' and 'low-lying hilly' areas. They have dense forest areas that host a diverse group of medicinal and herbal plants used for many health treatments in both humans and animals. Crops and livestock are the major sources of livelihood for these communities, who often move with their livestock to different parts for grazing. The data were collected by means of questionnaires from respondents in eight villages in each of the two districts surveyed. Interviews and discussions were the main methods for collecting information based on the questions in the questionnaire. Information was collected from especially renowned, knowledgeable people, sarpanches, progressive livestock farmers and elderly persons. A total of 64 informants, mainly residing in these hilly areas, were interviewed in the local language. They ranged in age from 37 to 78 years and were interviewed separately to obtain accurate information. Data were collected on the major livestock species in the area, size of flock/farm, major diseases, herbal and other treatments used, major plants/trees used, parts of plant used, plant byproducts used, technique to prepare the herbal medicine, application procedure, time and duration of treatment, recovery time and cost of treatment. The information obtained in the field was crosschecked with the literature available.

Results and discussion

Due to the rough terrain and poor transport facilities, local people consider ethnoveterinary remedies for livestock treatment to be most important in these hilly areas: 23 different ailments of livestock and their traditional treatments were identified and documented. The details of common ethnoveterinary remedies used along with the herb name, family name, local name, plant part used, mode of administration, disease condition, dose and recovery time are given in Table 1. Leaves (30%) were the most used, followed by whole plant and seeds (Fig. 1). The study showed a dependence of more than 70% tribal population on ethnoveterinary and herbal medication, whereas only 30% depended on allopathic or Western medication. A local veterinary doctor was consulted mostly in cases of complex disease conditions, surgery, dystocia or accidents. It was observed that traditional knowledge of herbal and local medicine still forms the first line of defence for treating livestock diseases. Milk, jaggery, butter, wheat flour and curd were the major vehicles used for administering medicines. Similar vehicles for administration were reported by Dilshad et al. (2009). These remedies were administered mostly orally and, in some cases, topically. The amount and doses were reported differently by all the respondents, indicating that there were no clear-cut standards for doses of these remedies. Also duration of treatment and response to treatment were not uniform, with different respondents reporting different treatment time and recovery time. Leaves, roots, fruit, flower, bulbs, seeds and stems were the commonly used parts of plants. Similar findings were reported by Abbas et al. (2002), Giday et al. (2003), Nfi et al. (2001), Ole-Miaron (2003) and Viegi et al. (2003).

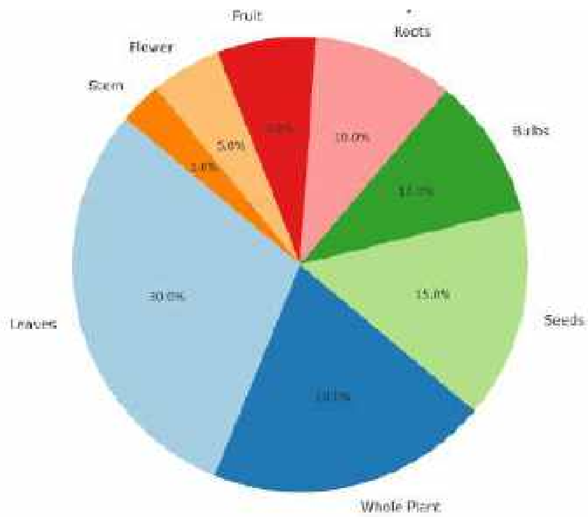

Fig. 1: Plant parts used

Farm size. Herd size varied from 2 to 200 animals. Large herds were mostly of sheep and goats. The most common ailments reported by the respondents in large farms/herds were indigestion, fever, stomach ache and allergy. In the case of cattle, most of the remedies were for bloat and tympany. Farmers with large herds preferred veterinary advice on a regular basis whereas farmers with smaller herds depended more on ethnoveterinary and homemade remedies. Farmers were also reluctant to take their livestock to a veterinary hospital and preferred the visit of a veterinarian to their farm.

Most common problems. The most common problems reported by livestock owners in these areas were bloat, tympany, indigestion, anorexia, diarrhoea, ecto-/endoparasites infection, fever, cough and allergy. Bloat, indigestion and fever were mostly treated using these local remedies. In case of ecto- and endo-parasitic infections, tribal farmers reported the use of antimicrobial drugs due to multiple parasitic infections and high resistance to other drugs and treatments. In the case of some surgical conditions like medial patellar desmotomy (MPD) or traumatic reticuloperitonitis (TRP), farmers depend on veterinary experts and did not rely on herbal remedies or local treatment. Similar treatments have been reported by Ishtiyak and Hussain (2017), Riyaz and Ignacimuthu (2023) and Tali et al. (2019) for treatment of indigestion, tympany and ecto- and endo-parasites.

Common remedies. The most common plants and plant byproducts used were *Trachyspermum ammi, Curcuma longa, Morus nigra, Aloe vera (L.) Burm. f., Trigonella foenumgraecum, Cannabis sativa, D.wrightii, Azadirachta indica, Thymus vulgaris L., Bambusabambos (L.) Voss, Allium cepa L.* Some of the plants were used for multiple treatments like pain, fever, indigestion, bloat etc. The most common plant families reported by respondents were *Apiaceae* and *Amaryllidaceae*. A few plants like *Allium sativum L, Allium cepa L, Trachyspermum ammi* and *Curcumalonga* were reported by 90% of respondents, indicating the trust and effectiveness of the ethnoveterinary practices used by tribal farmers. These remedies were used in treatment of multiple problems. Paste, crushed seeds and boiled leaves were the most preferred medicinal form used for administration. Similar results were reported by Dutta et al. (2022) and Khateeb et al. (2015). It was also observed that tribal people mostly trusted the easily available local household spices and herbs for treatment purposes.

Administration mode. Different methods of administration were used based on the plant type used and disease condition. The preferred method was oral, then topical for effective and fast results. The topical method was mostly used in case of injury, wound, allergy or inflammation condition. Chakale et al. (2021) reported similar findings of preferred oral route as faster compared to topical application.

Conclusion

The traditional ethnoveterinary system of treatment is the most trusted and important prevailing system in hilly areas of Jammu. It is more preferred in remote areas with poor availability of veterinary health services due to rough terrain. It is very important to promote cost-effective ethnoveterinary measures to control diseases in livestock. Ethnoveterinary practices are still used as the first line of defence by tribal people to control livestock diseases because of high production cost and resistance developed as a result of excessive use of antimicrobial drugs. It is very important to promote cost-effective ethnoveterinary measures to control diseases in livestock.

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Table 1: Details of ethnoveterinary remedies used by tribal farmers

No.	Botanical name	Family	Local name	Part used	Usage form	Admini-stration mode	Disease/ condition	Dose	Recovery period
	Achyranthes aspera	*Amaranthaceae*	*Puthkanda*	Whole plant	Paste	Oral	Swelling	Once a day	2–3 days
	Trachyspermum ammi	*Apiaceae*	*Ajwain*	Seed	Powder	Oral	Bloating	Once a day	2–3 days
	Azadirachta indica	*Meliaceae*	*Neem*	Leaves	Paste	Oral	Haemorrhagic septicemia	Once a day	5–7 days
	Bambusa bambos (L.) Voss	*Bambusa bambos*	*Baans*	Leaves	Leaves	Oral	Retention of placenta	Twice a day	1–2 days
	Cannabis sativa	*Cannabaceae*	*Bhang*	Leaves	Paste	Oral	Endo parasitic infection	Once a day	3–5 days
	Allium cepa L.	*Amaryllidaceae*	*Pyaaz, Gande*	Bulb, raw	Paste	Oral, topical	Cold, fever	Twice a day	2–3 days
	Aloe vera (L.) Burm. f.	*Asphodelaceae*	*Kuargandal*	Leaves, whole plant, raw	Paste	Oral	Stomachache	Once a day	2–3 days
	Cannabis sativa	*Cannabaceae*	*Bhang*	Leaves	Paste	Topical	Ectoparasitic infestation	Once a day	5–7 days
	Cedrus deodara	*Pinaceae*	*Deodar*	Oil or paste	Oil or paste	Topical	Insect infestation	Once a day	2–3 days
	Allium sativum L	*Amaryllidaceae*	*Thoom*	Bulb	Paste	Oral	Cough and cold	Twice a day	3–5 days
	Curcuma Longa	*Zingeberaceae*	*Haldi*	Rhizome	Paste	Oral	Joint pain	Once a day	5–7 days
	Morus nigra	*Moraceae*	*Shatoot*	Leaves	Paste	Topical	Wound injury	One a day	5–7 days
	Brassica Juncea	*Brassicaceae*	*Sarson oil*	Plant	Oil	Oral	Tympany	Once a day	2–3 days
	Allium cepa L.	*Amaryllidaceae*	*Ganda*	Bulb	Bulb	Oral	Anestrus	Once a day	10–14 days
	Citrus medica L.	*Rutaceae*	*Gargal*	Fruit	Raw	Oral	Poisoning	Once a day	1–2 days
	Elwendia persica	*Apiaceae*	*Jangli zeera*	Seed	Raw	Oral	Loss of appetite	Twice a day	4–5 days
	Equisetum diffusum D.	*Equisetaceae*	*Rampori*	Whole plant	Boiling	Oral	Urolithiasis	Once a day	3–5 days
	Ferula narthex Boiss	*Apiaceae*	*Hing*	Root	Raw root	Oral	Indigestion	Once a day	3–5 days
	Brassica rapa L.	*Brassicaceae*	*Shalgam*	Leaves	Raw	Oral	Retention of placenta	Once a day	1–2 days
	Datura stramonium L.	*Solanaceae*	*Dhatura*	Seeds	Crushed seeds	Oral	Urinary infection	Once a day	5–7 days
	Angelica glauca	*Apiaceae*	*Chora*	Root	Crushed root	Oral	Colic, acidity	Twice a day	3–5 days
	Thymus vulgaris L.	*Lamiaceae*	*Van jawain*	Leaves	Leaves	Oral	Diarrhea	2–3 times a day	3–5 days
	Prinsepia utilis Royle	*Rosaceae*	*Zintola*	Stem	Stem	Oral	Digestive disorder	Twice a day	5 days
	Trigonella foenumgraecum	*Fabaceae*	*Methi*	Flower	Raw flower	Oral	Fever	2–3 times a day	3–5 days
	Aconitum laeve Royle	*Ranunculaceae*	*Patis*	Root	Aqueous extract	Oral	Worms in liver	Once a day	2–3 days
	Skimmia laureola	*Rutaceae*	*Shungun*	Leaves	Raw leaves	Oral	Anaemia	Twice a day	5–7 days

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Analysing the Indigenous knowledge contributing to the survival of pastoralists in northern Kenya's dry areas

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Keywords: Indigenous knowledge, survival, dry lands, natural calamities

Abstract

Pastoralists in Northern Kenya have relied on indigenous knowledge for centuries to endure natural disasters such as droughts, famine, floods, and diseases. This study aimed to examine the types of indigenous knowledge applied by livestock keepers in Northern Kenya and how these practices are influenced by climate variability. Guided by resilience theory, data were collected through secondary sources, semi-structured interviews, focus group discussions, and direct observation. The findings reveal that indigenous knowledge is crucial for survival in Kenya's dry areas including a deep understanding of local ecology, facilitating migration to greener pastures during droughts. Pastoralists select livestock species based on their adaptability to specific ecological conditions, enhancing survival rates. Indigenous knowledge is crucial for survival in Kenya's dry areas, encompassing a deep understanding of local ecology and facilitating migration to greener pastures during droughts. Pastoralists select livestock species based on their adaptability to specific ecological conditions, enhancing survival rates—Indigenous weather forecasting methods guide movement, showcasing the effectiveness of traditional knowledge in anticipating environmental changes. Additionally, pastoralists possess extensive knowledge of wild edible plants used for food during drought and employ indigenous food preservation techniques, contributing to food security and sustenance. These findings highlight the critical role of traditional knowledge systems in enhancing adaptive capacity and sustaining livelihoods during calamities. However, the efficacy of indigenous knowledge is eroding due to increasing climate and socio-economic challenges, emphasising the need for sustainable interventions. Integrating Indigenous knowledge into formal policies, conserving biodiversity, and promoting hybrid approaches combining Indigenous knowledge with modern technologies is crucial. Capacity-building, financing for herd restocking, and biodiversity conservation are necessary to safeguard livelihoods amid climatic and socio-economic changes.

Introduction

Pastoralism is a critical economic and cultural practice, particularly in arid and semi-arid lands (ASAL), sustaining millions of livelihoods globally (Wafula et al., 2022). In Kenya, ASALs constitute over 80% of the country, supporting 70% of the livestock and 36% of the human population (KNBS, 2019). These regions experience limited rainfall—arid areas receive 150–550 mm and semi-arid areas 550–850 mm annually (Schilling and Werland, 2023). Kenya's ASAL counties have faced increasing drought frequency, with inter-drought periods shortening from 5–10 years to 2–3 years (Nyaoro et al., 2016).

Erratic rainfall and growing aridity exacerbate the vulnerability of pastoralist communities, which rely heavily on mobile livestock production. Additionally, severe El Niño floods in 1961-62, 1997-98, and 2023-24 have caused widespread loss of life, displacement, and property destruction. Despite these extreme climatic conditions, pastoralist communities have thrived in these environments over generations by relying on indigenous knowledge systems and practices. Conventional modern technologies and interventions have not effectively mitigated these challenges, but indigenous knowledge has played a crucial role in resilience and survival. However, there is limited documentation and integration of this knowledge into current adaptation strategies, which could otherwise strengthen community resilience to climate extremes. This study was guided by two objectives; to identify the indigenous knowledge used by pastoralists to survive natural disasters; and to examine the constraints limiting the effectiveness of indigenous knowledge in building pastoralist resilience.

Methods

Research sites

This study was conducted in Marsabit County, focusing on the Dukana and Sololo areas. It specifically targeted the Gabra and Borana communities, which are the largest ethnic groups residing in the county.

Data Collection Methods

The study involved 200 households selected through purposive and simple random sampling. Participants were 160 males and 40 females. Data was collected through interviews, direct observation, and focus group discussions. Trained enumerators administered questionnaires covering natural disasters, indigenous knowledge, and barriers to its effectiveness. Direct observations assessed environmental conditions and natural resources, while separate FGDs for men and women were used which provided additional insights and data triangulation.

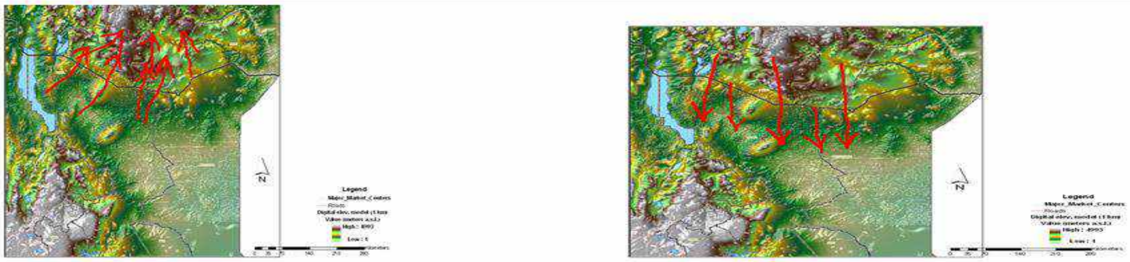
Data Processing and Analysis

Qualitative data were organized to align with the study objectives. Quantitative data collected from household interviews were carefully edited, coded, and entered into SPSS (version 28) for analysis. Descriptive statistics, such as frequencies and percentages, were computed to provide a comprehensive overview of the study findings.

Study Results

Seasonal Livestock Mobility

Seasonal livestock mobility is a crucial survival strategy for pastoralists in Northern Kenya, enabling adaptation to environmental challenges. *Badheessa Gannaa* (wet season migration) follows the first rains, with livestock moving to peripheral grazing areas, while dry season migration brings herds closer to permanent water sources, often crossing borders (see Picture 1). Before migration, elders send herders to assess range conditions in fall-back areas and negotiate access with local communities. Men migrate with the livestock, leaving women, children, and elders at the homestead.



Picture 1: Seasonal Migration of the Borana and Grabbras of Northern

Indigenous early warning signs of weather patterns

Pastoralists in Northern Kenya use various indicators to predict droughts. Black intestines in slaughtered animals were identified by 41% of respondents, hot temperatures by 16%, and tree leaf-shedding by 15%. Additionally, 12% noted bird sounds and movements, 11.5% referred to star positions, and 4.5% mentioned a clear, cloudless sky. Other signs given included female camels crossing their rear legs and urinating on their thighs, livestock restlessness and slow movement. Signs of impending rain include cattle shaking their rear legs, playful behaviour in bulls, livestock hesitating to enter their shed, the flowering of plants like Acacia *nilotica,* and specific star patterns.

Herd diversification by pastoralists

The Borana and Gabbras of Marsabit practice herd diversification, rearing camels, cattle, goats, sheep, and donkeys. This strategy optimizes ecological resource use, enhances food security, and increases resilience to drought, making it an effective adaptation to climate variability. Camels emerged as the most preferred by 72% of respondents for their resilience, high milk production, and medicinal benefits. Goats and sheep (22%) were valued for rapid reproduction and ease of restocking, while 4% favoured cattle for their market value. Poultry (2%) were kept for their low theft risk. Figure 2 gives details

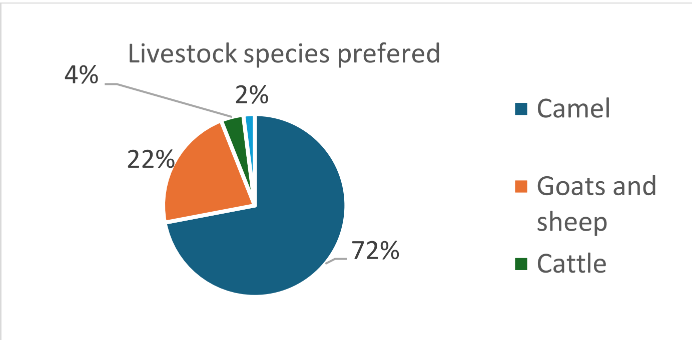


Figure 2: Livestock Species Preferred

Reliance on wild edible plants

Pastoralists in Marsabit rely on wild edible plants for survival during droughts and famines, with 86% of respondents affirming their use. Key plants for the Borana include Grewia tembensis (deka), Cordia gharat (mader), Zizyphus mauritiana (qurqura), Berchemia (jaj jab), Grewia villosa (ogomdi), and Lannea alata (kumude). The Gabra depend on Grewia spp., Carissa edulis, Balanites aegyptiaca (desert date), Adansonia digitata (baobab), and wild sorghum.

Indigenous ways of preserving foods among the pastoralists of Northern Kenya

Pastoral communities preserve meat and milk using indigenous traditional knowledge. Meat is cut into strips, sun-dried, deep-fried in animal fat, and stored in solidified fat in containers, known as enyas, opera, nyirinyiri, or koche depending on the community, lasting 6 months to a year. Milk is preserved by smoking gourds with Olea africana leaves, which act as natural preservatives, enabling the milk to remain consumable for extended periods, regardless of weather conditions.

Challenges affecting the efficacy of Indigenous knowledge
Challenges to livestock mobility

The study found that while livestock mobility is essential for Borana and Gabra pastoralists to access rangelands and share resources, climate variability, especially frequent droughts, has caused water shortages, depleted grazing, and conflicts. Migration routes up to 600 km expose livestock to harsh conditions, leading to deaths. Shared resources lead to overgrazing, feed shortages, and disease transmission, making this adaptation increasingly unsustainable under changing climatic conditions.

Barriers of early warning methods
Most households (75%) affirmed the reliability of traditional early warning methods, 14% believed they were only reliable in the past, and 11% deemed them unreliable. Focus group discussions highlighted that increasing climate variability and severity have reduced their effectiveness. Lwasa et al. (2017) attributed this decline to the disappearance of traditional indicators, cultural shifts, and evolving religious interpretations.

Barriers to herd diversification
Opiyo et al., (2015) emphasized that herd diversification is a vital long-term adaptive strategy for pastoralists in Northern Kenya, driven by livestock's varied drought tolerance. This is supported by Wako et al., (2017), who found that goats and camels are highly drought-resilient, efficiently utilizing poor-quality forage, while cattle and sheep suffer higher mortality due to their lower adaptability. Despite its importance the strategy faces barriers such as livestock losses from recurrent droughts, high restocking costs, degraded foraging resources, reduced labor due to schooling, and youth migration to urban areas, limiting diversification efforts.

Challenges of accessing wild edible plants
Pastoral communities have traditionally depended on wild edible plants (WEPs) during drought-induced famines. However, their availability has declined due to settlement expansion, restricted access to fenced areas, overharvesting for construction materials, overgrazing in conflict zones, and the spread of invasive species like *Prosopis juliflora*, which hinder the growth and accessibility of WEPs.

Challenges of Indigenous methods of storing food
Challenges affecting Indigenous food and milk preservation among pastoralists include poor hygiene in processing, leading to illnesses like diarrhoea, livestock losses limiting inputs, and droughts reducing food shelf life. Additionally, recurring droughts have depleted plants traditionally used to extend milk preservation, further impacting food availability and storage practices.

Discussion, Conclusions and Implications
Discussion: The study highlights the critical role of indigenous knowledge in sustaining pastoral livelihoods in Northern Kenya through adaptive strategies like livestock mobility, early warning signs, herd diversification, and reliance on wild edible plants. However, challenges such as climate variability, resource constraints, and socio-cultural shifts necessitate integrating indigenous knowledge with modern resource management and technological approaches for enhanced resilience.

Conclusion: Indigenous knowledge is vital for pastoralists' adaptation to climate variability, offering time-tested strategies for resilience. However, its efficacy is eroding due to increasing climate and socio-economic challenges, the need for sustainable interventions.

Implications: Integrating indigenous knowledge into formal policies, conserving biodiversity, and promoting hybrid approaches combining indigenous knowledge with modern technologies are crucial. Capacity-building, financing for herd restocking, and biodiversity conservation are necessary to safeguard livelihoods amid climatic and socio-economic changes.

Acknowledgement
We sincerely thank the Director General of KALRO, the Centre Director of KALRO-Biotechnology, and the participants for their invaluable support, guidance, and insights that ensured this project's success.

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The science-policy adaptive capacity building for local herding and government groups to reduce climate vulnerability: case of Gobi-Altai province, Mongolia

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Key words: Climate-pasture-livelihood nexus; pastoral vulnerability; climate adaptation; science-policy adaptive capacity (SiPAC)

Abstract

The effects of climate change and active use of natural resources are the key factors to pastoral social-ecological vulnerability in agriculture-based developing countries. Pastoral vulnerability is a base to measure how climate change affects pasture, livestock and the livelihoods of herding communities. It is explained by natural stressors and human factors of pasture use and vegetation cover change as a set of interlinked impacts on social and economic conditions and coping strategies of herder communities. Rural herding communities and local government units lack scientific information to better understand the nexus of Climate-Pasture-Livelihood and how it might impact their well-being now and in the future. They also have limited capacity building resources in science, policy, and its implementation. The science-policy adaptive capacity program (SiPaC) was implemented in Gobi-Altai province, Mongolia to build capacity of local herding communities, practitioners, and government units. The SiPAC served as a platform to facilitate knowledge, management, skills, networking, partnership and ultimately, formulation of local adaptation strategy of targeted stakeholders through scientific contributions, methodologies, training manuals, practical and interactive sessions tailored to local needs.

Introduction

In Mongolia, 57-70% of the local economy and 80% of total labour force in rural areas depend on animal husbandry (NSO 2020). The vulnerability of pastoralism is linked with natural stressors such as drought and zud (harsh winter condition) (Togtokh et al. 2014), human factors such as pasture use and vegetation cover change, the impacts on social and economic conditions and coping strategies of herder communities (Troy 2014). The western region of Mongolia, where Gobi-Altai province is located, is an arid, non-equilibrium environment with highly variable weather (Gomboluudev 2019) and affected by climate change related disaster extremes, water resources shortage, and cultural changes.

To effectively align adaptation policies and prioritise implementation measures, policy makers require comprehensive information obtained via vulnerability assessments of regions and various sectors (Benjamin et al. 2011). It is important for sustainable pasture use, pasture management planning, and the effective implementation of adaptive measures. Suvdantsetseg et al. (2020) found that local policy documents have ‘limited alignment’ with climate change responses, particularly inadequate adaptation measures adopted to strengthen social resilience. Gobi-Altai province has, indeed, not updated its development policy in accordance with Vision-2050, national development policy and global Sustainable Development Goals (SDGs). This finding revealed the urgent need to formulate new policies to align climate change adaptation and sustainable development at local level.

However, local governments have limited capacity to formulate science-based policy. Therefore, the science-policy adaptive capacity program (SiPaC), funded by Asia-Pacific Network on Global Change Research, was implemented in Gobi-Altai province. Building on the past pastoral social-ecological vulnerability assessment, the SiPaC program aimed at enhancing local herding communities, young leaders/researchers, practitioners, and government units to participate in, and connect to, local, national, and regional science and policy agenda (SDGs) on climate change adaptation and enable them to learn science-based pastoral management, best practices, and innovative solutions.

Methods

Description of study area. Located in the western Mongolia, Gobi-Altai is a sparsely populated province with total area of 141.1 thousand sq.km and a population of 58.4 thousand, 67 percent of whom live in rural areas and practice nomadic herding. The livestock sector, with its 3.8 million sheltered livestock generates 55% of the province’s GDP (NSO, 2024). The SiPAC was implemented in 5 sub-provinces (Biger, Bayan-Uul, Khaliun, Taishir, and Tugrug) of Gobi-Altai province (Figure 1).

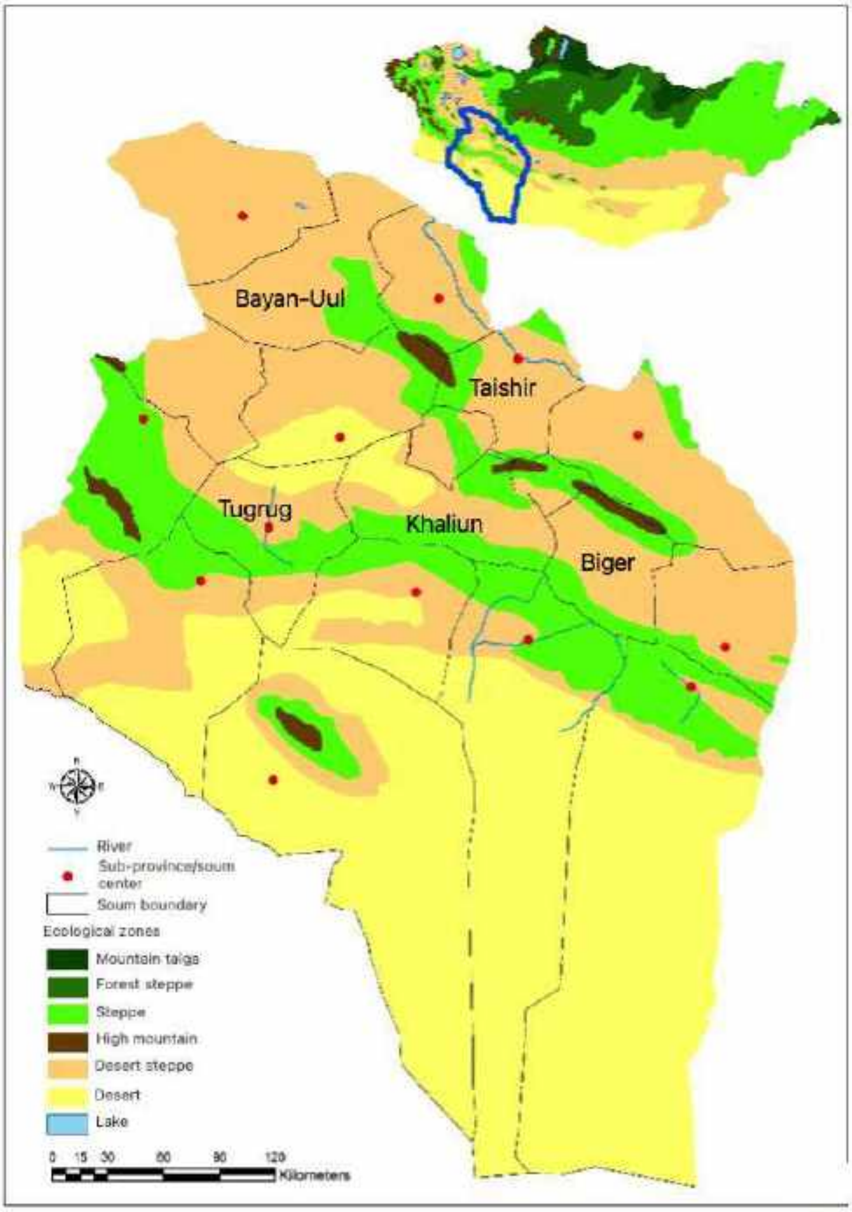

Figure 1. Location of study area.

The participants included diverse stakeholders of young leaders, herding communities, government officers, practitioners, and active persons, who were selected based on their interest, participation in problematic issues, and future contributions to the local development. The training used integrated training curriculum-based participatory approach through a variety of structured learning tools, methodologies including lectures, teamwork, leadership managements, and practical and interactive sessions to facilitate their knowledge, skills, formulation of local adaptation strategy or other documents, reduction of pastoral vulnerability and science-based pastoral managements. The interactive sessions provided theoretical presentations, lectures, and methodologies followed by exercises.

Results and Discussion

In total, five capacity building trainings were organized, each session was designed as a 2-4-day workshop to provide insights into specific topics including pastoral socio-ecological vulnerability assessment; local and national policy interrelation analysis; science-based policy training curriculum; and local strategic development plans. Trainings involved active participation by multiple academic researchers, policymakers, and representatives of rural herding communities, young leaders, and local government units.

There were pre and post-evaluation of the impact of training and feedback of trainees after the training was concluded.

Throughout the project period of two years, the representatives of five soums, Bayan-Uul, Biger, Taishir, Khaliun and Tugrug, learned about climate change and its effects on their environment, wellbeing and livelihoods, what strategies to implement to adapt and become more resilient against those adversaries, and did practical training on how to integrate adaptation strategy into local policy. As a result, the participants jointly developed the first draft of the adaptation strategy plan for their respective soums. In the final dissemination workshop, each team presented brief introduction of their draft strategy plan which would later be adopted by the respective local governments.

The SiPAC program was successful as it served as a platform to facilitate knowledge, management, skills, networking, partnership and ultimately, formulation of local adaptation strategy of targeted stakeholders through scientific contributions, methodologies, training manuals, practical and interactive sessions tailored to local needs.

Acknowledgements
We are grateful to APN for providing funding to support the project, and Mongolian Academy of Sciences and Governor's office of Gobi-Altai province for their kind support and assistance in organizing workshops.

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Poster presentations – Theme 2

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Building a community of practice around the network of rural living labs of the Grassland Management project in Uruguay

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Key words: Community of Practice; Rangeland Management; Workshops; Living Labs; Learning

Abstract

Since 2021, the Grassland Management project has been monitoring 30 livestock farms (Living Rural Laboratories) grazing natural pastures. The objective of the project is to contribute to the better management of natural pastures, through the use of good pasture management practices, with the aim of developing sustainable livestock systems. After three years, 130 workshops have been held with the participation of laboratories, the accompanying group of neighbouring producers, the technicians responsible for monitoring and the extension agency. These meetings take place in autumn and spring, are attended by 15 producers (on average per laboratory), field visits are carried out and evaluations are made. Currently, a total of 1800 people are participating in project activities. From August 2022, on the occasion of the first meeting of the Laboratory Network, the Community of Practice on natural grassland management started to operate. According to the theory of Community of practice, the participants of the Community share a common concern, a set of problems, or an interest in a topic, and are motivated to fulfill both individual and group goals. Three levels of involvement are identified: 1) the central core (30 producer families and technical team; 80 people), 2) the accompanying core (15 neighbours per Lab. + 450 people) and 3) the peripheral core - a heterogeneous group composed of multiple actors, research and private technicians (+ 300 people). Based on the evaluation conducted within the framework of the project, through a survey of participants, it can be concluded that the learning of new concepts and ideas is a process that 90% of the participants have shown, the remaining 10% have incorporated new approaches to what they already knew. Community building is an emerging feature of the project, which has been enhanced by the development of information technologies. It is envisioned as an information scaling strategy and a space for sharing the experiences of livestock producers. When the project ends, it will face the challenge of sustaining itself and ensuring its sustainability.

Introduction

The Grassland Management project has yielded pertinent information and findings from the monitoring of 30 living labs, encompassing the majority of the country's agro-ecological zones. A conceptual model has been developed that involves five macro-variables that are determinants in grassland management. These variables are combined in multiple ways, demonstrating that grassland management is a complex phenomenon. The variability and diversity of grassland systems, the transmission of capitalised learning, and the direct effect of these factors on the sustainability of grassland enterprises are all key elements of this model. The implementation of self-assessment and quantification protocols enables the standardisation of processes. The project provided over 1,900 participants with a straightforward and reliable method of estimating available pasture (the index on food plate [FPI]), which serves as a decision-making tool. As an outcome of the process, the network of living laboratories is now conceptualised as a community of practice that is continuously evolving and intends to persist, facilitating knowledge acquisition (Areosa, P. et al., 2021) y (Pereira, M. et al, 2023).

Methods

A living lab is a space designed for interaction and collaboration, fostering creativity and problem-solving. It is a platform for cultivating critical thinking and knowledge acquisition among the individuals involved (Bravo-Ibarra, 2019). Such spaces facilitate the intersection of technologies and people in authentic contexts (Zavratnik et al., 2019). The term "laboratory" typically denotes a controlled environment with variables that can be manipulated. In contrast, the concept of a "living laboratory" suggests a more open and dynamic approach, where the laboratory is integrated into the real world and its inherent complexities. The defining aspects of living labs include the following: Real environment: In contrast to the controlled environments of traditional laboratories, living labs operate in real conditions, including factors such as climate, pricing, and specific circumstances. This enables the efficacy of solutions to be assessed in authentic contexts, which may present distinctive characteristics and challenges. Open innovation is promoted by these laboratories through the involvement of multiple actors, allowing for the contribution of different perspectives to the development of more appropriate and sustainable solutions.

The laboratories serve as spaces for dialogue and learning, facilitating exchange and the construction of knowledge through the workshop methodology. Joint creation is another key feature of living laboratories, which are based on the participation of the community in the creation of solutions. The members and participants of the laboratory are not merely subjects of study; they are also pivotal contributors to the advancement of knowledge and technologies (Areosa et al., 2024).

Results

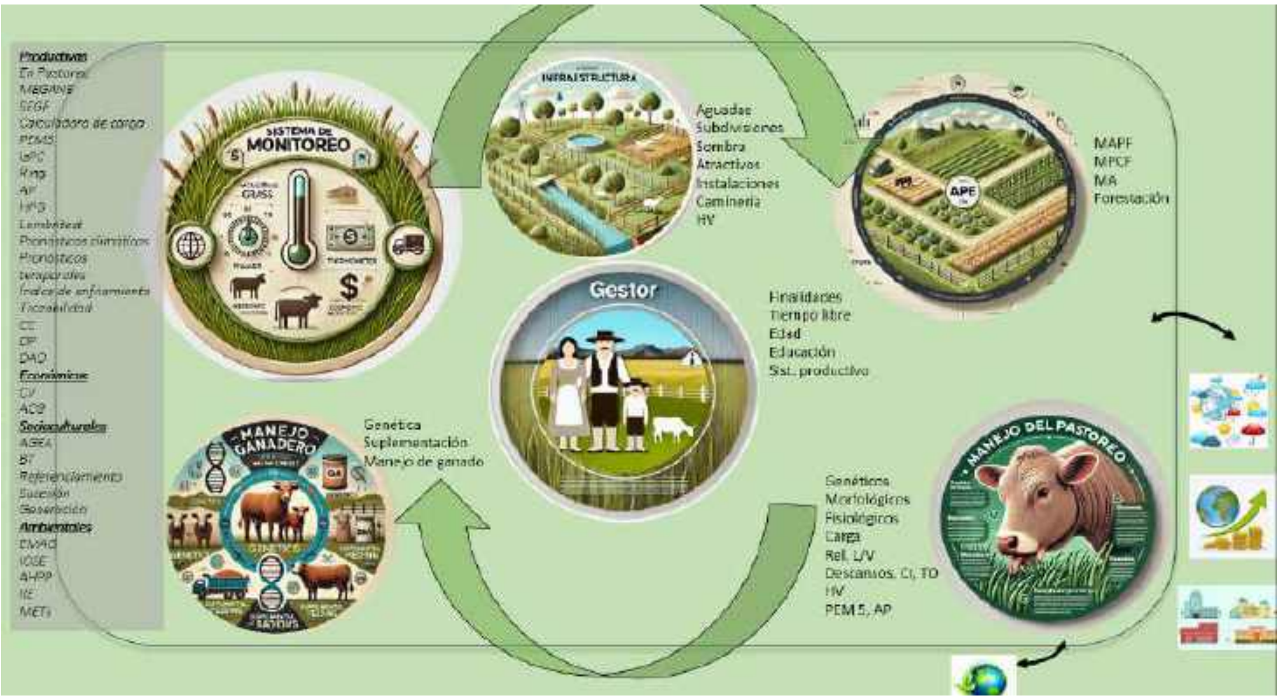

Figure 1. Conceptual model principal variables associated with effective pasture management practices.

The conceptual model generated by the project provides a systematic representation of the principal variables associated with effective pasture management practices. This product provides an evaluation framework for livestock producers, facilitating the planning and analysis of diverse scenarios and enabling prospective capacity and flexibility for adapting to changes. The macro-variables that warrant particular attention are: embeddedness in the context of infrastructure, the proportion of improved areas of strategic production, establishment ratio greater than 5 cm in the case of grazing management, strategic supplementation for livestock management and the importance of having a monitoring system in place. These approaches place an emphasis on process technologies and the soft skills (knowledge) of producers. In a complementary manner, the role of the natural field as a determinant of favorable environmental performance indicators is evident, providing systems with the resilience and resistance necessary to persist over time. The grassland management community of practice represents a learning community, comprising the living laboratory, dialogue workshop, and accompanying group components, which collectively form the laboratory network. This community demonstrates a capacity for synergistic and dynamic functioning, with learning outcomes that demonstrate a progressive improvement.

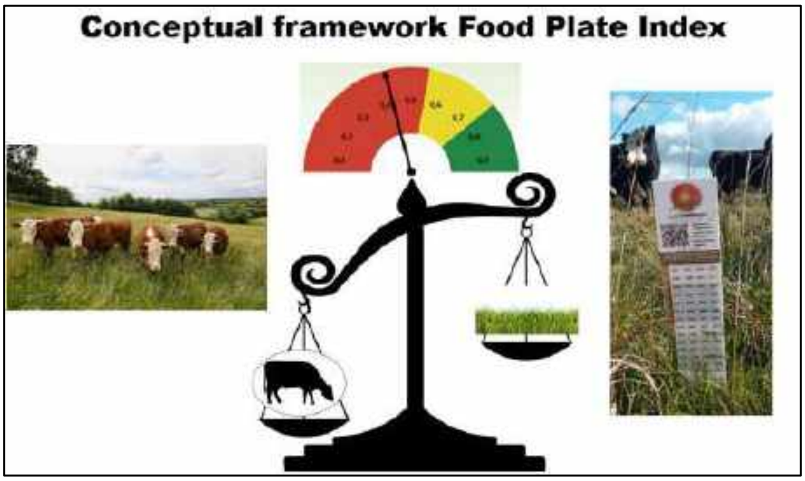

Figure 2. Food Plate Index method, proposed by the project and adopted by the 30 living labs.

Conclusions/Implications

The findings of the project substantiate the assertion that the long-term sustainability of livestock enterprises is contingent upon the macro-variables identified and their utility as self-assessment tools. These facilitate support, correction and the setting of new objectives, thereby enabling the construction of resilient family-business systems with adaptive capacity. This process, undertaken by each system, incorporates an appropriate degree of sophistication without compromising the fundamental simplicity, monitorability and protocolizability of the approach. In order to achieve this, it is necessary to promote reflective processes (critical thinking) that necessarily require a certain investment of time and motivation from decision-makers. This challenge is encountered in the process of extension, the development of learning and the acquisition of new skills, which undoubtedly represent one of the most significant impacts of this project.

Photographs: Dialogue workshops from 2021 to 2024 in the living labs

Acknowledgements
We would like to say a huge thank you to the 30 families who welcomed us into their homes to develop this project, as well as to the team at the Instituto Plan Agropecuario and to INIA for their constant support.

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Meal Plate Index: A simple and robust tool for decision making

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Key words: forage planning, allowance, grassland, budgeting tool.

Abstract

Cattle and sheep production in Uruguay is mainly based on natural grasslands. Research has shown that most of the country is overgrazed, so it is important to work with higher grass allowances. A simple, robust tool has been developed that livestock producers can use to budget for feed, called the Meal Plate Index. It is based on the fact that each category of cattle requires a certain amount of forage according to the season and the cattle performance objectives to be achieved - these values have been determined by national research - and is compared with the availability of existing forage, which is estimated using a centimeter ruler - developed in an extension project - that relates grass height to dry matter content per unit height and animal performance. The two factors, the amount of grass available and the need for forage supply, are relate, and according to the result of the index, if the result is between 0 and 0.6, we are in a red zone, in danger and urgent decisions are needed; between 0.6 and 0.8, yellow zone of caution and possible short term decisions; 0.8 to 1.2, green zone, with no immediate need for management changes, and values above 1.2, brown zone, which can only be reached in spring and summer, and due to the fact that most species are C4, this surplus is of very poor quality. Several field days and courses have shown that the index is easy to understand, while its application is strongly conditioned by the fact that the grass should be measured at least every season. Any technology or method that facilitates the measurement or estimation of forage availability will facilitate the use of the index and result in better livestock performance.

Introduction

The lack of timely decisions on pasture supply, affected by climate variability, has a significant impact on the productive and economic outcomes of livestock systems. In Uruguay extensive livestock production based on natural pastures faces frequent droughts, that affect both production and the sustainability of livestock enterprises and their families.

Animal stocking, measured in livestock units (LSU), is used to calculate stress based on the surface area, but does not consider the actual availability of pasture at any given time, which limits its effectiveness. Studies such as that by Do Carmo et al. (2019) show that controlling feed supply improves results, but adoption is low, highlighting the need to involve livestock farmers in decision-making and monitoring.

The objective of this work is to promote the sustainable development of pastoral livestock farming in Uruguay through simple methodologies that facilitate technical change and co-innovation. To this end, an approach is proposed based on monitoring of pasture and animals, pasture diagnosis based on supply, evidence-based discussion and facilitation of adaptive decisions is proposed.

These elements seek to overcome the limitations of livestock systems, which are characterized by their complexity, combining biological components and family contexts, which makes efficient pasture management difficult in an uncertain and variable environment.

In particular, the aim was to develop a simple tool that covers all aspects of feed planning and can be implemented quickly and easily.

Methods

This work was based on the experience that led to the development of the Meal Plate Index (IsPC), Duarte et al 2023.

A total of 35 producers participated in this work, with a predominance of cattle farming systems and a wide variability in land area and resource provision. Initial workshops were held to level knowledge and develop a monitoring protocol. The variables monitored were, for pastures, height measured with a ruler and calculation of availability in kg dry matter (DM) and, for animals, weight measured with a scale and definition of grass requirements according to category. The IsPC, which relates grass supply to demand, was calculated using color-coded ranges: Red (<0.6:) Danger deficit), yellow (0.6-0.8): Caution, Green (0.8-1.2): Optimal, and brown (>1.2): Excess.

The strategies and analysis included the IsPC evaluation carried out in seasonal workshops with technicians and producers, the management strategies with UML diagrams that facilitated the interpretation and prioritization of measures such as sale of animals, deferral of feed, supplementation, etc. The scaling included the field days carried out with technicians and producers.

Dissemination included producer-led field days, on-farm support to new groups, training through workshops and courses, dissemination through articles, seminars and agreements, and the inclusion of the IsPC in national programs.

This methodological approach allowed us to analyze the heterogeneity between farms and to develop a scalable monitoring system that combines technical indicators with participatory strategies.

The methodological-technical framework used in the project was structured around three main pillars: estimation of feed availability, evaluation of animal needs and adjustment of the "diet plate" by calculating the IsPC. Each of these components is described in detail below: Estimation of forage availability:

- Measuring grass height with a ruler in different pastures.
- Convert of these measurements to kilograms of dry matter available per hectare.

Calculate of animal requirements:

- Evaluation of animal weight with a scale.
- Classification according to production category (breeding, rearing, finishing).
- Determine grass requirements based on these categories and production targets.

Adjustment of the "meal plate" (IsPC):

- The relationship between total grass availability and total system requirements.
- Classification according to diagnostic ranges (red, yellow, green, brown).
- Identification and prioritization of management action through participatory workshops.

This approach allowed for comprehensive management of feed and animals, providing producers with a clear diagnosis of the situation on their farm and the IsPC with a practical tool to optimize production based on forage available resources.

To estimate the amount of forage available, the use of a ruler was developed, calibrated and recorded (figure 1).

There is a relationship between the height of the mat and the amount of grass available. This relationship is established or calibrated by seasonal cutting. To do this, at least 30 seasonal cuts are made, looking for variability in height, where the height is measured beforehand and then varies by agro-ecological area and by season, as the structure of the mat changes.

Figure 1.- Ruler developed to estimate forage available

A basic thing to know before taking measurements is the grazing area. Measurements must be taken where the cattle graze, i.e. in the grazing layer, and avoid measuring things that are not part of the diet, such as bushes and shrubs. Pastures have what is known as plant heterogeneity, i.e. different plant communities. Measurements must be made in proportion to the size of each of these. Measurements are taken at the height of the densest layer, i.e. where the highest proportion of forage is concentrated.

It is defined as the kilograms of forage dry matter (DM) per kilogram of cow liveweight (LW) (kg DM/kg LW) and can be calculated for any pasture if we know how much forage there is per hectare and if we know the stocking rate in kg liveweight per hectare.

Forage supply = kg DM forage/kg live weight

Previous experiments carried out at the Faculty of Agronomy have led to the establishment of values of forage supply required by breeding cows in each season, while the rearing data have been constructed based on the results of experiments carried out at UFRGS (Brazil). The suggested values are related to the productive expectations of each category in each season of the year.

Table 1.- Forage supply values for different categories of cattle in different seasons of the year (Do Carmo et al, 2019).

	Offer kg dry matter/kg live weight			
Animal category	Spring	Summer	Autumn	Winter
Rearing up to 300kg	1 - 2	2 - 3	2 - 3	2 - 3
Finishing +300 kg	4 - 6	4 - 6	4 - 6	8 - 10
Breeding cows	More than 6	More than 6	More than 6	3 - 6

In this way, knowing the number of animals in each category, their weight and the amount of forage required (Table 1), it is very easy to calculate the amount of grass required per category and, by adding all the categories, the amount of grass that should be present on the whole farm at the time of monitoring.

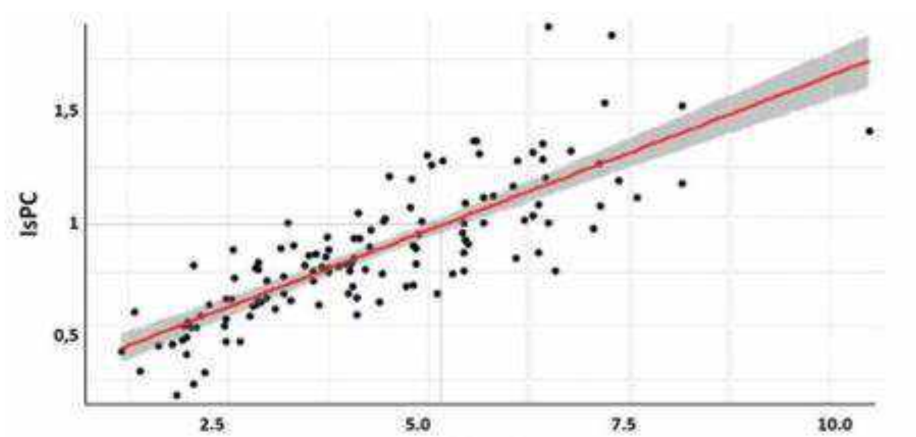
The IsPC is calculated by dividing the measured grass by the required grass (kg DM grass / kg DM required):

IsPC = measured grass/required grass and i.e. the result obtained is 0.96, it means that the meal plate is 96% full.

Results

In this work, grass height has a high positive correlation with IsPC (figure 2), which is a good single and simple indicator to estimate it, since this parameter depends mainly on the availability of grass and not on the needs of the animals.

IsPC = 0.143 * height + 0,233 (R^2 =0,65)



Height (cm)

Figure 2.- Regression graph between height (cm) and IsPC

Table 2. The following recommendations arise from the application of the IsPC:

IsPC	Color	diagnosis	suggestions
> 1.2	Brown	excess forage, loss of quality	adjustments to manage excess feed and loss of quality
0.8 – 1.2	Green	optimal, complete plate	no immediate need for management changes
0.6 – 0.8	Yellow	caution, targets at risk	short term possible decisions
< 0.6	Red	danger, animals at risk	urgent decisions required

Discussion

By working for several seasons with producers and their families, who seasonally monitored pasture and livestock, calculated the IsPC on their farms and discussed alternatives to adapt to the situation, we were able to develop a simple and effective methodology so that each producer, accompanied by other producers and their technician, could identify and choose the best decisions to make.

The IsPC was an indicator designed in a participatory manner and is important for monitoring and adjusting the relationship between availability and demand for pasture, based on the seasonal objectives of each category. It is important to mention that to calculate it, it is necessary to measure the height of the pasture. This fact is fundamental to quantifying the availability of food to be distributed in the "meal plate" of the pasture. It is also interesting to note that the IsPC is directly related to the height of the pasture.

The scaling up and dissemination of the IsPC tool has developed the lessons learned:

- Producers' experiences of monitoring, IsPC construction and workshops were shared at field days to demonstrate the overall methodology and results.
- Three-day courses have been held, with the aim of developing the capacity to take the necessary measures to establish the IsPC and to identify measures to maintain the IsPC.

The difficulties in scaling up arise from the fact that it is a technology that involves the implementation of group spaces that create, and then reflect on, an objective index to identify appropriate management practices. It is necessary to adopt practices to measure pasture and livestock (the culture in this regard is insufficient) to then identify appropriate management practices according to the IsPC which relates the available forage to required forage.

Conclusions/Implications

Despite the challenges of scaling up IsPC with a necessary cultural shift towards systematic measurement, its implementation offers a valuable decision-making tool for producers. IsPC improves pasture and livestock management, ultimately contributing to more efficient and sustainable agricultural practices.

Acknowledgements

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Rangeland monitoring can engage graziers

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Key words: Extension; Pasture; Burdekin

Abstract

Long-term monitoring is critically important in understanding how rangelands change across time in response to climate and management. In Queensland, the state-wide monitoring system called QGraze was established to monitor long-term pasture condition. The system has not only provided an opportunity to detect change in rangeland condition, but also engage with and build capacity with land managers in the livestock industry.

Beginning in 1991, the Queensland state Department of Primary Industries (DPI) in collaboration with land managers, installed nearly 450 sites on grazing lands across the state. Since then, these sites have been used by several projects to help inform the current state of rangeland condition and trends, such as monitoring the spread of the exotic grass *Bothriochloa pertusa* in the Burdekin district in North Queensland.

Just as importantly, enhanced engagement with graziers occurs as a result of surveying QGraze sites on their properties. This allows for the collaborative sharing of information and knowledge between DPI staff and the local grazing community. Graziers are interested to learn about their pasture and land condition in finer detail and the changes over time. The subsequent discussion regarding the contributing factors is valuable to inform their management decisions. Given the long timeframe over which monitoring has occurred, these conversations often span multiple generations, managers, and seasonal conditions. In turn, DPI staff are provided with perspective and context around the factors contributing to rangeland condition.

Due to the dedicated maintenance and monitoring of the sites by staff, QGraze provides a valuable resource for a combined understanding of the natural resource base underpinning Queensland's grazing lands.

Introduction

Native pastures provide the feed-base for a vast section of Queensland's grazing industry (ABARES, 2024). They also provide vital ecosystem services, and their management impacts major downstream ecosystems like the World Heritage Listed Great Barrier Reef – (GBR). Unfortunately, there is evidence of declining land condition through overgrazing and lack of resting (Gardener *et al.* 1990; McKeon *et al.* 2002). This includes declines in ground cover, loss of perennial grasses, invasion by the exotic *B. pertusa* and woody thickening, e.g., of the shrub *Carissa ovata* (currant bush)(De Corte *et al.*

1991; Rogers *et al.* 1999). Long-term monitoring of this native pasture resource is thus crucial for maintaining sustainable grazing land management and for the health of important ecosystems. Much of Queensland's grazing lands incorporate large spatial heterogeneity and are subject to high rainfall and climate variability within and between years (O'Reagain et.al., 2014). Detecting and interpreting temporal changes in the state of grazing lands can be difficult. While some changes in pastures are drastic, for example following fire, others are more subtle, such as the gradual loss of key perennial grasses or woody thickening and are less obvious to land managers. Furthermore, the recollection of past conditions can be subject to several cognitive biases which can lead to a misrepresentation of actual events (Roediger & Butler, 2011). Monitoring provides an objective record which helps to track changes in pasture composition and ground cover, identify trends in species diversity, and assess the overall health of vegetation.

Method

The Queensland Grazing Land Monitoring Project (QGraze) was established by the then QDPI in the early 1990's to implement a program to monitor change in condition across Queensland's grazed rangelands. At the time it aimed to provide a contribution to the National Rangelands Monitoring Program (Queensland Government, 2005). Nearly 450 permanent monitoring sites (Figure 1) were installed across a range of vegetation types and pasture communities. Sites are 4-hectare and consist of five 200m transects, spaced 20m apart, with each transect marked with a permanent centre peg. Twenty evenly spaced quadrats (0.25m²) are assessed along each transect, recording pasture species frequency, and estimates of ground cover and tree canopy cover. At each site 100 assessments are made along a series of 200m transects, recording pasture species frequency, and estimates of ground cover and tree canopy cover. Broader site estimates of soil condition, biomass and relative contribution to the biomass from the most dominant species are also recorded. Set point photos are taken, and tree basal area is calculated using a dendrometer.

Figure 1: Distribution of QGraze sites across Queensland.

Following the survey, data is processed and stored on a central data server. A report is also shared with the grazier giving the frequency of the main species, the condition of the site, comparisons with previous assessments and images from the fixed transect markers.

Results

QGraze in the Burdekin region.

The Burdekin River in NE Queensland has a catchment of approximately 140 000 km2 and is one of the main sources of sediment to the GBR lagoon (Furnas, 2003). Nearly 100 sites were installed in the catchment, with surveys first conducted from 1992 onwards. During this decade many sites were surveyed up to three times, however during subsequent decades monitoring frequency declined, due to changes in funding and government priorities. In 2014 several sites were re-surveyed as part of a project focussed on the spread of the exotic stoloniferous grass *B. pertusa* (Stacey, 2014). With the purpose of adding to the understanding of *B. pertusa* spread, several properties were re-surveyed in 2020/2021 while a further 10 properties were surveyed in 2024 as part of the DPI's Reef Water Quality Grazing Extension Service. Despite the intervening 25 years since two of these sites were surveyed, both were intact, and the owners/managers of both properties knew the location of the site. This was despite one of the properties changing ownership during the period. This suggests that these monitoring sites are valued by the graziers. The 2024 survey sites represented a range of properties, which were managed by the owners, or employed managers, and some properties had changed ownership, including through family succession.

Understanding trends

Besides the site report that a grazier receives, district comparisons over time can also be made, giving both an indication of the influence of seasonal conditions and relative trend of the condition of that site. This contributes to a shared understanding of the rangeland condition across a district and the impact of an individual grazier's management. For example, a comparison of the change in the frequency of the pasture grasses Indian couch (*B. pertusa)* and Black Spear (*Heteropogon contortus*) across seven properties within a district showed trends which suggest the influence of prevailing broader seasonal conditions (Figure 2).

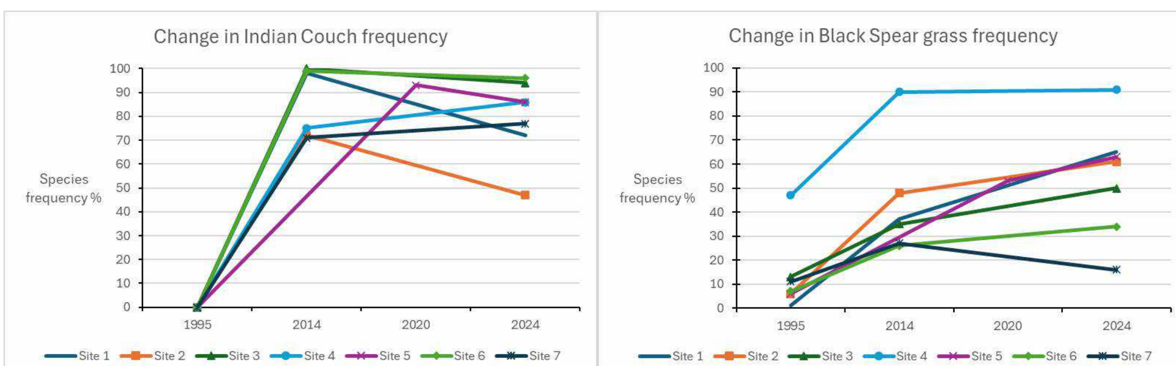

Figure 2: The change in frequency of Indian couch and Black Spear grass across seven sites on the same land type/pasture community with a maximum distance of approximately 80km between sites.

In 1995 Indian couch was not detected at any site but they all experienced a rapid increase by 2014 (or 2020 for site 5) and then all but two declined in frequency again between 2014 and 2024. Similarly Black spear grass increased at all sites between 1995 and 2014/2020 and maintained this increase in all except one site between 2014 and 2024. Similar patterns across these properties which varied in management systems suggest that seasonal conditions are an important factor in the spread of Indian couch.

Discussion

Sustaining Relationships

A fundamental component of DPI's delivery of extension services to the grazing industry, is placing the grazier at the centre of the activity and working *with* them to build capacity (Williams et.al, 2020). The installation of permanent monitoring sites on-property helps relate the science that QDPI does, to the grazier's own circumstances and decision-making. During the 2024 round of surveys, each visit was preceded by a conversation with the grazier discussing the site. Invaluable context for the site was given by the grazier during these conversations, such as history of fire, sown pasture species, and infrastructure development. Often the conversation would expand to include wider property and industry themes. On many occasions the grazier could recall the officers who installed the sites. These conversations were particularly beneficial for new extension and technical officers. Not only did they provide historical context, but also indicated to DPI officers what issues were important and what events may have been formative to the grazier's land management practices.

Industry capacity

The follow up report also provides an opportunity to continue and expand the relationship – allowing DPI staff to provide feedback on how sites have changed, place the results in a wider regional context and share the experiences of other graziers. Sometimes this can provide confirmation for a grazier that their management systems are achieving desired land condition outcomes. It can also initiate further discussion and an introduction to the range of DPI extension services. Customised support can follow, which addresses the multiple aspects of managing a beef business while building as broader professional relationship.

QGraze sites provide a sustained reason for ongoing, meaningful engagement between DPI staff and graziers. This interaction helps preserve and transfer corporate knowledge, ensuring that valuable expertise and historical context are not lost amidst staff movements, changes in ownership or generational transitions. DPI investment in this multi decade engagement enhances trust and promotes informed decision-making, ultimately supporting the long-term resilience and productivity of land management practices.

Conclusion

QGraze has provided a unique opportunity to objectively track changes in Queensland's grazing lands spanning multiple decades. Monitoring these sites has developed the technical skills of QDPI staff and given new officers the chance to connect with multiple generations of the grazing community. Effective agricultural extension is built on valued, trusted relationships – QGraze offers the chance to further develop these relationships and support practice change.

Acknowledgements

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Beyond grasslands: valuing the societal contributions of India's rangelands and pastoral systems

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Key words: Himalayan rangelands; socio-cultural contributions; ecological significance; pastoral systems.

Abstract
Rangelands and pastoral systems in India have traditionally been viewed primarily through the lens of livestock production, often overlooking their broader societal contributions. India's rangelands, particularly those nestled in the high-altitude Himalayan regions, are much more than mere grazing lands; they are lifelines for pastoral communities like the Chopans and Gujjars and are crucial to the country's ecological and cultural fabric. The rangelands of Jammu and Kashmir, Himachal Pradesh and Uttarakhand, with their rich biodiversity and fragile ecosystems, play a pivotal role in maintaining ecological balance. They support a unique form of pastoralism, where traditional practices have evolved in harmony with the environment, ensuring the sustainable use of these landscapes. Beyond their ecological significance, these rangelands are reservoirs of indigenous knowledge and cultural heritage, sustaining communities that have thrived in these challenging terrains for centuries.

This paper highlights how these landscapes contribute to food security through livestock rearing, support biodiversity, regulate water cycles, and sequester carbon, thus playing a crucial role in mitigating climate change. The research presents compelling case studies from Himalayan region, demonstrating how traditional pastoral systems have preserved these rangelands but and enhanced their resilience to environmental changes.This novel perspective underscores the need for holistic valuation methods that capture the dynamic interplay of ecological,economic, and cultural dimensions, paving the way for more sustainable and equitable rangeland governance and social cohension.

However,these vital landscapes are increasingly under threat from land-use changes, climate variability, and the marginalization of pastoral communities in policy-making. This paper advocates for a more inclusive approach to valuing rangelands,recognizes their full societal contributions and integrates them into national and regional development strategies.It seeks to influence policy frameworks that will ensure the sustainable management of rangelands by safeguarding them for future.

Introduction

India’s rangelands have traditionally been associated with livestock grazing while this perspective underscores their role in food production. It fails to capture their broader societal, ecological, and cultural contributions. In regions such as Jammu and Kashmir, Himachal Pradesh, and Uttarakhand, rangelands support biodiversity, sustain pastoral livelihoods, and maintain ecological processes that benefit society at large (Sharma et al. 2003). Communities such as the Gujjars, Gaddi and Chopans have practised pastoralism for centuries, adapting to the challenges of these fragile landscapes while maintaining sustainable resource use (Ingty 2021). In order to manage rangelands sustainably and guarantee that they continue to offer vital resources and services (Singh et al. 2021), this indigenous knowledge is crucial. Livestock rearing is a primary livelihood activity for millions of people in India, contributing to household income and local economies (Mitra 2013). However, land-use changes, climatic unpredictability, and the exclusion of pastoral voices from policy-making processes pose growing risks to these crucial ecosystems. According to Roe et al. (2009), rangelands have deteriorated as a result of pastoral communities' absence from land-use planning and decision-making procedures.

This study seeks to shift the narrative surrounding India’s rangelands from a narrow focus on livestock production to a holistic valuation that encompasses ecological, cultural, and economic dimensions. By drawing on case studies from the Himalayan region, it aims to demonstrate the multifaceted contributions of rangelands while advocating for policies that secure their sustainable management. Through the use of customs and traditions that have accumulated over the ages, pastoral societies like the Chopans and Gujjars have established complex interactions with these environments. This is something that requires attention to study these areas more. In India, rangelands especially those found in the high-altitude Himalayan regions have long been underestimated for the contributions they provide to society, frequently being relegated to the status as animal grazing areas(Bhasin 2011). This limited viewpoint ignores the many functions these landscapes perform in sustaining pastoral communities, safeguarding cultural legacy, and ensuring ecological equilibrium. In addition to being essential for raising cattle, the rangelands of Jammu and Kashmir, Himachal Pradesh, and Uttarakhand are also important ecosystems that support biodiversity, and control water cycles, all of which help to slow down climate change(Wagner 2013).

Methods

A qualitative approach was employed to understand the ecological and societal contributions of rangelands: that includes literature review related to the published studies on biodiversity, carbon sequestration, and water cycle regulation in India’s rangelands that provided a foundation for this research. Along with that case studies to document examples from the Himalayan regions of Jammu and Kashmir, Himachal Pradesh, and Uttarakhand are analyzed to illustrate the diverse contributions of rangelands while highlighting the interplay between traditional pastoral systems and rangeland sustainability. Interviews and focus group discussions with Gujjar and Chopan pastoralists were conducted to capture indigenous knowledge and cultural practices.

Results

Rangelands here serve as vital ecological corridors, linking fragmented habitats and supporting diverse species. Pastoral practices, that surprisingly involving almost every member of the family without any discrimination on the behalf of age,sex,gender , such as rotational grazing, enhance ecosystem resilience by allowing vegetation to recover and reducing soil erosion. Carbon sequestration potential in grassland soils is substantial, contributing to climate change mitigation. Additionally, these landscapes play a critical role in hydrological cycles, facilitating groundwater recharge. Rangelands also play a crucial socio-economic role, especially for marginalized communities like the Gujjars, Chopans, and other pastoral groups in India. These communities depend on rangelands for their livelihoods, and the services provided by these landscapes form the backbone of their economic activities. Rangelands are integral to the livelihoods of pastoral communities, providing grazing resources for livestock that sustain local economies which in turn will help sustain the national economy. These communities contribute to food security through the production of dairy, meat, and wool. Furthermore, the migratory routes and seasonal camps of pastoralists preserve traditional knowledge and foster social cohesion within and between communities.

The results highlights that women's involvement in pastoralism often extends to decision-making processes about herd management and land use. In some cases, especially in Uttarakhand, women may also take on leadership roles in community-level governance of rangelands, advocating for sustainable practices and mediating conflicts over resource use. However, despite their significant contributions, women there often face gender-based discrimination and limited access to resources and decision-making power.

Rangelands contribute to the broader rural economy by providing resources that support secondary industries, such as handicrafts and local markets there in addition to the direct income and livestock products, livestock by-products, such as hides, wool, dung, and manure which are valuable. In many rural areas, cow dung is used as a source of fuel, while wool from sheep and goats is used in weaving industries. Nonetheless, the problems of direct access to market, value-chain and intermediaries were reported. Seasonal movement between different grazing areas allows pastoral communities to optimize grazing and prevent overgrazing in any single area. Mobility was found to be a helping hand to creates economic linkages between different regions, with pastoralists engaging in trade, exchanging livestock, wool, and other goods as they travel. So,this way mobility has provides social benefits too, as it fosters inter-community connections and collaboration, which can help with managing common resources and resolving conflicts but it also creates conflicts too.

As the results supported the Dangwal(2009), rangelands of the Himalayan regions, hold significant cultural value for the communities that depend on them but some are started to settle down in one place or chose to be less mobile in terms of frequency. These landscapes are not only resources for livelihood but also integral to the spiritual, social, and traditional practices of pastoralists. Rangelands in Uttrakhand and Himachal often host sacred spaces, such as temples, shrines, and sacred groves, which are considered vital for the spiritual life of pastoral communities, however, Kashmir is exception. For example, in the Himalayan regions, sacred groves are protected areas within rangelands where the community believes that natural spirits dwell. These groves are not only areas of biodiversity conservation but also sacred spaces that influence local religious practices and social norms. These cultural practices help reinforce the connection between the community and the land. Additionally, social identity is often tied to the practice of pastoralism. The deep knowledge of rangeland ecosystems and livestock management is passed down through generations, shaping a community's sense of identity and belonging. Indigenous knowledge systems play a central role in the cultural aspect of rangeland use. pastoral communities includes knowledge about animal behavior, grazing cycles, plant species, and weather patterns. In the context of rangelands, this traditional knowledge enables communities to adapt to changing environmental conditions, optimize grazing, and manage the health of both livestock and landscapes. This knowledge is often codified in cultural practices, local governance structures, and community-based management systems that promote the long-term health of rangelands.

Discussion

The findings reaffirm the multifaceted value of India's rangelands, extending beyond their utility as grazing lands. Traditional pastoral practices exemplify a model of sustainable land management, balancing productivity with ecological health. These practices have evolved in harmony with the environment, ensuring the resilience of both human and natural systems. Culturally, rangelands house sacred sites and pilgrimage routes, reflecting their spiritual significance and their consideration of herd as a member of family is show their sense of belongingness. Rangelands also serve as reservoirs of indigenous knowledge, encompassing animal husbandry practices, medicinal plant usage, and ecological stewardship strategies even young members of communities understand these things. This knowledge, if leveraged, can inform contemporary conservation and development policies. Not only this but also empowering women in these communities can enhance the effectiveness of rangeland management and contribute to overall socio-economic development. However, the degradation of rangelands due to unsustainable agricultural expansion, infrastructure development, and climate change poses a significant challenge. Policy frameworks that prioritize industrial and urban development often marginalize pastoral communities, leading to the erosion of traditional knowledge and land-use practices. To safeguard these landscapes, a paradigm shift is needed in how rangelands are valued and managed. This includes:

- Integrating rangeland conservation into national climate adaptation and biodiversity strategies.
- Establishing participatory governance models that empower pastoral communities in decision-making processes.
- Promoting research and development initiatives focused on sustainable pastoral systems and rangeland restoration.

The societal contributions of rangelands ranging from food security and biodiversity conservation to cultural preservation highlight their importance in achieving sustainable development goals. Weber et al. (2004) argue that pastoralists possess detailed knowledge of their environment, which is crucial for sustaining their livelihoods and maintaining ecological balance. It also elaborates on the cultural and socio-economic functions of rangelands, providing deeper insights into their importance beyond just ecological roles while recognizing and enhancing these contributions is crucial for fostering resilience in the face of environmental and socio-economic challenges. However, rangelands also contribute to the broader national economy in ways that are often undervalued in conventional economic assessments. The cultural and socio-economic functions of rangelands are central to the livelihoods of pastoral communities in India. Rangelands not only sustain food security and economic productivity but also preserve rich cultural traditions, social identities, and community ties. The integration of indigenous knowledge and sustainable practices is essential for maintaining these functions in the face of challenges such as climate change, land-use pressures, and socio-political marginalization. Understanding and valuing the full spectrum of cultural and socio-economic contributions of rangelands is crucial for developing policies that ensure their conservation and the continued well-being of pastoral communities. According to Fernandez-Gimenez (1999), such religious connections to the land help ensure its sustainable management as the communities perceive themselves as guardians rather than exploiters of these spaces. Although rangelands are essential to rural economies and the environment, policy discussions have frequently overlooked their governance. The study highlights the need for more inclusive and participatory governance, arguing for policies that incorporate pastoralists' traditional knowledge into land management frameworks and acknowledge their rights. These regulations need to encourage sustainable grazing methods and guarantee that pastoral communities are involved in rangeland resource management.

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The role of pastoralists' indigenous knowledge in managing South African mesic and semi-arid rangelands

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Key words: Knowledge co-production; Rangeland management; Pastoralism

Abstract

Rangeland management decisions by pastoralists are largely based on experiences which include but not limited to ecological relationships, animal health and land use practice. Recent droughts have stretched the natural resources, management skills and the livelihoods of pastoralist to their utmost limits. The aim of this research was to gain a better understanding of how pastoralists in the semi-arid and mesic rangelands utilize indigenous knowledge in their rangeland management. Face-to-face interviews were conducted to establish how South African pastoralists incorporate indigenous knowledge in their rangeland management and monitoring. Data obtained from the interviews was analysed using content analysis. Insights that emerged from the analysis included categorizing the rangeland by using such as vegetation and livestock indicators. Vegetation indicators included plant colour, plant diversity and abundance; while livestock foraging time and livestock health were livestock indicators. In order to allow rangeland recovery, interviewed pastoralists in the mesic rangelands detailed to divide the rangeland into '*soet veld'* [characterised by palatable grasses that have low fibre content and maintain their nutrients in the leaves throughout the winter] and '*suur veld'* [characterised by unpalatable grasses that have high fibre content and tend to remove their nutrients from the leaves during winter], which are utilized by livestock during different seasons. In the semi-arid regions, pastoralists practice transhumance between different vegetation types; while allowing rangeland recovery in the grazed area. Pastoralists also explained to incorporate western scientific knowledge with their indigenous knowledge to modify their grazing practices in order to minimize overgrazing and rangeland degradation. Therefore, this study emphasizes that movement towards sustainable rangelands requires transdisciplinary methodologies for an improved understanding of pastoralists' knowledge and management practices of their local rangelands.

Introduction

South African rangelands cover approximately 80% of the country's land surface (DAFF 2018). A large portion of livestock farming in the country occurs in arid or semi-arid rangelands that are vulnerable to climatic variability and climatic changes. Therefore, management of rangelands need to simultaneously consider the demands of various threats.

Pastoralism is an ancient livestock production system that was developed 7 000 years ago in response to long-term climatic changes (FAO 2018). Any decision by pastoralists is based on various knowledge which include ecological relationships, natural resource management, animal health and land use practice. According to Thomas et al. (2020), movement towards sustainable agricultural production is centred on an improved understanding of pastoralists' knowledge and learning processes. Insights on how a pastoralist understands their farming environment, and knowledge encounters between pastoralists are all crucial for pastoralists' knowledge assessment (Reed et al. 2010). Therefore, the aim of this study was to gain a better understanding of how South African pastoralists utilize indigenous knowledge in rangeland management.

Methods

This study engaged qualitative research focusing on multiple case studies, as described by Meredith (1998). Semi-structured interviews were used to investigate pastoralists' agro-ecological knowledge utilization in rangeland management. Pastoralists chosen for the study were goats, sheep and cattle herders. A total of 17 and 27 pastoralists from the mesic and semi-arid rangelands respectively formed part of this study. Mesic and semi-arid rangelands were represented by pastoralists from the Eastern Cape Province, and the Northern Cape Province in South Africa, respectively. Questions for the interviews were related to grazing lands utilization, and indicators used to monitor rangeland condition. Content analysis as described in Braun and Clarke (2012) was used to analyse data.

Results

Indicators used to monitor rangeland condition

Good rangeland: Grazing areas which visually appear to have a bright green colour were described as good rangeland condition in both study sites. Plant species such as *Pentzia incana*, *Limeum africanum* L. subsp. *africanum*, *Vachellia karroo*, Scutia myrtina, *Olea europaea* L. subsp. *cuspidat*e, *Portulaca oleracea*, *Themeda triandra*, *Cynonodon* sp., *Cenchrus clandestinus* and *Digitaria eriantha* were listed as indicators of good rangeland condition. Pastoralist emphasized the need for continued monitoring of such palatable plants to reduce degradation and overgrazing.

Poor rangeland: Pastoralists in the semi-arid rangelands explained that decreases in palatable shrubs such as *Didelta spinosa* and *Eriocephalus ericoides* indicate a poor grazing area. The high abundance of unpalatable shrubs such as *Tylecodon* sp., *Solanum elaeagnifolium*, *Opuntia aurantiaca* and *Euphorbia ferox* were listed as indicators of poor rangeland condition. One pastoralist reported to use foraging time as an indication of rangeland condition.

"*I usually let my animals out in the morning on their own without a herder, and they normally return to the homestead around 4pm. However, if this time passes and the livestock is not back, it is normally an indication that something is wrong or they have not eaten enough, meaning that the condition of the veld is bad. Then I either send out my herder to go and investigate the matter or I go myself*".

Use of indigenous knowledge in rangeland management

Pastoralists in the mesic rangelands described to improve rangeland condition by making use of livestock to spread *Themeda triandra* seeds through faecal matter. Pastoralists also described to alternate cattle grazing with goats and sheep grazing to utilize different grass heights in the rangelands. However, pastoralists emphasized the importance of continued monitoring for plant height to reduce root damage.

Livestock handling was described to be an important aspect of rangeland condition. A pastoralist in the mesic rangeland, detailed to have been taught by his father not to whip livestock, as this results in stress; and the livestock destroy vegetation and soil from running around haphazardly. Additionally, pastoralists in both study sites described limping to be an indication of poor rangeland condition with wet soil or ticks' presence.

Mobility between different vegetation types was described as an indigenous practice by the pastoralists. The semi-arid pastoralists use the Succulent Karoo as a winter grazing area, and the Nama Karoo is used as a summer grazing area. Similarly, pastoralists in the mesic rangelands move their livestock to graze on the soetveld in winter and move to the suurveld during the summer season.

Discussion

The use of palatable plant diversity as an indicator for rangeland condition is common amongst African herders (Samuels et al. 2018). The current study's results of the use of livestock behaviour to monitor rangeland condition, are concurrent with Dabasso et al. (2012).

Transhumance is practiced to exploit seasonal availability of natural resources (Ntombela et al. 2024); and forms part of ethnic identity across global indigenous communities (Blench 2001). The transhumance routes followed indicate a rich understanding of natural resource distribution and availability in the rangeland.

Pastoralists have over many years, accumulated and transferred indigenous knowledge; and it is from this knowledge that decisions are made. Therefore, knowledge and goals need to be integrated into rangeland management for increased and sustainable production. This requires expertise and methodology integration of social sciences into the rangeland profession. Research such as this current one could potentially add to the agricultural education sector of South Africa to highlight the value of agro-ecological knowledge in livestock production and rangeland management, leading to knowledge co-production.

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Typology of subjectivities in relation to grass management

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Key words: typology of subjectivities; grass management; extension; grasslands.

Abstract

In Uruguay, most cattle and sheep herds graze on natural grasslands. Research indicates that overgrazing is widespread. As part of the Grassland Management (GM) extension project, research is being developed to identify the different ways in which ranchers think about what they understand by GM. This set of different ways is called a typology of subjectivities. From these differences, five ways of thinking about GM emerge.

They are, 1- from the whole (which is associated with rotational grazing and implies considering cattle and sheep herds, soil, pasture and human resources), 2- from the grass, 3- from measurement, 4- from visual observation and 5- from the body condition of cattle herds. Based on similarities, it is possible to generate two macro-groups that facilitate analysis. The proactive rational macro-group (groups the whole, the grass and measurement) and the reactive rational macro-group (groups visual observation and body condition). Each macro-group has its ontological dimension (what to look at?), epistemological dimension (relationship between the rancher and their reality) and methodological dimension (how to look?). The average GM subjectivity profile for all the cases analysed (26 farms) prioritizes the whole or grass view and rejects visual observation (which implies that they prefer to measure).

One of the advances of this project is the identification of methodological views in each macro-group. These views are the gateway for technical assistance and rural extension (TARE). This means that TARE must work orienting their strategies according to each macro group rationality. From which it is deduced that it would not be correct to emphasize measurement and not work with the more traditional producers who focus on the visual observation (as suggested by the traditional theory of rural extension).

Introduction

In Uruguay, most cattle and sheep herds graze on natural grasslands (Pereira Machín, 2011) Research indicates widespread overgrazing (Paruelo et al., 2000). As part of the GM extension project, research is being conducted to identify the different ways in which farmers think about and understand GM. The project, launched in 2021, seeks to improve grassland management by identifying good practices that promote sustainable systems (Fiore et al., 2020). As stated by Freire (1973) it is difficult to change a person if you do not know how that person thinks and how they interpret their reality. By understanding how they think, learning strategies can be properly designed to fit their needs, values, and practices. This study analyses the subjectivities regarding GM of 26 ranchers.

Methods

A qualitative methodology was used, based on structured interviews with 26 ranchers, analysing their perceptions regarding GM. The establishments were chosen in the following way: a public call was made to participate in the project, and those that, according to the technicians' knowledge and/or consultations, were doing interesting things from a pasture management point of view were selected. The interviews included questions about grazing dynamics, livestock management, and emergency response.

Regarding grazing dynamics, the questionnaire questions referred to: what they look at to manage pasture, what stocking rate they use, whether they implement occupations and rest periods, criteria they use to make decisions, whether they know their stocking rate, how they plan grazing, whether they have specialized areas according to species (sheep and cattle), how they conduct field visits to make decisions.

Regarding livestock management: whether they have specialized areas according to species (sheep and cattle), whether they manage fixed lots, whether they supplement or not, whether they use improvements or not, which categories they use them with, etc.

Regarding emergencies: questions were asked about which emergencies they faced, with emphasis on the measures taken during droughts, especially.

The responses were analysed qualitatively, interpreting them to identify emerging themes that allowed for the establishment of differences.

Results

Five types of subjectivities were found regarding GM:

- **Prioritizes the whole:** A systemic vision related to rotational grazing that considers technical and human elements (Cros et al., 2004).

- **Prioritizes the grass:** Prioritizes grassland management as the basis of sustainability, emphasizing that "grass makes grass" (Bove, 2023).

- **Prioritizes measurement:** Uses indicators such as the Food Plate Index (FPI), a simple but robust forage budget, for data-driven decision-making (Duarte et al., 2021).

- **Prioritizes observation:** Based on the visual interpretation of grass and animals through a "trained eye" (Segarra Ciprés and Bou Llosar, 2004).

- **Prioritizes the body condition of the animals:** This is the traditional view that values accumulated experience as the main guide (Morales et al. 2005).

The following are representative statements of each of these types of subjectivity:

"Grass management involves taking into account the system, which includes the grass, the animals, the soil, and the human factor”. (prioritizes the whole)

“The first step is to assess the grass: the grass itself creates more grass”. (prioritizes the grass)

“If you cannot measure, you cannot manage”. (prioritizes the measurement)

“The eye measures by observing and makes good estimations” (prioritizes the observation)

“The first step is to observe the body condition of the cattle." (prioritizes the body condition)

Discussion

The five approaches can be grouped into two broad groups that we call "rational-proactive" and "rational-reactive." We believe this is an appropriate approach due to the conviction that within each macro-group there are similarities, exchange dynamics, and grey areas that make it advisable to work with the broad groups, not with the isolated types. The name respects the original classification of the Instituto Plan Agropecuario (proactive and reactive), emphasizing that both approaches are rational.

This classification highlights the epistemological dimension (the relationship between the producer and "their" reality: proactive or reactive), which is linked to the ontological dimension (what to look at in reality: the grass or the livestock). The novelty is that this research incorporates the associated methodological dimension (how to look: measuring or observing). This dimension is important because it gives value to the fact that there are not only "objective" forms of knowledge through measurement, but also through observation (all rationales). But also, it should be said that it is through these methodological views that TARE services express their intervention strategies.

The "rational-proactive" comprises three related visions: those who look at the whole (practice rotational grazing), those who look at the grassland, and those who measure. The three views focus on the grass with nuances. Those who practice rotational grazing have a global vision (not just plants). Those who focus on grass and those who emphasize measurement share common core values: grass makes grass, and without measurement it is impossible to manage it. It is likely that those who practice rotational grazing also share them. Those who measure use numbers, records, and instruments such as the green folder, the FPI (they are likely to be younger and with more women presence).

The "rational-reactive" macro-group comprises two related views: those who use visual observation and those who look at the body condition of the animal. We could say that both aspects characterize the traditional livestock producer. Those who observe visually prioritize the experience that accustoms the eye to "see well."

Intervention strategies must consider the two major rational logics described above. For the "rational proactive" macro-group, the intervention strategy must work with instruments such as the green folder, or the FPI. The numbers speak for themselves and can be the basis for moving towards scaling proposals. For the "rational reactive" macro-group, the proposals must be adapted to the cultural specificities of the group. The numbers must be accompanied by images that speak for themselves and the systematization of experiences that are illustrative.

In both cases, two considerations apply. First, the rancher workshop/group is an appropriate tool that constitutes the innovative core of a process that then poses the challenge of achieving scalability, what was previously called dissemination. And the challenge arises because much of the learning that occurs at the "workshop/group" level is the result of interactions and experiences that cannot be scaled on their own. Second, technical messages should seek to integrate the productive, economic, and environmental aspects. It can be difficult for the producer to understand them separately, especially the environmental aspects (Vanclay, 2004). The environmental dimension tends to be an integral concern in the rational proactive, while in the rational reactive it refers more to the economic dimension (that the company continues to generate income and work).

Conclusions

The study identifies the existing subjectivities in relation to the way producers manage grass. Recognizing these subjectivities is key to designing effective interventions. The study identifies five different ways of understanding pasture management, which can be grouped into two main types: rational proactive and rational reactive. This characterization respects previous work carried out by the Instituto Plan Agropecuario. The innovative contribution of this research is in two aspects. First, it allows us to better understand the heterogeneity that exists within each typology (the different perspectives). Second, it allows associating a methodological perspective with each typology. This gives the research an applied character. That is, it guides us to specify the intervention strategies in better terms.

By prioritizing the rational character of the two typologies, it follows that the central idea from the TARE services should not be to promote the transition from visual observation to measurement. Rather, we must work with all producers, adapting the materials to cultural specificities when necessary. Traditionally, ATER theory suggests working with the most receptive (in this case, the rational proactive typology) and waiting for natural diffusion (scaling) to occur. Here we propose, to accelerate changes, to work with everyone, which implies recognizing the different subjectivities. We know it is a challenge: it is easy to say but difficult to apply.

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Arizona/Utah range workshop and tour – building on 46 years of success

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Key words: Rangeland; Workshop; Education; Ranchers, BLM

Abstract
The Arizona/Utah Range Livestock Workshop & Tour builds cooperation and understanding between public land grazing permittees and federal agency personnel through science-based education. The workshop provides information on livestock production practices and addresses controversial grazing issues in a non-confrontational environment. Topics range from animal handling, vaccination, and health to solar development, partnering with public land agencies, and recreation effects.

Introduction
The Arizona strip is a vast track of land located along the border of the states of Arizona and Utah in the United States. It covers over 3 million acres, and due to its accessibility limitations imposed by the Grand Canyon it is primarily accessed by ranchers in Utah and Nevada. The vast majority of this land is public land and is owned by the citizens of the United States of America, as such it is managed by the Bureau of Land Management (BLM).

Ranchers have been grazing livestock in this area since the 1800s and is currently the source of 100,000 Animal Unit Months (AUMs) of grazing, with an economic value of $7.1 million/year (Heaton, 2024). and is especially important in winter months.

In the mid 1970s grazing on the Arizona Strip became a contentious issue in Southern Utah, Northern Arizona, and Southern Nevada due to the completion of the "Hot Desert" Environmental Impact Statement coupled with the designation of the Desert tortoise as an endangered species. Many allotments were closed and ranches were forced out of business. The AZ/UT Range Workshop was developed by Utah State University Extension and the University of Arizona Cooperative Extension in response to these issues with the goal to bring ranchers and government agencies together to work on these problems and learn how to best manage allotments. The first workshop was held in 1978 and has continued for 46 years as a free workshop with the goals of strengthening relationships and bringing cutting edge science-based knowledge to its participants. This workshop' funding is sponsored by ranchers, local businesses, and conservation districts.

Today, the workshop consists of two days of workshops, presentations, and vendor displays with a third day being spent on a rancher's allotment learning about their range improvements, innovations, and participating in hands on workshop to learn how to manage allotments better.

These workshops are evaluated by University Faculty to determine the effectiveness of each workshop and to help guide the following years workshop topics and tour locations. Continuous evaluation and adaptation ensure that the range livestock workshop remains aligned with the educational needs of grazing permittees and supports effective collaboration between ranchers and public land agencies. Looking ahead, USU Extension will strive to continue this program's long-standing success by delivering science-based education and enhancing relationships between ranchers and government agencies for years to come (Heaton et al. 2024)

Methods

Needs Assessment As mentioned in the introduction the workshop is evaluated each year with the results serving as a needs assessment for the following year. The results of the evaluation are distributed to the planning committee annually to help guide topic selection. Once topics are selected, speakers are then identified and booked for the workshop which takes place annually in March.

Goals and Objectives The goals of the AZ/UT Range workshop are to increase knowledge of participants on the previous selected topics. A pre/post evaluation is given at the end of each workshop to evaluate overall knowledge gain on each topic covered at the workshop. The evaluation also collects data on the demographics of each participant, overall satisfaction of the workshop, venue, vendors, food, and to identify information that participants would like to learn about the following year.

The tour is likewise evaluated with a focus on the stops of the tour and knowledge gained on different topics covered at each stop with a pre/post survey. Information is also collected on participants preference for the following year's tour location and overall topics.

Evaluations and Analysis As previously mentioned, evaluations are distributed at the end of each workshop. The evaluation includes a pre/post survey to determine the percentage of knowledge gain. Short answer questions to determine changes in behavior, and collects information on participants age, occupation and how often they have attended this workshop.

To calculate the percentage knowledge gain for the group, use the following formula was used for absolute percentage change:

$$\text{Absolute Percentage Change} = \frac{\text{Post-Test Score} - \text{Pre-Test Score}}{\text{Pre-Test Score}} \times 100$$

Results

Evaluations from the 2024 Arizona/Utah Range Workshop and tour evaluated 9 presentations with a pre/post survey and found significant knowledge gains in each of the topics covered. The topic with the most substantial growth was "Vence" (Virtual Fencing) which is a topic that had not been covered in prior years. The least impactful topic was "Plant Response to Grazing" (see Fig. 1), which had been covered in prior years and was also demonstrated on the tour in 2024. In addition to the percent of knowledge gain a simple t-test was used to evaluate each topic and found a significant difference in knowledge gained across all topics.

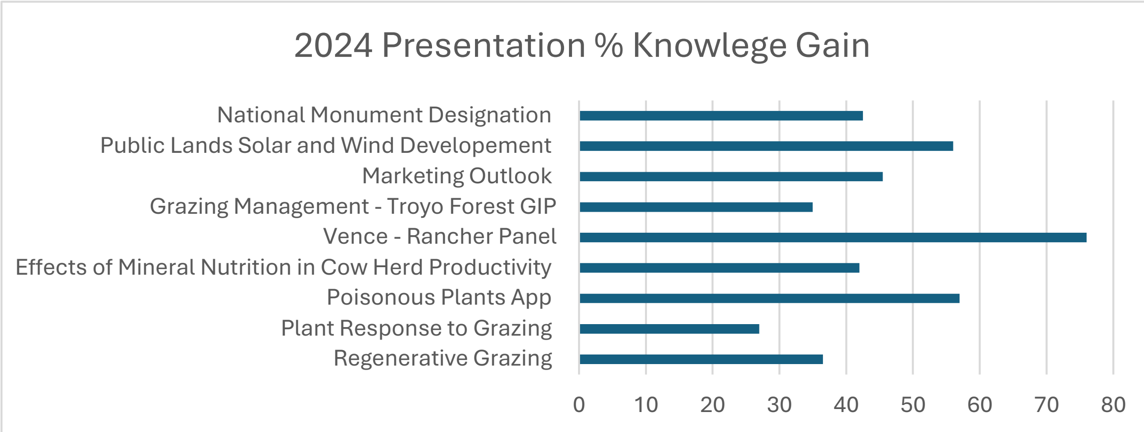

Fig. 1. Graph showing % knowledge gain by presentation topic.

Demographics and Behavioral Change:

Evaluations of the Arizona/Utah Range Workshop and Tour for the past 20 years have identified changing trends as well as reenforced old ones. Attendance has stabilized around 255 participants/year, but the age demographic has changed significantly over the past 20 years. (see Fi 2.). In 2003 we found that 64% of our participants were over the age of 50 with 34% being under the age of 50. Recent evaluations found that 68% of participants are under the age of 50. In fact the largest demographic in 2024 was in the age range of 20-29 years old, making up 40% of all participants. Participants perception on different topics also show a favorable change of at least 69% of participants indicating that they will change their behavior as a result of what was learned at this workshop. (See Table 1.).

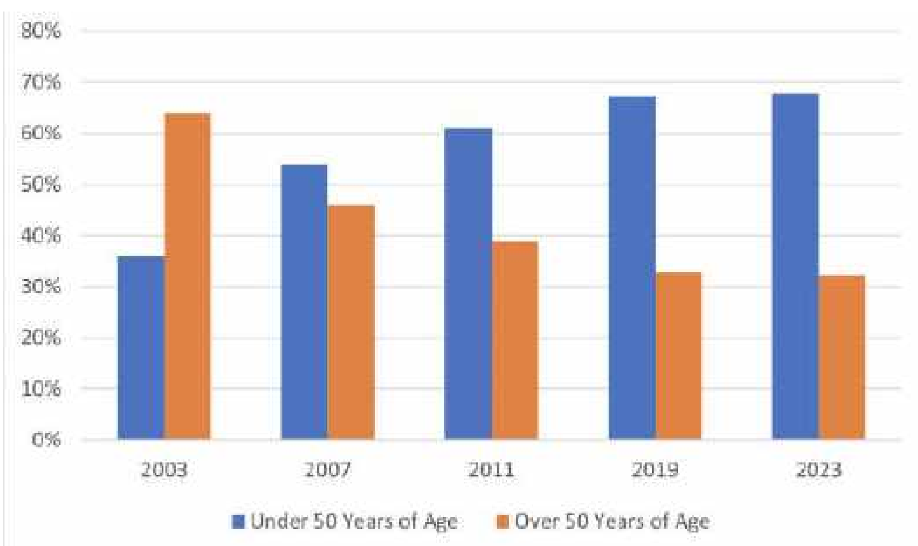

Fig 2. Age Demographics 2003-2023

Table 1. Participants perception of knowledge change post workshop (N=154)

	%		
Topic	YES	NO	N/A
Do the sponsors displays influence your purchasing decisions	84	16	0
Were Sponsors displays educational?	91	9	0
This workshop Improved my awareness of the topics covered	99	0	1
This workshop Provided new knowledge	99	0	1
This workshop Provided new skills	90	6	4
This workshop Modified my opinions and/or attitudes	83	12	5
This workshop Will improve advice I give to others	92	1	7
I am likely to use some aspects of this activity In my farm/ranch/home operation	74	5	20
I am likely to use some aspects of this activity in an educational program that I will plan or participate in	69	6	25
I am likely to use some aspects of this activity As a resource I will make available to producers	69	10	21
I am likely to use some aspects of this activity As a professional development tool for my peers	69	9	22

Discussion

The Arizona/Utah Range Workshop and Tour has demonstrated positive overall findings in knowledge gain to its participants across multiple topic areas consistently for its 46 years of operation. The workshop provides participants with opportunities to expand their knowledge, skills, and relationships with other stake holders in range management.

The workshops evaluations capture knowledge gains and behavioral changes adequately but reveal the need for adaptations to better capture impacts of the workshops additional goal of building relationships between government land management organizations and ranchers. Some publications on this workshop have been published through Utah State University Extension with additional research needing to be done on long term impacts from this workshop on ranching operations on the Arizona Strip.

To build on the 46 years of success that this workshop has demonstrated, organizers will need to continue to focus on the needs of participants by continuing to focus on new technologies, practices, and marketing opportunities that participants require to stay relevant in today's industry. With a large shift in population age demographics this workshop is uniquely positioned to have a large impact on the new generation of ranchers in the southwestern United States. In conclusion this workshop has been very impactful in providing science-based information on a wide variety of topics and additionally has served as a blueprint to other similar workshops across the western United States. It is well known for its ability to bring land managers together and solve problems.

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Case study of Extension outreach to a small acreage and urban grazing operator in Salt Lake County, Utah, U.S.A.

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Key words: water contamination; interface; sustainable management

Abstract

Utah State University (USU) Extension provides outreach and technical assistance to urban and small acreage producers to help operations navigate local environmental and urbanization challenges. According to the 2020 U.S. Census, Utah was the fastest-growing U.S. state from 2010 to 2020. Most urban development is concentrated along Utah's I-15 corridor, known as the Wasatch Front, which is sandwiched between major mountain ranges. Salt Lake County is Utah's most densely populated county, and in 2020, it housed 36% of Utah's total population (U.S. Census Bureau 2020). Land acquisition is a significant concern for local producers due to high land costs and population density (≈ 1,600 people/square mile). The USDA Census (NASS 2017) reported that most farms (66%) were between 1 and 9 acres and therefore most producers in Salt Lake County farm or graze small acreages that interface residential communities. Salt Lake County has an arid climate and low annual participation rate (34 cm) so supplemental irrigation is essential to sustain many landscape plants (Kopp et al. 2013).

Rapid urbanization has strengthened local interest in the preservation of remaining farms and grazing lands. For example, Salt Lake County government developed an urban farming initiative that explores opportunities to lease County-owned land parcels to local agriculture operators. In 2023, a private landowner/leaser contacted USU Extension seeking assistance to enhance the environmental function of the property. The 5,000 square meter parcel could legally house up to 6 horses and was surrounded by adjacent wetlands that ultimately drained into an area watershed. Extension worked with the client to develop an urban interface plan, design a rotational grazing pasture system, and address soil management and water quality concerns. Key takeaways from this case study illustrate ways Extension can work with small acreage operators in urbanized areas to enhance sustainable management and environmental stewardship of fragmented agricultural landscapes.

Introduction

The Cooperative Extension Service in the U.S. provides research-based, non-biased information and outreach to residents. Traditionally land grant Universities specialized in mechanical arts and the agricultural sciences and are still vanguard providers of technical support to local producers and land managers. Statewide, Utah has lost about 20% of its agriculture lands (2.7 million acres) in the past 60 years to development and mining extraction which has impacted food security, clean water, wildlife habitat, and recreational opportunities (Jeremias 2024). Nearly all farms and ranches in urbanized Salt Lake County have been converted to homes and businesses and many remaining agriculture properties are fragmented and surrounded by public and private development. Animal managers in urban areas, particularly those with surface water bodies, face an elevated risk of the public coming into contact with contaminates such as pathogens and nutrients that originated from their operation. A 2023 outbreak of Shiga toxin producing *Escherichia coli* O157:H7 in Utah sickened at least 13 children who were thought to be exposed via untreated irrigation water. City dwellers are not always attuned to the dangers of untreated water bodies. In the Utah case, the sickened children were drinking and playing in contaminated water thought to have originated from animal feces in open reservoirs. A subsequent Center for Disease Control (CDC) incident report cited a need to better educate the public on the dangers of human and animal exposure to contaminates in untreated water. Each year the Utah Department of Environmental Quality monitors several water bodies within Salt Lake County for waterborne pathogens and Harmful Algal Blooms (HABs). Cyanobacteria are aquatic bacteria that photosynthesize like algae and form blooms in surface water bodies with high nutrient loads, often from sources such as manure run-off and landscape fertilization that reaches storm drains. Therefore, waterborne pathogens and HAB blooms directly connect property management decisions with public health and safety concerns in urban areas. HAB warnings are frequent in Utah in the summer months and impact residents who visit public parks and open spaces with access to reservoirs, streams, and open canals carrying water. Posted warnings inform visitors that HABs produce dangerous toxins and pose a serious health risk to humans, pets, livestock, and wildlife exposed to the water. From personal experience, many in the public are poorly informed on the exposure risks of waterborne pathogens and HABs. Our Extension office fields several calls each year from the public with questions about potential health implications to both people and pets. Therefore, the objectives of this case study are to detail a site management plan that was developed with one urban horse manager on best management practices that both enhanced the property site and minimized the risk of nutrients and pathogens contaminating water sources. Discussion from this case study carries relevance to city managers that must conscientiously navigate decisions pertaining to the co-existence of urban agriculture operations and adjacent communities.

Methods

Three site visits were made to a 5,000 m^2 horse farm in 2024. The property was assessed for size, proximity and orientation to adjacent properties and uses, slopes and other geographical features, water bodies, pasture condition, manure management, barn and corral lay-out, irrigation infrastructure, soil conditions, and existing flora and fauna. Approximately a third of the farm site housed the barn, parking area, and corral and was owned by the operator. The remaining property (pasture) was leased from the County. Another property immediately adjacent to the farm site was also housed horses and was leased from the County. The leased parcels were connected to and part of the Holladay Lions portion (153,000 m^2) of Big Cottonwood Regional Park which is owned and operated by Salt Lake County Parks and Recreation. The broader public park features natural areas, wetland drainage areas, playgrounds, sports fields, and a recreation center. Site assessment observations for the study area are organized under the subsequent pasture, manure, and landscape headings.

Pasture

At the time of site visits, there was very little vegetative growth on the leased pasture area. A major priority of the property manager was to increase vegetative growth in the pasture in an effort to restore seasonal grazing potential. The adjacent corral and barn were zoned to house up to 4 horses, and the leased property was zoned for 6 horses. The operator wanted to utilize the 3156 m^2 pasture for forage. A small seasonal stream bordered the pasture area on two sides. During the first site visit in May 2024, the stream contained water and flowed toward wetland drainage areas. The stream delineated the property boundary between two leased parcels, so the manager had fenced along the stream to keep the horses out of the waterway and restrict their movement off property. Natural vegetative growth on the streambank was lush and diverse with desirable species, such as timothy (*Phleum pratense*) in abundance. The natural existence of timothy and other wet thriving plant species indicated adequate soil moisture. The manager did have access to treated water via the corral, however the pasture did not have permanent irrigation infrastructure at the time of site visits.

Manure

Environmental Protection Agency (EPA) and state animal feeding operation (AFO) regulations prohibit any discharge of manure or feed into a federal water or water of the state (USU 2024). There is no minimum amount of contamination, or number of animals exemption. There is a grazing exemption where livestock within the pasture can directly access water but only if there is adequate vegetation present across the entire area. Horses produce about 5.4 metric tons of manure per year, and that amount doubles with bedding included. Therefore, six horses housed on a 5,000 square meter parcel will generate 65.3 metric tons of waste per year. During site visits, the manager was disposing all waste via sanitation collection. Although discarding manure into a landfill is not ideal from a nutrient recycling perspective, it is a safe disposal method. The site was assessed for feasibility of on-site composting because many local gardeners seek out sources of nutrients like composted animal manures. Manure storage ordinances vary by state and municipality, but a pile must typically be distanced a minimum of 30.48 meters away from streams, ponds, or wells. Nutrient values vary from source and type, but horse manure contains roughly 0.7% N, 0.4% P_2O_5, and 1.1% K_2O (Stock and Miller 2019). Manure that enters water sources via run-off or windblown dust can contribute to nutrient loading in surface water bodies causing algal blooms and other environmental degradative processes.

Landscape

The land manger prioritized landscape improvements including dead plant matter removal, noxious weed control, planting of desirable trees, shrubs, forbs, and grasses, and diversification of landscape plants. Trees and shrubs are important assets to pastures since they help cool the landscape in the summer and provide a windbreak in cold weather. Root systems stabilize streambanks and hillsides, reduce run-off, and operate as landscape filters that trap materials and settle sediments. Diverse landscape plantings also enhance habitat for beneficial insects and urban wildlife. Dense vegetation keeps the soil covered and helps trap and reduce dust. Our Extension team worked with the land manager to identify desired vegetation, identify and manage noxious weeds including appropriate herbicide options for use around water bodies, discuss long-term control of invasive trees and shrubs, and draw connections between soil conditions and appropriate plant selections.

Results

Pasture

Given the limited size, proximity to wetland soils, and testimony from the manager that the pasture stayed green most of the year, it was determined that established pasture grasses would likely receive adequate moisture most weeks through subsurface irrigation. The manager was encouraged to manually run a sprinkler during grass seed germination and prolonged periods of dry conditions. Soil samples collected from the pasture area indicated a loamy soil with normal pH (8), very high salinity (3-5 dS/m) and high to very high phosphorus and potassium levels (mg/kg). Samples within the pasture area were difficult to collect due to extreme soil compaction, so the manager was advised to till the soil prior to seeding to lessen surface compaction. There is a correlation between blade height and root depth, so the manager was instructed to restrict grazing until the pasture was 17.8 to 20.3 cm in height. Grazing below 7.6 cm drastically impacts root mass which weakens the grass stand and pre-disposes the pasture to weed invasion (Barnhill and McKendrick 2008). The manager was encouraged to divide the pasture acreage into two to three paddocks and develop a rotational grazing plan which confines animals in one section of paddock while non-grazed areas 'rest' and produce forage. In Utah, most irrigated paddocks can be re-grazed after three to four weeks of 'rest' and a minimum of four paddocks are necessary for sustainable rotational grazing systems. The leased pasture footprint was insufficient for four confined paddocks, so the manager was encouraged to utilize the corral when pastures needed rest and to feed hay. One suggestion was to allow horses paddock access for a few hours in the morning and evening to ensure the nutritional needs of animals were met while eliminating excessive trampling. It was also advised to only irrigate after grazing to avoid hoof compaction on wet soils.

Manure

Water test results from two on-property sample points and one additional sample point on public park property identified water highly contaminated with coliform with much of the contamination being from *E. coli*. *E. coli* levels from the two on-property samples both tested >2,400 Org/100mL and a sample taken on public park property tested 550 Org/100mL. Although not all *E. coli* bacteria make people sick, the test results do indicate that fecal material was entering water sources. Adjacent parcels of land leased by other managers also allowed for equestrian use, so the precise source/s of contamination was unclear. Drinking water should have <1 colony/100mL of water, and no *E. coli* present. Recreational water, streams or lakes are considered safe if *E coli* is <235 Most Probable Number (MPN)/100mL in any one sample, and an average <126 MPN/100mL from 5 samples during a 30-day period (UDWQ 2021). Based on water and soil test results, manure spreading on pasture was not advised. Soil test results indicated very high phosphorus levels which raised concerns of excessive nutrient loading in nearby water sources. On-site composting and/or exposed manure storage was also not advised because it would be difficult to locate a pile 30.48 meters away from a water body and a third of the property was severely sloped. The operator could consider a fully contained manure storage system where run-off is prevented and manure could be collected by local gardeners instead of being transported to the landfill. The manager was advised to divert any clean water (i.e., rain, snowmelt) run-off away from the corral and consider establishing vegetated peripheral berms around the paddocks to prevent run-off from the pasture perimeter. Increased vegetative growth in the pasture would increase water infiltration rates, reduce run-off, improve nutrient and water holding capacities, alleviate soil compaction, and induce soil structure formation and hence should be prioritized in short and long-term site improvement activities.

Landscape

During the first site visit, the land manager shared efforts to vegetate streambanks with native plants. The manager was advised to leave the streambank vegetation undisturbed and consider planting seeds to minimize digging. Berm plantings around pasture perimeter should include plant choices that are not hazardous or harmful to the horses and provide the animals an escape from the elements. Due to the elevated salinity levels in the pasture soil samples, the manager was advised to select plants tolerant of elevated salts. Many Utah native riparian plants have moderate to low tolerance of high salinity and/or compaction, so it is best to select plants with higher tolerances to existing site conditions. Other areas of the property were more favorable for heat and drought tolerant plant selections. The land manager was informed that drought tolerant trees and shrubs should receive frequent irrigation prior to establishment. Our advice was to spread the timing of the new plantings out so she could keep up with the irrigation needed to establish new landscape plants. Our team advised that areas identified for invasive species removal should also be targeted for new plantings to ensure disturbed ground was filled by desirable species. Finally, we encouraged the land manager to take advantage of appropriate plants that are readily available and easy to plant, such as willow whips, which are easy to harvest and root. Qualitatively, the manager shared that she has seen greater abundance in flora and fauna (birds, insects, native species) since initiating efforts to improve and diversify landscape plantings.

Discussion

Findings from this case study illustrate a need for livestock and grazing educators to work with livestock operators in urban interfaced areas. Since conducting site visits, our Extension team learned that Salt Lake County Parks and Recreation is looking to phase out lease opportunities for equestrian use on park land. An updated Master Plan projects efforts to revegetate and enhance natural areas in park land currently leased for equestrian use. Multiple horse operators with short term County leases have expressed interest in our findings, as they present a case to park officials that horses can be housed on park property in an environmentally sustainable way that also protects health and safety. Recent discussions with the Utah Division of Water Quality and Department of Agriculture and Food officials have highlighted the role of urban livestock and water degradation. More education and oversight are needed to help protect water sources in densely populated areas. Case studies that evaluate site details and constraints and provide appropriate recommendations offer a perceivable conversation bridge between user groups and officials which can both improve management practices and preserve the existence of livestock management operations embedded in urbanized landscapes.

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Finding common ground: Collaborative adaptive management for conservation and livestock-based livelihoods in the Greater Yellowstone Ecosystem

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Key words: co-production; participatory research; range sheep systems; social-ecological ecosystems; transhumance

Abstract
Rangeland social-ecological ecosystems experience conflicting social goals for land use that can stall progress towards effective governance and land management. This can be detrimental to social and ecological wellbeing. In the western United States, disparate land use goals for wildlife conservation and ranching within sustainable rural communities have led to polarized management contexts and legal challenges. At the US Sheep Experiment Station (USSES), a federal research ranch located in the Greater Yellowstone Ecosystem (GYE), researchers, diverse community partners and organizations, and ranchers are asking: what would happen if conflicting groups agreed to manage the land together in a participatory, co-production manner within a scientific research project framework? Could we learn to work with, rather than control, the rangeland social-ecological system and one another to achieve common objectives and outcomes? In this study, we report on the initial phases of the USSES Collaboratory, a multi-year collaborative adaptive rangeland management project focused on rangeland domestic sheep systems, rural livelihoods, biodiversity conservation, and climate adaptation. Initial social and ecological assessments have been used to inform the development of management goals and experimental treatments for a participatory grazing experiment. We report early key lessons from the baseline social assessment and initial objectives-setting workshops, which will inform how we work to bring divergent viewpoints together to build common ground based on increased trust and a new, shared understanding of complex systems dynamics.

Introduction

Rangeland social-ecological systems include multiple ecological processes and societal goals including livestock production, biodiversity conservation, and recreation, and management for numerous ecosystem services (Reid et al., 2014). The potential for conflict over uses of these systems is particularly high for privately-owned working lands where ranchers or pastoralists operate within a patchwork of public-private land ownership near protected areas (Bindi, 2022). Local-scale conflicts over management and policy can become regional, national, or even international discourses (Epstein et al., 2021; West, 1994). Diverse and competing demands of rangelands' social-ecological systems highlight larger social issues related to incongruent values and goals for local food systems and conservation (Barry & Huntsinger, 2021; Loconto et al., 2020). If left unaddressed, disagreements over land use values lead to continued frustrations and actions that drive negative social and ecological outcomes (Webel & Galtung, 2007).

These conflicts are evident in the Greater Yellowstone Ecosystem (GYE), the broader ecological region that surrounds Yellowstone and Grand Teton National Parks, federally-protected areas in the US Intermountain West. Here, rangeland-based livestock production shares a diverse and complex landscape with numerous protected species across a patchwork of public and private land ownership patterns. Various actors, including state and federal public agencies, conservation organizations, ranching organizations, and others have experienced substantial conflicts over priorities for land use in this region (Epstein et al., 2021). However, in the ever-changing western US, exurban development and increasing climate variability have induced shifts in ecological dynamics which are threatening the goals of multiple actors at once, including those who have long been foes. As conservation organizations, public land management agencies, ranchers and the ranching industry, and researchers increasingly recognize the value of working together, new opportunities are emerging to transform long-standing environmental conflicts. Transdisciplinary research, which actively engages the knowledge of diverse societal partners and scholars to address society's most challenging problems, offers a methodology by which researchers can initiate new conversations to bridge the social divisions (Reid et al., 2021).

Methods

This paper reports early results from "The Rangeland Collaboratory", a transdisciplinary rangeland research project designed to address adaptive capacity and conflict in rangeland domestic sheep systems in the US Intermountain West. Initial results include: 1) an overview of a baseline social context assessment, and 2) management objectives and hypothesized synergies/trade-offs developed from participant workshops in 2024. The project is based at the US Sheep Experiment Station (USSES), a commercial scale (19,400 ha) research sheep ranch operated by the United States Department of Agriculture - Agricultural Research Service, Range Sheep Production Efficiency Unit (USDA-ARS-RSPER). The USSES is on the eastern edge of the GYE and is comprised of sagebrush steppe and montane/sub-alpine rangeland systems in Clark County, Idaho and Beaverhead County, Montana, USA.

Collaborative adaptive management (CAM). CAM is a form of adaptive management that uses the action-oriented methodologies of participatory research to braid the knowledges of multiple land management and scientific communities with experimentation resulting in the promotion of learning over time (Wilmer et al., 2018). Researchers and partners identify goals, objectives, experimental treatments, indicators for success, and triggers for action. As a management plan unfolds, the science-stakeholder team monitors and evaluates results and options for adaptation and modifies the management plan based on their own learning. Additional levels of learning may be achieved as the team recognizes limitations of their earlier assumptions and modifies actions, objectives, or even the project goal in a co-produced iterative process.

Structure of the Collaboratory. The project is modelled after the Collaborative Adaptive Rangeland Management experiment implemented at ARS's Rangeland Systems and Resources Research Unit in Colorado, USA, but includes several modifications for the USSES context (Augustine et al., 2024). Throughout 2023-2024, social scientists at USSES conducted a baseline assessment of stakeholders involved in ranching, conservation, public administration, recreation, or research in the surrounding region. This assessment involved semi-structured interviews, participant observation, literature review, and initial meetings with various individuals or groups to elucidate key perspectives of public actors (Wilmer et al., 2018). At the same time, the research team conducted plant community and animal science assessments at USSES. Then, we developed an experimental design outlining key parameters (e.g. management of a band of white-face range sheep, no additional fencing), the requirement for certain areas of focus (livestock, social, wildlife, and vegetation outcomes), and identification of which management decisions stakeholders could use in adaptive management (livestock and vegetation management, social activities, etc.). We held a group tour and subsequent meetings throughout 2024 to identify core objectives for a forthcoming adaptive management plan.

Results

Social baseline data reveal context of conflict and collaboration. The GYE has fostered complex forms of conflict among environmental and agricultural interests over priorities for land use, livestock grazing, and wildlife habitat, particularly on public lands viewed as having particularly high conservation value. For example, wildlife advocates and agencies have long worked where livestock and wildlife goals overlap to maintain habitat for some of the continent's most iconic species, such as grey wolf (*Canis lupus)*, grizzly bear (*Ursus arctos horribilis),* Greater sage grouse (*Centrocerus urophasianus*) and big horn sheep (*Ovis canadensis)* whose populations have been substantially reduced due to agricultural expansion and settlement of the region. Conservation advocates we interviewed describe themselves as working to protect and help wildlife, ecosystems, and public access to natural resources. They advocate for increased legal protections and programs to enhance wildlife populations and mobilized litigation efforts to this end. They also take on public education roles and organized support for land management changes, such as reductions in public grazing permits. The ranching industry has sought to maintain the financial and ecological viability of individual ranching operations, and the vitality of rural communities dependent on ranching. Ranchers we interviewed described themselves as stewards of the land. They seek to maintain their ranching lifestyles, cultures, and businesses, and their access to transhumant grazing practices on federal lands. Pressures from a globalized market, increased environmental regulation, and the interactive effects of social and climatic change have prompted them to adapt genetics, range management, and marketing to new realities, and to engage in more collaborative and advocacy activities.

Despite these dynamics, many forms of collaboration have supported solutions for wildlife and land management issues. By the early 2000s, some conservation and ranching advocates across the western US grew tired of persistent conflict and came together to conceptualize "The Radical Center" (White, 2008). This idea recognizes the common need to steward healthy ecological and social systems, and to prevent exurban development (Brunson & Huntsinger, 2008). It motivated a conversation about how enhanced financial and social viability of ranching operations and communities could help limit exurban development and therefore help conserve wildlife habitat.

Table 1: Stakeholder-developed rangeland management objectives (blue cells), and the hypothesized relationships among them, including potential synergies (green cells) and trade-offs (grey cells) for a ranch-scale grazing study in the Greater Yellowstone Ecosystem case study.

	Social systems	Livestock systems	Wildlife biodiversity	Vegetation biodiversity
Social systems	**Multiple uses multiple perspectives; reduce conflict; promote healthy local food systems; increase community adaptive capacity; intergenerational learning**	Increased adaptive capacity, fair wages and profit; reduced conflict; connectivity to local food systems	Increased awareness and connectivity to ecological systems and wildlife; reduced conflict; increased multi-party buy in for science-based management	Increased awareness and capacity to manage for vegetation biodiversity
Livestock systems	Reduced access for livestock to seasonal grazing ranges; increased competition for land use from recreation or development; loss of social license to operate	**Improve animal performance and ranch profitability**	Decreased disease, depredation, or habitat competition; improved trust, reduced conflict in management of livestock-wildlife interactions	Livestock grazing and/or prescribed fire management used to enhance heterogeneity, which bolsters livestock system flexibility
Wildlife biodiversity	Increased negative interactions among public users and wildlife; increased conflict over conservation efforts	Increase disease, depredation, or habitat competition among livestock and wildlife	**Maintain and improve connectivity, biodiversity; reduce conflict with humans**	Increase biodiversity, connectivity, and heterogeneity to enhance wildlife and plant community outcomes
Vegetation biodiversity	Negative effects of multiple land uses, including recreation, urban development or other uses on plant communities.	Negative livestock grazing impacts on riparian or upland biodiversity; loss of biodiversity due to invasion in turn reduces livestock performance	Habitat modification via development, invasive plants, or fragmentation reduce processes that support landscape and regional-scale conservation outcomes	**Maintain or increase habitat heterogeneity and connectivity, and core native rangeland plant communities; reduce invasion**

Identifying objectives for the USSES Collaboratory. In addition to the social baseline assessment, we also engaged participants in the initial USSES Collaboratory meetings to identify which social and ecological objectives they want to prioritize for the participatory grazing experiment. The scientist team provided guidance that objectives needed to include social and livestock systems, as well as wildlife and plant biodiversity realms. Participants outlined key desired future conditions and discussed potential trade-offs and synergies among objectives, which the science team expanded (see Table 1). During objectives workshops, participants discussed the challenge of successfully balancing multiple objectives. They also identified common themes in supporting healthy ecological and social communities, learning, reducing conflict, and coming together on the land.

Conclusions/Implications

We have outlined methodology for the USSES Rangeland Collaboratory, a co-produced research project seeking to find common ground on rangeland systems in the GYE. The baseline social context assessment provides a grounded view of cultural and political dynamics within the GYE, and it will inform more meaningful engagement and learning for participants in the future. Next steps include the development of culturally-oriented activities within the larger project to foster outcomes towards social objectives. We will also co-develop key indicators, treatments, and monitoring plans to advance adaptive management for project objectives over the next two growing seasons via a participatory ranch-scale grazing study. Collaboration with wildlife experts and engagement with agricultural economists will be key to identifying systems level outcomes and synergies/trade-offs among objectives.

Some twenty years after 'The Radical Center' was conceptualized, the GYE face new challenges as climate, land use, and community change dynamics continue reshaping the conversation (Martin, 2019). The USSES Collaboratory follows a CAM model which lends the power of research to help rangeland stakeholders bridge social worlds. Our initial experiences suggest that the complexity of the project creates the need for investment in problem exploration. It is not reasonable to expect research data to sufficiently bridge divergent goals among rangeland actors. The challenge of finding common ground now requires a concerted effort to transform conflict via depolarization, systems-thinking, and science-based solutions that together create a shared, creative search for a new, peaceful reality (Webel and Galtung, 2007; Zecher, 2024). Across the GYE, CAM may require intentional infusion of social sciences and the humanities, including peace studies, which have been valuable in other rangeland systems for challenging assumptions about human-nature relationships and pointing toward productive conflict transformation (Butler & Gates, 2012). Our early workshops indicate the potential of Collaboratory participants to engage in respectful dialogue and problem exploration, but the challenge ahead will be to co-develop creative strategies that actually move the community beyond the livestock-wildlife divide at the USSES and across the GYE.

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THEME 3. TECHNOLOGY, INFORMATION SYSTEMS, COMMUNICATION, AND BIG DATA TO AID MONITORING AND DECISION MAKING

Data collection and data platforms

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The value proposition for systematic long-term vegetation studies

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Key words: long-term; monitoring; value; custodianship; legacy.

Abstract

Long-term vegetation observations are rare but essential for the effective management of our natural assets. Studies of 3-4 years allow us to discern short-term variability, but long-term trends are only detectable over multiple decades. Through a meta-analysis of several medium to long-term studies in Australia—Kidman Springs, 30 and 50 years; Koonamore, 90+ years; the Brigalow Catchment study, 60 years; the Wambiana grazing trial, 26 years; several Australian Wildlife Conservancy sites across northern Australia, 19+ years; and one site in the USA, Jornada, 105 years—we discuss their benefits, the challenges, the management of the resulting data and information, and their future. We will argue that such sites are vital for the determination of the effects of perturbations caused by fire, thinning, grazing, water diversion, soil erosion, pollution, pathogens, weeds, insect pests and feral animals. They provide points of validation for a variety of types of models, help us better understand the systems involved, and inform management. Quite often these benefits are unpredictable and depend on multi-disciplinary synthesis. The interpretation of the data from such sites can be enhanced by integration with longer term remote sensed data. Ongoing measurement, management and custodianship is, however, often fraught. Measurements that were designed, for example, in 1920, are not always seen as relevant today, a disincentive for participating researchers. Support from the institutions managing the sites has proved variable. Sites can be attractive for a sponsoring body for their sheer age, but usually there is little understanding of the discipline involved, or what is required for their continuation. The expectation for data and information from such sites has changed profoundly with time. Repositories and observatories like the Environmental Data Initiative in the USA and TERN in Australia provide data from several long-term sites. We can expect changes and expectations to evolve into the future.

Introduction

Long-term vegetation observations (>30 years) and their derived trends are essential for the effective management of our natural assets. Studies of 3-4 years are able to discern short-term variability, but long-term trends are only detectable over longer time periods (Peters et al. 2014). This is particularly the case with systems that have slow dynamics, such as tussock grassland and forest ecosystem, or soil carbon pools. Rangeland species such as Brigalow have recently been aged at an average of 150 years. Controlled field observations can greatly contribute to the determination of the short to long-term effects of perturbations caused by fire, thinning, grazing, water diversion, soil erosion, pollution, pathogens, weeds, insect pests and feral animals. Müller et al. (2010) listed six main objectives of long-term research, which are the understanding of: (i) large-scale variabilities, (ii) interactions of short-term and long-term fluctuations, (iii) self-organisation, (iv) rare events and disturbances, (v) impacts of anthropogenic use of landscape resources on ecosystem functions, and (vi) generation of knowledge and data for the development and evaluation of ecosystem models. The challenges for long-term research have been found to include sustaining funding, partnership development, maintaining continuity in objectives, and linking scientists and data through communication and cooperation (Gosz et al. 2010).

The enclosures, catchments, management areas, and plots (referred to henceforth as 'sites') reviewed here meet the definition of research infrastructures: a set area or suite of areas within which land management manipulations and experiments (such as variations in fire frequency or the application of different rates of fertiliser) can take place over the long-term. The type of commitment to manage and measure such sites over time extends beyond normal political and funding agency time frames. Australia's National Collaborative Infrastructure Strategy (NCRIS) was established to support facilities that fall outside research grant time frames or outside funding criteria (Phillips, 2018). The Terrestrial Ecosystem Research Network (TERN), an NCRIS infrastructure, for example, has established 'surveillance' plots across the country to provide calibration sites for the assessment of vegetation coverage (Guerin et al. 2020). It will be many years, however, before these plots reach the longevity of the sites being examined in this paper. Existing long-term sites can provide insight into future challenges that may face TERN and similar Global Ecosystem Research Infrastructures as well as continuing to provide useful benchmarks.

Based on a desktop study of five long-term research sites in Australia and the USA, and two medium-term sites, we examine their value, the challenges, and their data legacy. We offer a prognosis for the future for them and other such sites. With the exception of one relatively new suite of sites, they are survivors of their kind, at least in Australia.

Methods

The long-term sites include two studies at Kidman Springs (30 and 50 years), the TGB Osborn Reserve (Koonamore) enclosure (90+ years), the Brigalow Catchment Study (60 years) all in Australia, and the Jornada site in the USA, 105 years (Specht et al. 2024). The shorter-duration sites include monitoring of adaptive fire management at multiple locations in northern Australia by the Australian Wildlife Conservancy (AWC, ~20 years), and the Wambiana grazing trial (26 years). We documented the original purpose for the sites, the value that had been gained over their lifetime, their recorded legacy, and the challenges that had been faced. Using this process we were able to highlight commonalities across sites, the opportunities presented by their existence, and reflected on the management options for their continued survival and how the data and information gathered at each site is handled.

Results
Management of these sites, with the exception of the AWC sites, is confined to public authorities, such as government departments, universities and federal research agencies, usually in combination. For example, Kidman Springs is run by the Northern Territory (NT) government with CSIRO staff, a federal research agency, contributing to measurements, while the NT Department of Agriculture and Fisheries has run the fire experiment. The Jornada long-term Ecological Research (LTER) site is also supported by multiple programs and institutions, notably the US Department of Agriculture (USDA) and New Mexico State University (NMSU). AWC, a not-for-profit organisation, runs its sites in collaboration with landholders, including Indigenous groups and the AWC itself (Fitzsimons 2015). The TGB Osborn Reserve, however, has been singularly managed since its establishment by the University of Adelaide (UofA). Most sites have attracted funding for research work or training at various occasions along their life span which has helped their sustainability through contributions to management and the ability to demonstrate value.

The utility or value of the study sites ranged from providing points of validation for landscape-scale models of pasture yield (Jornada: Hartman et al. 2020; Robinson et al. 2018), the effects of climatic or land-use change (Jornada: Christensen et al. 2023), hydrological and soil change due to land clearing, land use and management change (Brigalow: Thornton and Elledge, 2022), the detection and attribution of changes due to CO_2 (Brigalow: Orton et al. 2023), to the economic and ecological benefits of managing for climate variability (Wambiana: Neilley et al. 2018). Through these sites, the impacts of different fire regimes and whether they are achieving management goals has been assessed (Kidman Springs: Cowley et al. 2014; AWC: Legge et al. 2011). Observations reaching beyond the lifetime of an average research project has allowed the development of relationships and hence understanding of the systems involved. Quite often these benefits have been serendipitous and unforeseen. The sites are valued by their respective researchers for their curiosity value as they return for the next measurement. By enabling evidence-based decision making they provide economic benefit for important economic activities like livestock production; they also mediate/reduce the impact on biodiversity and downstream ecosystems like the Great Barrier Reef. To study sponsors, such as government, it is likely that the value is demonstrated at a higher level, such as the inclusion of findings in government policy, in response to a Senate Inquiry, or when used in a court of law. These measures are unlikely to be of equal appeal to every audience, and hence will provide varied and perhaps limited justification for continuing a study.

All sites have faced challenges to their existence. The longer-term sites have all experienced uncertainty of funding and continuing agency support. Maintaining the original objectives especially over a long time is always problematic: standards, staff and technology all change and the understanding of the purpose and sense of responsibility for each site wavers. The duration of the Jornada site is remarkable for the continued support (albeit with breaks) of the USDA and NMSU, augmented by membership of the LTER. Koonamore has enjoyed continuous support from the UofA, but has recently turned to crowd-funding for basic maintenance. It was used for regular teaching for many years, but the advent of remote learning and the distance from the university campus (400 km) has limited this to annual measuring trips by volunteers. AWC is committed to testing the effect of interventions and management practices which assist in maintaining the ecological health of their sites.

The expectations of data availability from such sites has changed profoundly with time, from paper records, journal articles and theses, through to the open data delivery we see today (FAIR; Wilkinson et al. 2016). Repositories and observatories like the Environmental Data Initiative in the USA and TERN in Australia provide data from several long-term sites and the management of these sites has had to adapt to meet the new conditions and expectations of open science. We can expect the same changes and expectations to evolve further into the future.

Discussion

Our analysis shows that the data from these sites are valuable in many ways. On-ground observations provide the point of truth for satellite imagery and record floristic changes not provided by the satellite record. Multidecadal monitoring of single treatments or land use in a discrete area provides a unique opportunity to document responses to climate change, having removed externalities that confound these observations in mixed use and management systems. Custodianship of the sites and observations over time is difficult to maintain, however. The attraction of being involved in scientific measurements of such sites dwindles with time as building on the shoulders of others is not an easily marketable quantity for academic promotion. Unless there is a fixed and well-invested bequest, the cost of running long-term sites becomes challenged by other, more state-of-the-art, investments, such as flux towers, square mile radio telescope arrays, and Free-Air CO_2 Enrichment (FACE) experiments. The (managers of) long-term sites could be well-advised to incorporate such facilities in their sites to retain currency.

It appears that to survive, these sites need to be multi-purpose, maintain a clear sense of value for all concerned, encourage and acknowledge collaboration, and ensure there are rewards for involvement (see Alber et al. 2021). Protecting the sites by membership of a network might prove advantageous (viewing the strength of the LTER network around the world as an example) as would linking with major observatories and data repositories such as TERN. The data collection at long-term sites is often different from the standardised data collected by such observatories so strategic links will need to be made, but such a move will help ensure the legacy of these sites is secure. Making the data easily discoverable and providing regular analyses for a range of societal actors and national accounts will illustrate the value of the sites.

It is clear that these sites require active champions, ensuring a flow of quality results and endorsements of their value. A program of marketing to relevant stakeholders and potential funders is required and this would be best managed by sharing within a network of similar sites. Creating a catalogue of similar sites (mid- to long-term), and stratified according to type and use, would be a good first start in creating such a network.

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Review of a regional scale grassland condition monitoring method

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Key words: grazing; pasture; longitudinal; frequency; comparative analysis

Abstract

This paper outlines the review and development of site selection and field data collection protocols for enabling the continuation of the state government's Western Australian Rangeland Monitoring System (WARMS) beyond 2024. The primary purpose of WARMS remains to detect change in the condition and trend of the extensive rangelands across Western Australia. The Department of Primary Industries and Regional Development (DPIRD) aims to align WARMS with the move to risk-based monitoring and assessment outlined in DPIRD's Framework for Sustainable Pastoral Land Management.

Regular reviews of monitoring methods, collaboration with industry stakeholders and governing bodies are required to ensure the system's robustness and relevance for management of public lands.

A revision of DPIRD's grassland field site-selection and data collection protocols is presented with two main goals: (1) to improve monitoring effectiveness by aligning sites with key pastures and broad ecosystem types identified in ecological State and Transition models (Richards et al. 2023), and reducing the total number of sites monitored; and (2) to modify site spatial configuration and align data collection with national standards for fractional cover data collection, while maintaining longitudinal continuity with the WARMS program. The co-location of nationally comparable sites with suitable WARMS sites would be an efficient way to provide the ground measured data needed for calibration of remotely sensed fractional cover estimates, if the changes in data collection protocols prove compatible with previous WARMS condition trend detection. Methods for using remote sensing data to directly monitor rangeland condition and degradation risk will be explored.

In 2024 we began a field program of monitoring pasture condition using the existing WARMS site layout in tandem with the star transect layout for cover measurement in the Kimberley region of Western Australia. Data from the two transect configurations will be analysed to assess the practicality of substituting the existing WARMS measurement layout for the star layout without compromising the long-term trend detection.

Introduction
A revision of DPIRD's grassland field site-selection and data collection protocols is required because of DPIRD's desire to assist with the collection of SLATS data for contribution to the national database (Barnetson et al. 2017, Sparrow et al. 2020). There is also recognition that maintaining continuity with the existing WARMS program and data within available resources is valuable and worthwhile (Watson et al. 2007, Reeves et al. 2023).

A variety of methods are used in Australia to access ecological conditions including: % or relative cover using remote sensing (Than et al 2022, Scarth 2012, Ali 2016, Barnetson et al. 2017); ecological monitoring/validation on a tiered system (i.e. some sites visited more frequently than others) (Sparrow et al. 2020); SLATS (QDES 2022), and; landscape function analysis (Tongway and Hindley 2004).

Using WARMS data, we can determine rangeland condition trend over time and tree/shrub crown cover across a range of ecosystems (or states) (Novelly et al. 2008). The major causes of condition change events are seasonality, grazing, fire and flood. Time since fire is also a factor, and not currently considered; however, if it was decided that it was of value, high-quality spatial fire scar data could be incorporated into this dataset.

Instances where we have been able to detect or infer condition change at WARMS sites are relatively rare. This is because condition change generally occurs over an extended time period and requires more than one driver (i.e grazing pressure and seasonal rainfall). We have a large existing dataset that could be used to estimate *how many* times an event is likely to occur within a given period of time. The results could be used to inform the revisit and reporting cycle required to detect those changes, but this cycle is likely to be more influenced by resource availability and timelines.

DPIRD is intending to improve the method for allocating monitoring sites with consideration of geographical distribution and stratified to be representative of key pastures as identified during the development of the Land Condition Standards. A link to remote sensing is envisaged, so that the existing sites are validation and ongoing on-ground monitoring sites as part of a (yet to be developed) remotely sensed cover/condition system.

We have set out to ensure that the new data collection system will be comparable with the previous system by using initial measurements of collected at WARMS sites using both WARMS and SLATS transect layouts (Craig and Thomas 2008, Muir et al. 2012) to assess if the datasets are comparable or if there is a step change in the frequency of perennial pasture species occurrence.

Our objectives are:

- to improve monitoring effectiveness by aligning WARMS sites with key pastures and broad ecosystem types identified in in ecological State and Transition models
- to modify site spatial configuration and align data collection with national standards for fractional cover data collection, while maintaining longitudinal continuity with the WARMS program
- reduce the total number of long-term sites monitored, where possible without compromising the longitudinal data

Methods
The method and practicalities were discussed internally prior to collecting data from WARMS transects and SLATS star transect at 13 sites in 2024. We grouped the existing Kimberley grassland sites to determine

the number of sites for statistically robust analyses of key and non-key pasture groups identified during the development of the Kimberley Land Condition Standards (Fletcher et al. 2022).

WARMS grassland sites were shortlisted for field data collection early in 2024, targeting relatively stable sites categorised as Wet-dry tropical eucalypt woodlands of the Kimberley (Richards et al. 2023) or Pindan pastures (Craig and Thomas 2008, Ryan et al. 2013).

The orientation of SLATS transects is fixed, whereas existing WARMS sites may be any orientation. The layout for ratings of presence/absence of perennial species in 100 quadrats (0.49m^2) on the star transects is 33 on each transect, plus 1 random. Some sites did not include the 100th quadrat.

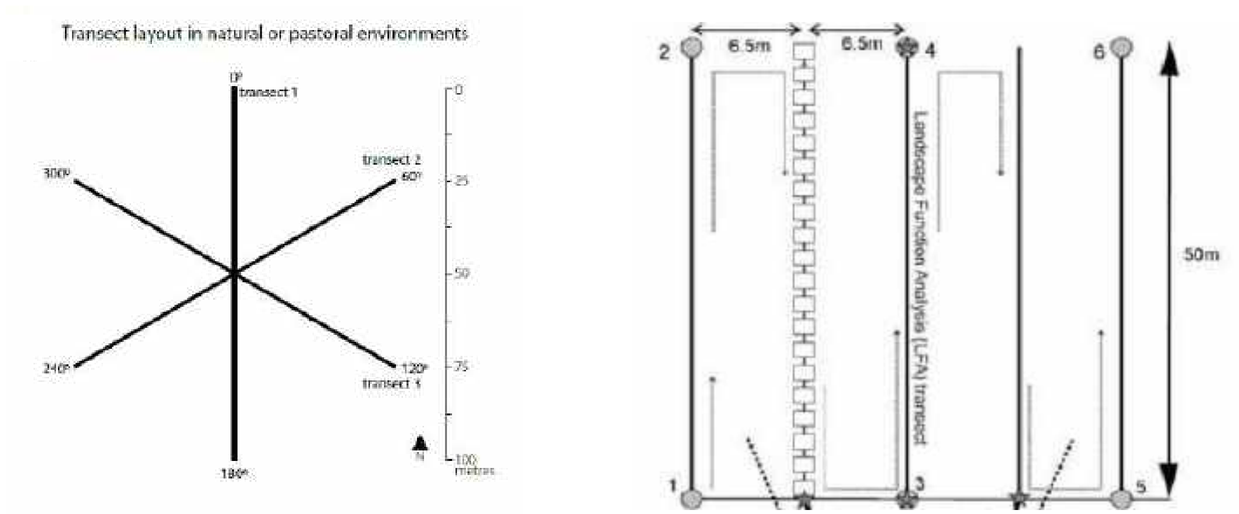

Figure 1. SLATS star transect layout with orientation (Muir et al 2012) (left) and WARMS transect layout (Craig and Thomas 2008) (right).

Data were collected from the WARMS transects then the SLATS transects were centred over the WARMS site and data collected from the SLATS transects.

Preliminary analysis of the data collected in 2024 is in progress using the Bray-Curtis method (K. Reeves pers. comm. 2024).

GIS and analysis of remotely sensed data will be used to select WARMS sites that meet the SLATS site criteria (P. Ramzi pers. comm. 2024), while maintaining longitudinal continuity with the WARMS program. Fractional cover data collected by DPIRD on pastoral leases cannot be displayed on the public TERN site without permission of the lessee, however, the applicable data collected are uploaded to the national TERN database for use in deidentified applications.

Quantifying a change in data collection methods involves several steps to ensure that the new method provides comparable and reliable data (Caughley and Sinclair 1994, Specht et al. 2015, Kaplan et al. 2021). Steps used in our approach are listed below:

1. **Baseline Establishment:** extensive data has been collected using the current WARMS method in rolling three-yearly assessments from 1994-2020. This will serve as the baseline for comparison. Parallel data collection is in progress using the SLATS site layout method and the current method during a transition period (2024-2025) that will be used to establish a preliminary dataset.

2. **Comparative Analysis:** A side-by-side comparison of data collected simultaneously by both methods is in progress and will be used to help identify systematic differences. Statistical tests (e.g. paired t-tests) will be used to determine if there are significant differences between the datasets from the two methods. Exploratory work is in progress.
3. **Calibration and Adjustment:** Calibration curves or adjustment factors will be developed to align the new method's data with the baseline data as required. Correction factors will be applied to the new data if systematic biases are identified.
4. **Error Analysis:** Error metrics such as Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Bias will be calculated, if necessary, to quantify the differences. The uncertainty associated with both methods will be assessed to ensure that the new method's uncertainty is within acceptable limits. The new method's uncertainty should not exceed that of the previous method unless justified by significant cost, time, or coverage advantages. For example, if the WARMS method has a standard error (SE) of 5%, the new method needs to be within this range or correctable using calibration models if biased. Acceptable MAE or RMSE might be ≤10% of the average quadrat counts in test sites.
5. **Validation:** Validating the new method with independent data sources or through external benchmarking will not be possible within the scope of this study, as the data are unique. Cross-validation by splitting the data into training and validation sets will be used to verify the robustness of the new method when enough data are collected to allow this.
6. **Longitudinal Studies:** Change detection techniques will be used to identify any significant deviations that might result from the method switch, if required.
7. **Documentation and Reporting:** The process, including the rationale for change, methods used for comparison, calibration, and error analysis will be documented and peer-reviewed internally and in scientific papers such as this to validate the approach and ensure transparency.
8. **Implementation of New Method:** Gradual implementation of the new method will not be possible, due to labour and expertise availability. The implementation of the new method is planned for completion in the WA grasslands in 2025, subject to DPIRD resources and priorities, and the results of a review of existing WARMS sites that are considered suitable for SLATS (in progress). Establishment of an ongoing regular data analysis system will be considered, so that issues arising from implementation of the new method are detected early and necessary adjustments can be made.

Results

Existing sites grouped according to pasture type

380 existing WARMS sites were considered and categorised according to key and non-key pasture groups set out during development of the Land Condition Standards for the Kimberley. One WARMS site was dropped from categorisation as it is the sole example of Lovegrass alluvial plain pasture in the dataset and lacks similarity to other pastures (Reeves et al. 2023). Pasture groups included in the development of state and transition models for the Kimberley included black soil plain pastures, frontage grass pastures and ribbon grass pastures. Pastoral value (categorised from very low (<2.5 cattle units (CU)/km^2) to high (>8 CU/km^2), fragility (after Craig and Thomas 2008) and suitability for remote sensing (Mundava et al. 2015, Ali et al. 2016) were discussed for each group. High pastoral value pastures suitable for remote sensing include marine plains and black soil plains, characterised by relatively low tree cover with generally good condition pastures that are fairly 'uniform'; low value examples include rocky and inaccessible country that is unlikely to be grazed by cattle Recommendations for consideration regarding the number of sites required for future monitoring are presented in Table 1.

Table 1. Existing WARMS sites grouped according to pasture characteristics

Pasture group	No. sites	Comment/s on pastoral value, fragility, other	Action to be considered
Hills/hard spinifex pastures	0	Low value, low fragility, suitable for remote sensing	None
Black soil plains pastures	137	High value, low fragility, suitable for remote sensing	Reduce, investigate which to keep and where to install under-represented 'states'
Frontage grass pastures	28	High value, high fragility	Increase to ~35
Ribbon grass pastures	99	Moderate value, high fragility	None
Coastal plains pastures	20	Range of values, range of fragility, localised, pastures in this group are very different from each other, some would be suitable for remote sensing	Investigate further
Pindan pastures	36	Low value, may be more fragile than previously published due to tussock grass component	None
Soft spinifex pastures	35	Low value, may be less fragile than previously published, suitable for remote sensing	None
Curly spinifex pastures	21	Low value, low fragility, probably suitable for remote sensing	Increase to ~30
Curly spinifex-annual sorghum hill pastures	3	Very low value, probably suitable for remote sensing	Drop entirely or increase

Summary of frequency data collected in 2024

Frequency data from 17 sites including that presented in Figure 2 below will be used for initial comparative statistical analysis. The clustered bar graph compares the frequency of desirable plant species, the frequency of quadrats without perennial plant species and the frequency of burnt quadrats, across the 17 sites assessed using both site layouts. The x-axis represents monitoring sites labelled sequentially, the y-axis indicates the frequency percentage (0 to 100) for the analysed variables, and the z-axis separates the data by variable and site layout. This set includes data from 4 sites collected in 2020, prior to method development discussions.

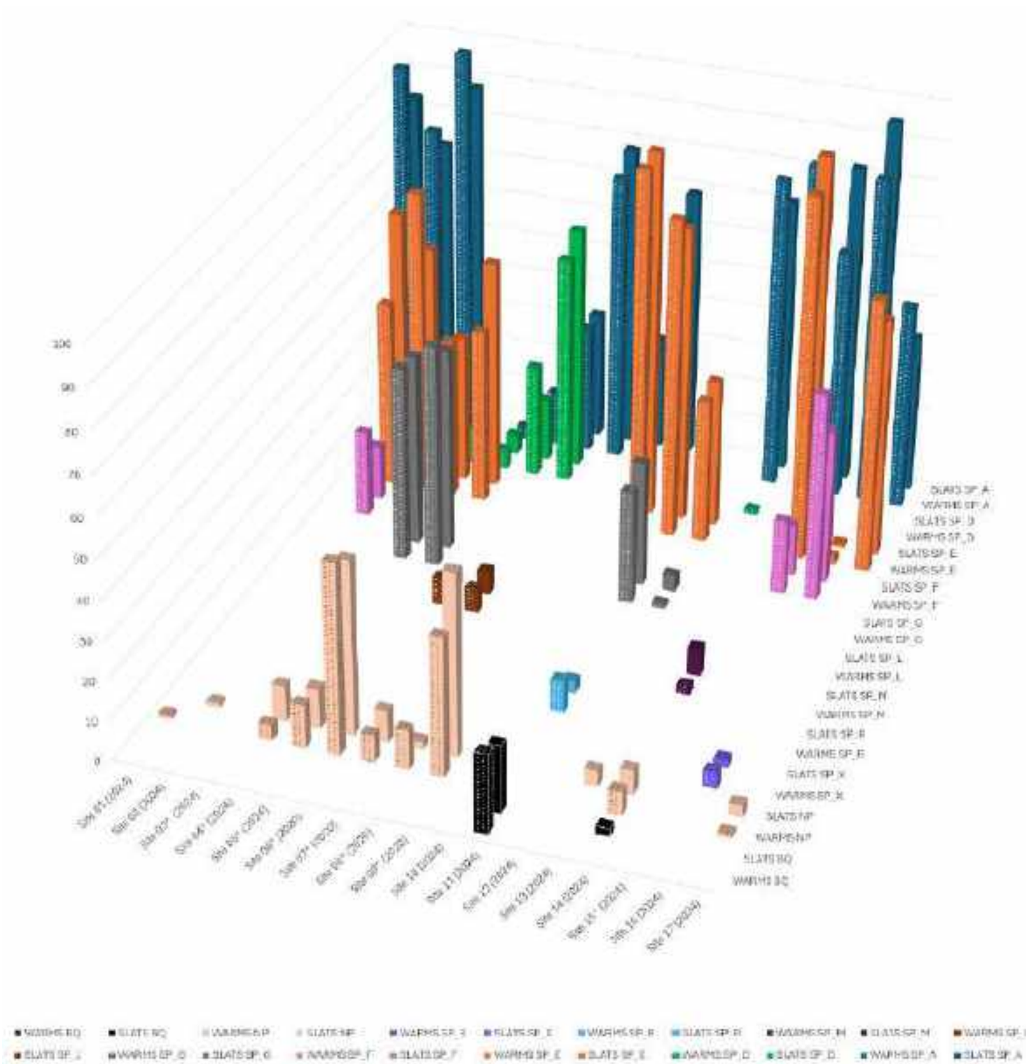

Figure 2. Comparative frequency data from sites assessed to date (*frequency data from 99 quadrats)

Discussion

We plan to collect additional data from shortlisted sites in 2025 to add to the comparative dataset.

Some SLATS star transect data may not be suitable for the TERN dataset, but will still be useful in this review and comparison with WARMS site data (P. Ramzi pers. comm. 2024).

Methods for using remote sensing data to complement on-ground monitoring of rangeland condition and degradation risk will be explored as part of this project, and may be useful in some pasture types for assessing the optimum number of on-ground data collection sites required and informing the optimum length of the epoch (revisit interval) required within our parameters to detect change.

The documentation of the change in the data collection method will allow the practicalities of substituting the existing WARMS measurement layout for the SLATS star layout without compromising the long-term trend detection to be quantified and analysed, which may assist other long-term ecological studies outside of the project area.

Establishment of an ongoing regular data analysis system is recommended to detect issues arising from implementation of the new method early, so that necessary adjustments can be made.

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Use of commercial rumen boluses to evaluate hot and cold weather impacts on cattle grazing rangelands

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Key words: humidity; livestock; sensors; humidity; wind

Abstract

Cold and hot temperatures can impact cattle health and wellbeing while grazing rangelands. Commercial rumen boluses can now remotely provide an indication of body temperature as well as an index of water intake. Ten 2-year-old Corriente heifers were monitored using smaXtec classic rumen boluses during June-August 2023 and January-February 2024 in a 312-hectare rangeland pasture near Prescott, Arizona USA. Reticular temperature measurements with and without proprietary adjustments for drinking water as well as activity indices were recorded every 10 seconds and reported as 10-minute averages. For analyses, temperatures were averaged hourly, every 3 hours and every 24 hours. During both summer and winter water-intake adjusted reticular temperatures (ART) varied by 0.6 C, and it was highest during late evening (1800 to 2159 hours) and lowest in the morning (0900 to 1159 hours). During the summer, ART was more closely associated with wet bulb globe temperature (WBGT) than air temperature, thermal heat index (THI), relative humidity and weather measures on an hourly basis. On a 24-hour basis, ART increased as WBGT and THI increased during the summer. During the winter, ART was most closely related to ambient temperature (AT) on an hourly basis. On a 24-hour basis during the winter, ART decreased during windy days, and ART initially increased with higher relative humidity and then decreased when relative humidity was over 70%. Estimated daily water intake decreased during periods of higher relative humidity during both summer and winter. Rumen boluses appear to be a useful tool to remotely monitor and study cattle responses to hot and cold weather while grazing extensive rangeland pastures.

Introduction

Livestock are regularly exposed to heat and cold stress, and impacts of predicted climate change will likely adversely affect animal wellbeing and productivity during the near future (Polley et al. 2013). Cattle must maintain a narrow range of core body temperature for optimal health. Extended exposure to high temperatures, relative humidity and solar load increase the risk of heat stress occurring during the summer (Shephard and Maloney 2023). A rise in core body temperature often followed by behavioral changes in water intake, feed intake, and activity occur during heat stress. If heat stress persists, negative effects on production, reproduction, and immune responses are known to occur (Lees et al. 2019a).

In the winter, cold stress can occur when animals are unable to maintain homeothermy due to low temperatures or wind chill (Shepard and Maloney 2023). Cattle exposed to extended cold stress, can experience a change in physiological processes, behavior, and hormone regulation, which may negatively impact performance (Wang et al. 2023) Despite, current climate trends and the public's concerns over animal welfare little research has been done to understand the extent of heat or cold stress for cattle grazing rangelands.

Rangelands are vast and often contain rugged terrain, which makes observations of cattle well-being difficult and labor intensive. Recent development of on-animal sensors, such as global positioning systems (GPS), accelerometers, and other devices, as well as the internet of things have facilitated real-time remote monitoring of the activity and health of livestock on rangelands (Nyamuryekung'e 2024). A rumen temperature bolus with radio frequency identification worked as a non-intrusive proxy for core body temperature to identify heat load in feedlot cattle (Lees et al. 2019b). The objective of this proof-of-concept study was to evaluate the effectiveness of a commercial rumen temperature bolus for monitoring the behavior and well-being of cattle in response to summer and winter weather conditions grazing a central Arizona rangeland.

Methods

The study took place at Deep Well Ranch (DWR) located 16 km north of Prescott, Arizona, United States. The study pasture NDP encompasses 312 ha with an elevation gradient of 1,460 to 1,520 meters. Deep Well Ranch falls within the Cold semi-arid (Bsk) of the Köppen climate classification and has an average annual precipitation of 487mm. The terrain is primarily rolling hills dominated by perennial grasses of black grama (*Bouteloua eriopoda* (Torri)), dropseed (Sporobolus spp.) and purple three-awn (*Aristida purpurea* Nutt).

A total of 28 registered 2-year-old Corriente heifers grazed the study pasture. Ten of the 28 heifers were randomly selected and administered smaXtec Classic Boluses (Graz, Austria) on April 7, 2023. The boluses recorded four metrics: reticular temperature (RT), adjusted reticular temperature (ART), activity index, and a water intake index. These metrics were measured every 10 seconds then averaged into 10-minute intervals, except water intake which is averaged into a single 24-hour value. Adjusted rumen temperature is a measure of reticular temperature excluding temperature changes from drinking events. All metrics except RT use proprietary algorithms to calculate the indices. SmaXtec boluses use long range Bluetooth to communicate with a base station, which sends data in real time to the internet using a SIM card with a cellular network.

All weather data were collected at the Prescott Regional Airport, which is 7 km from the study pasture. Ambient temperature (AT), relative humidity (RH), wind speed and solar load were recorded at 5-minute intervals. Thermal Heat Index (THI) was calculated using equations from Hahn et al. (2009), and Wet Bulb Globe Temperature (WBGT) was calculated using equations from Clark et (2024).

Both the smaXtec and weather data were averaged into 3-hour and 24-hour intervals from of June 1, 2023, to August 28, 2023 (summer) and from January 5, 2024 to February 29, 2024 (winter). The smaXtec and weather information was compiled into two data sets, one for 24-hour averages and another consisting of eight, 3-hour time periods within a day.

For the 3-hour data, an independent repeated measures analysis was performed for each combination of weather and smaXtec metric. Summer and winter analyses were conducted separately. The analyses were completed using PROC MIXED in SAS (Littell et al., 2006). The covariate structure was autoregressive, AR(1). The independent variable was one of the weather metrics (ambient temperature C°, relative humidity, solar load, THI, WBGT or wind chill). The dependent variable was one of the smaXtec metrics (RT, ART, or activity index). Heifer was the subject for all analyses. Linear, quadratic and cubic effects for each weather metric were evaluated. The best fitting models were selected based on the smallest Akaike Information Criterion (AIC) score (Littell et al., 2006).

For the 24-hour data, the same approach was used for the summer and winter analyses. An independent repeated measures analysis was performed for each combination of weather and SmaXtec metrics. The covariant structure was again autoregressive AR(1). The independent variable was one of the weather metrics, and the dependent variable was one of the smaXtec metrics. The subject was heifer. Linear, quadratic and cubic effects were evaluated for each separate weather metric.

Results

Summer

Using 3-hour data, RT and ART were nearly the same in early morning and late at night (Fig. 1). A clear divergence between RT and ART occurred mid-morning (06:00 to 08:00) when RT and ART decreased. During late afternoon and evening, RT and ART increased. Reticular temperature experienced a larger drop than ART in the morning. The best fitting model for ART was a cubic relationship with WBGT ($P<0.001$). Initially, ART dropped as WBGT increased. Adjusted reticular temperature then gradually levelled out and increased when WBGT was greater than 15º. The second-best model for describing changes in ART was a cubic relationship with RH ($P<0.001$). The cubic relationship indicated that ART rapidly increased from 0% to 40%, then ART continuously declined until 85% RH at which ART increased again. The activity index showed a clear diurnal grazing pattern with higher levels in the morning and evening (Fig. 2). The best fitting model for activity was a cubic relationship ($P<0.001$) with RH. Modelled activity levels steadily increased as RH increased up to 50%. If RH was greater than 50% any increases in the activity index were gradual. A negative linear relationship ($P<0.001$) with solar load the second-best model for describing changes in the activity index.

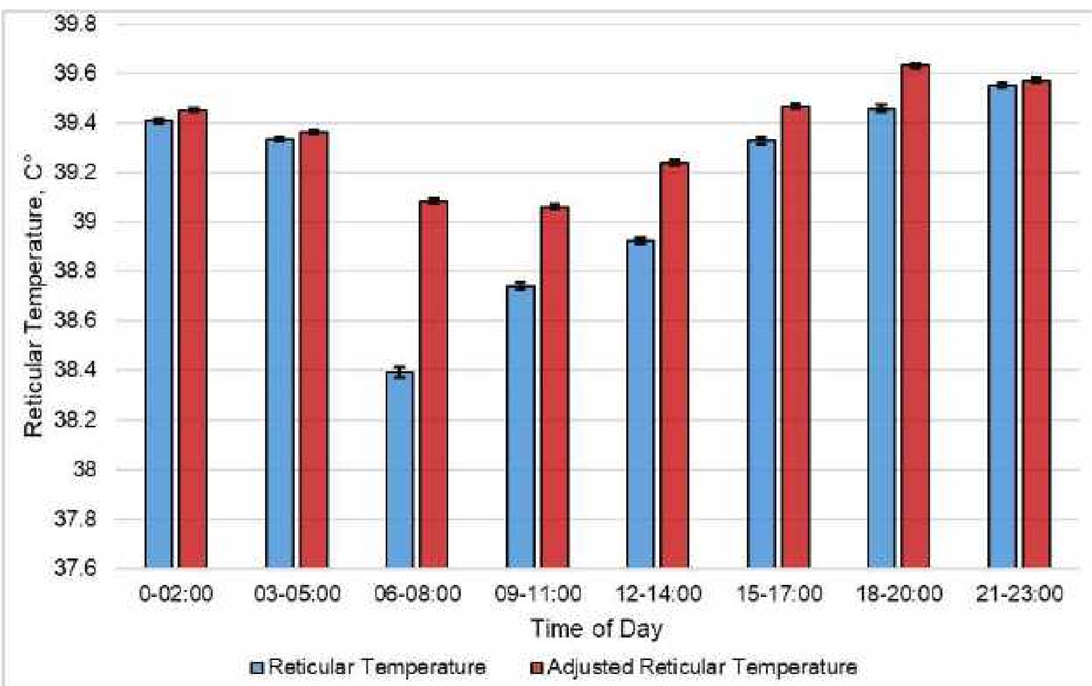

Figure 1. Least-square means of reticular temperature (RT) and adjusted reticular temperature (ART) averaged for each 3-hour period during the summer period. Error bars represent standard errors.

Using 24-hour averages, the best fitting model for ART was a quadratic relationship with WBGT ($P<0.001$) The model suggested that ART decreased when daily WBGT was less than 16. However, ART increased if daily WBGT values were greater than 16. The THI was the second-best predictor of ART with a positive linear relationship. As THI increased, ART increased. The water intake index decreased linearly with increasing RH ($P<0.001$). Days with the highest water intake had the lowest relative humidity. The second-best weather metric for modelling changes in the water intake index was a linear relationship with solar load with a linear relationship ($P<0.01$). The water intake index increased with increasing solar load.

Winter

Like the summer study, RT and ART were similar in early morning and late at night (Fig. 3). Both RT and ART started decreasing at 06:00 and reaching a low between 09:00 and 11:00 then increasing in the afternoon. A quadratic relationship ($P<0.001$) with ambient temperature was the best model for describing changes in ART using 3-hour data. As AT increased to 2°C, ART also increased, but at warmer temperatures ART began to decrease. There was also a quadratic relationship ($P<0.001$) between ART and wind chill with a quadratic relationship. Adjusted reticular temperature increased until wind chill reached zero, after zero ART declined with increasing wind chill. The best fitting model for the activity index (3-hour data) was a quadratic relationship with wind speed ($P<0.001$). The activity index increased with increasing wind speed until approximately 6 m/s. At higher wind speeds the activity index began to decline.

The best fitting model for ART using 24-hour data was a cubic relationship with wind speed ($P < 0.01$). The model suggested ART gradually increased with increasing wind speed until 5 m/s. After wind speeds surpassed 5 m/s, ART increased more rapidly. The activity index was also related to wind speed using 24-hour data. Activity increased linearly ($P<0.001$) with wind speed. Like summer, the water intake index was related ($P<0.001$) to relative humidity (quadratic relationship). Water intake was lower at higher levels of humidity.

Discussion

The higher values of ART compared to RT during midday demonstrate the proprietary algorithm used in ART helps account for drops in reticular temperature resulting from drinking water. The temperature of the drinking water was cooler than RT, thus consuming water lowered RT. Values of ART appear more consistent than RT during periods when cattle normally drink. Thus, ART should be a better metric than RT to use as an estimate of core body temperature. However, neither ART nor RT fluctuated by more than 1°C daily. As mentioned by Shephard and Maloney, (2023) homeothermy of cattle can fluctuate by 1°C daily and varies between species, seasons, and lifestyle stages, which creates difficulty for establishing a "normal" range for core body temperature. Therefore, cattle in this study likely did not experience heat stress. More research is needed in an area with hot temperature lasting for longer durations than central Arizona, as cool nighttime temperature at the study site would likely mitigate heat load. Higher ART values were observed during periods with a higher WBGT, which suggests ranchers in the region should monitor WBGT rather than just ambient temperature or THI to identify periods with increased risk of heat stress.

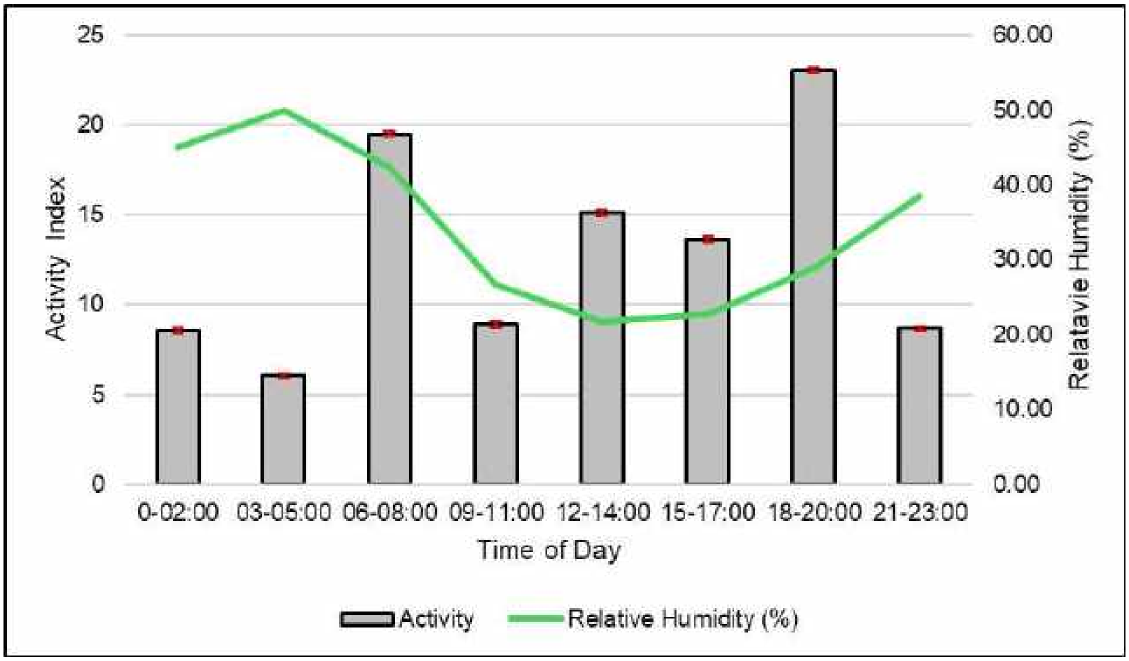

Figure 2. Relationship between the smaXtec activity index and relative humidity throughout the day during using 3-hour data. Columns are the least-square means of the activity index, and the error bars represent standard errors. Values are averages of the entire summer study period.

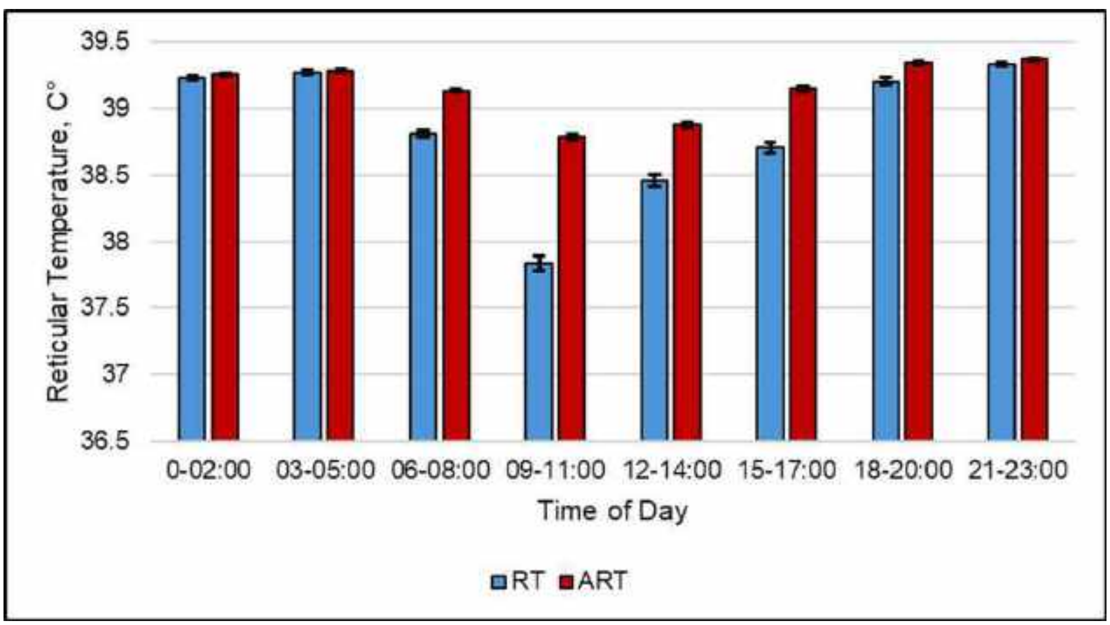

Figure 3. Least-square means of Reticular Temperature (RT) and Adjusted Reticular Temperature (ART) during 3-hour periods averaged over the winter study period. Error bars represent standard errors.

Relative humidity was related to many of the smaXtec bolus metrics in both 24-hour and 3-hour summer data sets. We found the strong association of RH and smaXtec metrics to be surprising because humidity is typically low at this Arizona study site. We speculate the reason RH is so influential is due to the association with monsoonal weather patterns. Periodic rains and cloudy weather occur during the monsoon season (July and August), which likely reduces solar load and ambient temperature. The water intake index decreased when RH levels increased throughout the study. Days with higher RH are correlated to wetter days in the region. During periods of high RH, there may have been moisture on the vegetation, potentially reducing cattle water demand.

During the winter, AT was useful for modelling adjusted reticular temperature within a day. However, wind and relative humidity were more associated with ART than other weather variables on a daily time scale. Wind speed was associated with daily activity changes. Estimated water intake appeared to decrease during periods of higher relative humidity. The impact of wind, relative humidity, and temperature suggest storm events likely influence cattle behavior and ART (a potential proxy for core body temperature) on rangeland during winter months. In this study, cattle appeared to either adapt to cold conditions or were not exposed to cold conditions long enough to result in cold stress. There were no apparent periods when cattle ART decreased for a sufficient time to suggest cold stress. If these boluses are to be used for detecting cold stress, more research in an area with colder conditions than central Arizona is needed.

The combination of a core body temperature metric (ART, adjusted reticular temperature) and an activity index were recorded every 10 minutes and the boluses reliably transmitted the data daily. This technology is promising and shows potential to monitor the well-being of cattle grazing rangelands throughout the summer and winter. The smaXtec rumen boluses worked well with very few issues. This sensor has potential for ranchers and researchers remotely monitor rangeland cattle behavior and core body temperature, but more research is needed in other locations and with other cattle breeds.

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Construction of a 200-year annual domestic livestock distribution geographical dataset for Australia for the pre-digital era 1788 to 1980.

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Key words: Livestock; grazing distribution; pastoral history

Abstract

Domestic livestock statistics across all Australian jurisdictions have been collected since 1788. Cattle, sheep and horse numbers for the period were digitised from paper sources. Statistical district boundaries were also digitised from mapping sources for each year and coded to link to the digitised livestock records. Estimation of pre-European vegetation, natural waters, the development of stock water areas (bores, small dams), irrigation (fodder crops and pastures) and protected areas were used to distribute livestock within each statistical district for each year.

This work focuses on historical data as part of an undertaking to produce a comprehensive Australian high resolution time series map (1km2 grid) of livestock from 1788 to 1980. Such data is of use in grazing system models and other applications such as estimating long term methane emissions to help understand the long-term impacts of domestic livestock grazing pressures on the landscape and atmosphere.

This data collection shows a decline in data quality, due to the declining number and increased areas of statistical districts reporting livestock population. The results document the expansion of domestic livestock in area and numbers from first settlement and the probable distribution at a finer scale.

Introduction

Providing an estimate to historical grazing distribution within Australia will provide better understanding and background to the current environmental impacts. Climate variability and grazing pressure on the rangelands are well documented in McKeon et al. 2004 p 19, along with impacts on the Great Barrier Reef (Lewis et al. 2021), changes in native pasture composition (Dixon 1892; Carr and Turner 1959a; Harrington et al. 1979; Rolls 1981 pp 111,129), scrub and/or woody regrowth (Rolls 1981 p 185; Wilson 1990) and soil degradation (Carr and Turner 1959b; Rolls 1981 pp 129, 246). This dataset will facilitate exploration of issues such as land clearing, woodland thickening and methane emissions (Hempson et al. 2017). Domestic livestock within this paper refers to only horses, cattle and sheep, with feral livestock numbers not being included.

This work focuses on historical data prior to 1980 as part of an undertaking to produce a comprehensive Australian high resolution time series map of livestock from 1788 to current for use in grazing system models such as AussieGRASS (Carter et al. 2000). To this end, annual livestock population data that was available for all Statistical Districts was acquired and digitised. Mapping sources that showed the statistical districts or similar spatial entities were collected and used to estimate likely spatial boundaries at the time of collection. Later a disaggregation method was used, that proportioned the livestock population in each statistical district, in each year, to likely grazing densities that would be experienced. These are shown as an animal equivalent estimate per kilometre (AE km2).

Methods

Livestock numbers for each jurisdiction (six States and two Territories) were digitised from historical records and followed the progression of European land management throughout the 19th century (Fig. 1). Many of the livestock statistics were not continuous, and temporal gaps at the statistical district level were common. In these years, livestock totals for the jurisdiction were provided and used to estimate numbers for the statistical districts based on a percentage breakdown from the years where recorded data were present.

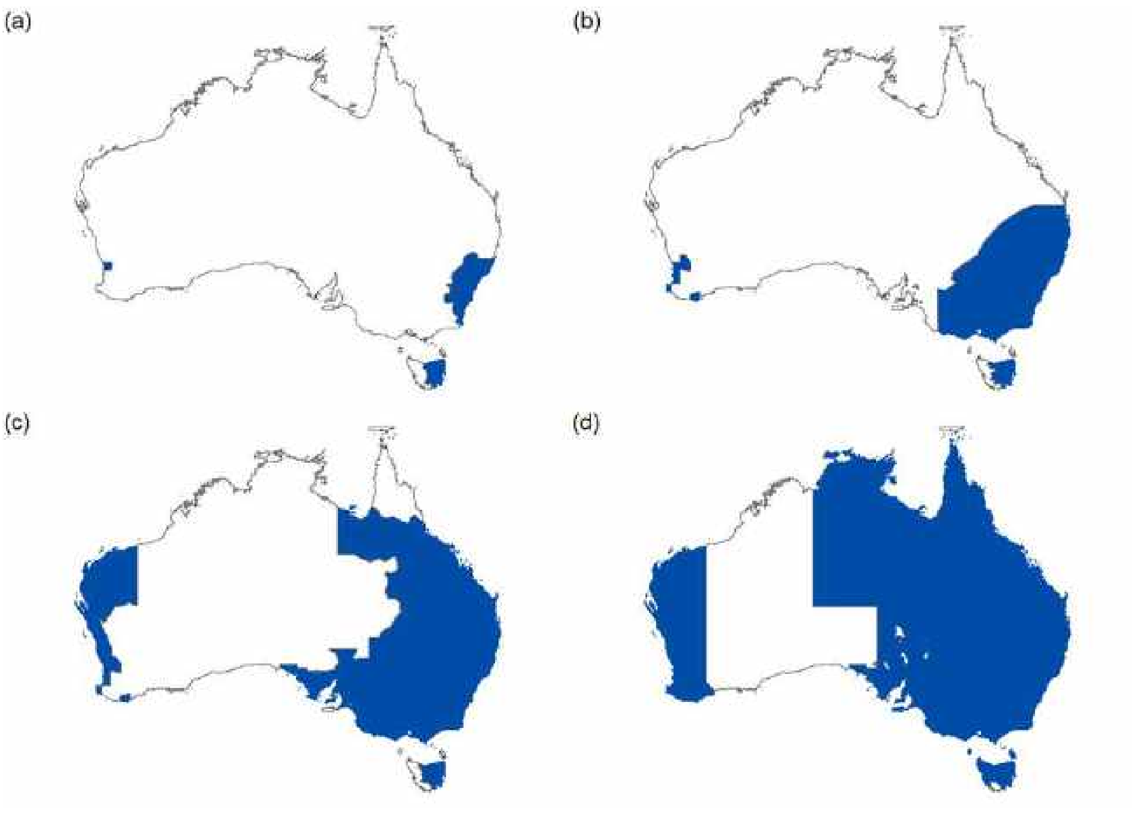

Fig. 1. The statistical districts shown in blue that were created within Australia by (a) 1830;(b) 1850; (c) 1870; and (d) 1890. The continent was fully covered by 1891, excluding major saline areas.

Mapping was based on maps used at the approximate time of the original data collection and where possible the same spatial entity as described in the textual records (i.e. local government area, police district, county etc). The spatial boundaries were subsequently captured by GIS using current digital cadastral information as a basis. The livestock numbers were converted to a common unit being dry adult equivalents (450kg cow or horse). Sheep numbers used a conversion of 7 sheep to 1 adult equivalent, with horse and cattle numbers being assumed as the same adult equivalents (Stone 2004 p194).

A common map code was added to the livestock (tabular) and statistical district data (spatial). This allowed a spatial join to be performed within ArcGIS Pro (Environmental Systems Research Institute 2024), creating a yearly spatial dataset showing the relevant livestock data within a spatial boundary. A heuristic livestock distribution was generated via ArcGIS Pro to downscale the livestock record for each statistical district for any given year. The distribution was based on a grazing land class that estimated the grazing pressure likely to occur in the statistical district based on the grazing land class and availability of water. The full methodology including the historical background, data sources, mapping references, and the determination of land grazing classes and associated land development features is described in Irvine et al. (2024).

Results

A median livestock distribution for all years from 1788 to 1980 is shown in Fig. 2. Biannual distribution maps are shown in Irvine et al. (2024). It is also shown that from the natural state of grazing lands, approximately 992,905 km2 of Australia had been improved by 1980 via clearing, water improvements and fencing, enabling an increased livestock density across the continent.

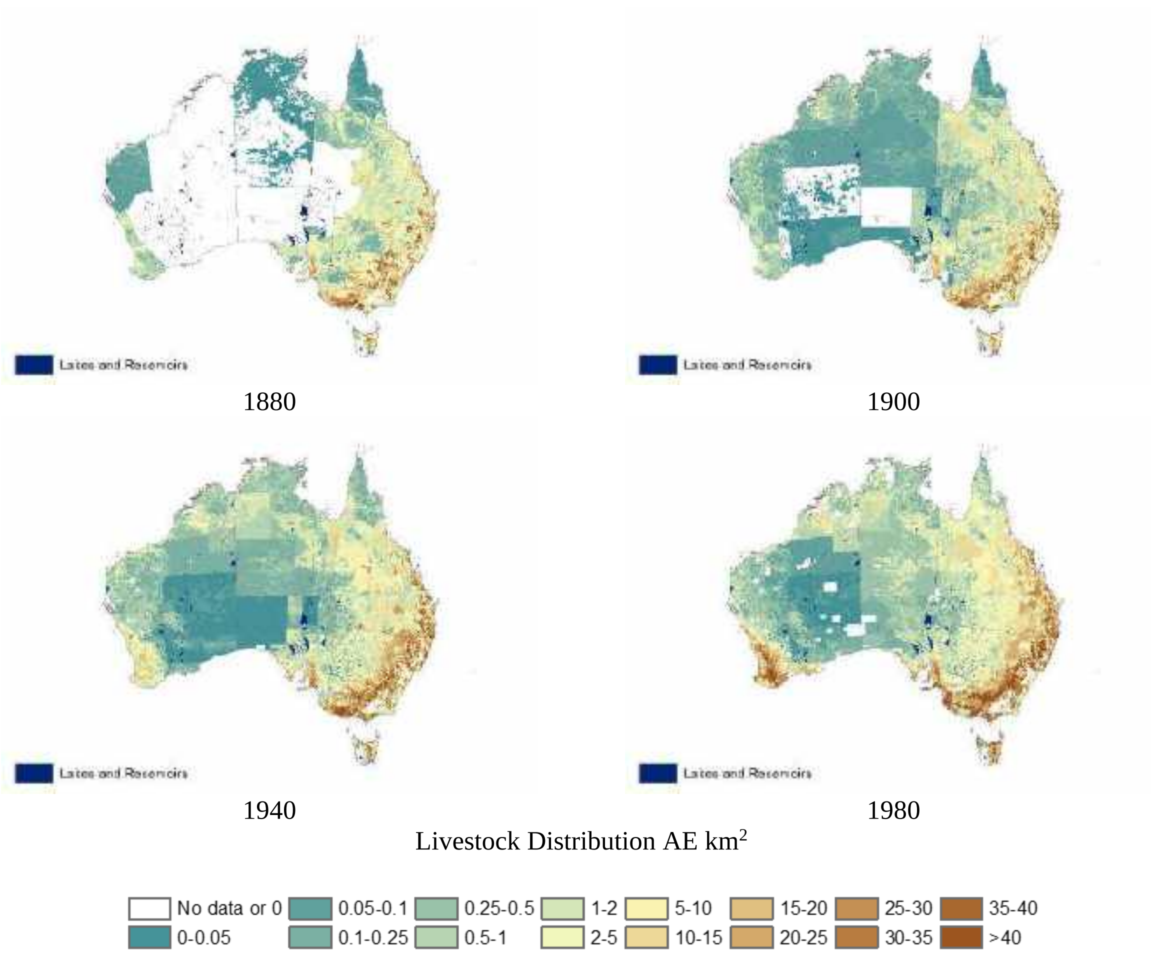

Fig. 2. Livestock distribution calculated for selected years.

In contrast to the continuous land improvement and increased livestock population, the statistical districts being used have decreased in number (Fig. 3) and are larger in area due to recent local government area amalgamations.

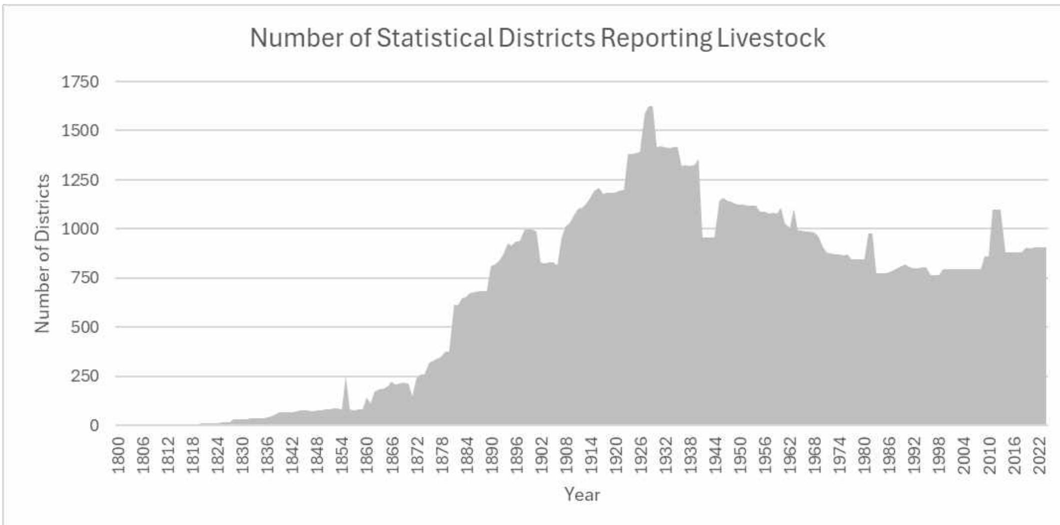

Fig. 3. The number of statistical districts reporting livestock have generally been declining since the 1920's.

Discussion

This study has accumulated all readily available Australian livestock population numbers collected at a statistical district scale, in a standardised format, proportioned to likely grazed areas and presented at a 1km resolution. However, significant gaps and limitations still exist due to the absence of records and/or inability to find all records.

The dataset generated from this analysis is a step in the process of estimating historical total grazing pressure, extending knowledge to previously unknown areas. It provides a standard baseline for any investigation to any aspect of Australian historical livestock populations, providing a grazing distribution to any spatial area.

The statistical record is being seen as degrading in quality mainly due to the amalgamation of pastoral statistical districts in recent years (Fig 3.), leading to a current discussion on the suitability of livestock data for analysis (Fordyce et al. 2023). This has likely led to changes and the development of new methodologies for the collection of livestock statistics, as noted by the Australian Bureau of Statistics (2024).

Acknowledgement

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Decision support – models and tools for integrated rangeland management

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Back to the future – site, science and sustainability

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Key words: buffel grass; central Queensland; site data; GRASP model; calibration

Abstract

Inter-annual rainfall variability across Queensland, Australia, is among the highest in the world. This variability coupled with episodic periods of drought and flood and highly variable forage supply pose major challenges for grazing management in Queensland. Since the mid-1990s, researchers have successfully used historical and current pasture data with the GRASP biophysical model to simulate pasture growth in the grazing lands of northern Australia. The FORAGE online system provides a unique combination of pasture modelling (GRASP model), remote sensing and climate forecasts to support grazing land and environmental management decisions. Here we look 'back to the future' to build on previous research, transfer our past knowledge and experience in modelling grazing systems to new researchers, and use the traditional, highly valued but resource-intensive site data to improve the GRASP land type models used in the FORAGE decision support system. Four fenced sites were established in regionally dominant Brigalow softwood scrub and Brigalow blackbutt buffel grass (*Cenchrus ciliaris* cvv. Biloela, Gayndah) pastures. We use detailed soil, pasture and rainfall measurements collected over three years (2020 – 2022) to represent key biological and physical pasture processes in the GRASP model. Across the years, the sites varied in rainfall (3 – 138% above long-term median), average buffel grass dominance (69 – 98% of total yield), peak pasture yield (2742 – 4343 DM kg ha^{-1}) and sward nitrogen yield (19 – 34 kg N ha^{-1}). We use this data to improve the FORAGE modelled estimates of long-term buffel grass pasture productivity in the broader Brigalow softwood and Blackbutt land type pastures in central Queensland. This will inform grazing and environmental land management decisions that promote both sustainable natural resource use in grazing lands and profitable grazing industries.

Introduction

Grazing with beef cattle and sheep is the dominant land use in Queensland, Australia, occupying nearly 86% of Queensland's 173 million hectares. Gross value of production from cattle and calves was estimated to be $6.6 billion and 35% of Queensland's primary industry commodities in 2024 – 25 (Queensland Government 2024). Almost 25% of the Queensland herd (~2.5 million cattle) grazes over 11.1 million ha in the Fitzroy Basin (MLA 2022).

Buffel (*Cenchrus ciliaris* L.) grass is an introduced strongly tufted, erect (60 – 100 cm tall), perennial, summer-growing grass that occurs on range of soil types containing reasonable fertility. The productivity, adaptation and drought tolerance of buffel grass make it the most widely established sown pasture in Queensland, estimated to be 'dominant' on 5.8 million ha (Peck et al. 2011), and a major contributor to the Queensland grazing industry.

The considerable inter-annual and decadal rainfall variability experienced in Queensland (Klingaman et al. 2013), and associated major temporal variability in forage supply, pose a major challenge for the sustainable and profitable management of grazing businesses (O'Reagain and Scanlan 2013). Since the mid-1990s, researchers have successfully used historical and current pasture data with the point-based GRASP model (McKeon et al. 2000) to simulate pasture growth in the grazing lands of northern Australia. The GRASP pasture growth model has been calibrated for over 100 native pasture sites across Queensland (Day et al. 1997) and has been widely used in the rangeland environments to predict year-to-year variability in forage supply and to estimate safe carrying capacities in the highly variable climate of northern Australia (e.g. Day et al. 1997; Walsh and Cowley 2011; Whish et al. 2014). However, there is little site data to predict pasture growth of long-term established buffel grass pastures in Queensland.

The Queensland Government developed an operational online information system – FORAGE – to facilitate decision support for grazing and environmental land management practices (Zhang and Carter 2018). The FORAGE system provides land managers with property-scale information relating to rainfall, ground cover, soil erodibility, land types, tree density, seasonal climate outlooks and pasture growth simulated using the GRASP grazing system model.

Here we look 'back to the future' to build on previous research, transfer our knowledge and experience in modelling grazing systems to new researchers, and use the traditional, highly valued but resource-intensive site data to calibrate buffel pasture GRASP models at four locations within 75 km from Emerald (23°31´S and 148°09´E), central Queensland. In this paper we outline the systematic approach for buffel grass model calibration, review the calibration results and extend the site models over time. We briefly discuss the use of the buffel site calibrated models across similar soil types and pastures, and the potential use of calibrated models to improve the FORAGE modelled estimates of long-term buffel grass pasture productivity in the broader Brigalow softwood and Blackbutt land type pastures in central Queensland.

Methods

Paired SWIFTSYND sites were established on the regionally dominant Brigalow blackbutt (sites 'A', 'B') and Brigalow softwood scrub (sites 'C', 'D') (State of Queensland 2022) buffel grass (cvv. Biloela, Gayndah) pastures at three grazing properties within 75 km from Emerald, central Queensland.

Fenced (to exclude livestock, wildlife and feral grazers) 30m x 30m sites were established during November (B, C, D) and December (A) 2019 on good condition buffel grass pastures that were established approximately 15 years previously. Preparation of the sites each year involved using brush cutters to remove dead material to 5 – 10 cm and remaining litter before spring rains.

The extensively cleared, Brigalow blackbutt sites (A, B) were established on hard setting, sandy clay loam to medium clay (brown sodosol) soils, whilst the Brigalow softwood scrub sites (C, D) were established on periodically cracking, light – medium clay to medium heavy clay (black vertosol). All sites were densely covered with medium tall (34 – 40 cm) Gayndah dominant buffel pastures, with the taller (~1.0 – 1.5 m) Biloela buffel grass a third of the pasture sward at the D site (Table 1).

Detailed pasture measurements were collected four times a year over 2020 – 2021 period using the methodology of Day and Philp (1997). Following the declaration of 'La Niña' an extra year of sampling

(2022) was undertaken at all sites to optimise the capture of potential growth when not water-limited. The measurements taken at each site provide the minimum information required to determine pasture and soil parameters for the pasture growth model GRASP. Site measurements included pasture yields and composition (‘Gayndah’ buffel, ‘Biloela’ buffel, ‘Other grasses’, ‘Legumes’, ‘Dicots’), heights, grass basal area, cover and plant nitrogen (N) content. Climate files for each site were obtained from SILO (Jeffrey et al. 2001) and combined with site-specific daily rainfall data (tipping bucket rain gauge). Soil water, Colwell phosphorus content, soil profiles and bulk density measurements were also collected at each site. In this paper we used three years of data in the calibration of ‘B’ and ‘D’ sites, and only the first two years of data in the calibration at ‘A’ and ‘C’ sites.

The GRASP model was used to simulate pasture production at the fenced buffel pasture sites through calibration using GRASP Calibrator (version 1.33 Build 7177). A systematic approach for model calibration (Scanlan et al. 2008), and the adjustment of parameter values to achieve the ‘best fit’ between model and site data, was employed to ensure key biological and physical pasture processes were well represented in the GRASP model. The latest versions of GRASP CEDAR (version 2.1.04 date 30/11/2023) and CEDAR default parameter file (cedardefault_v_2_1_03.prv dated 19/1/2024) were used. Long-term (1876 – 2024) annual (1 Oct- 30 Sep) ‘Year Type’ seasonal analysis for rainfall and pasture growth percentiles were derived for each calibrated site model using historical climate data.

Results

Site description

Annual rainfall (Jan – Dec) varied across the sites with the B and D sites receiving less rainfall than A and C sites during the study, however, all sites received rain in 2021 and 2022 that was well above (31 – 138%) their long-term median annual rainfall (Table 1). The long-term average annual rainfall and year-to-year variability (co-efficient of variation) for the sites ranged from 579 mm and 0.36 at B site to 619 mm and 0.40 at A site.

During the relatively drier 2020 growing season, peak pasture and N yield were greatest at the Brigalow blackbutt B site (Table 1). During the wetter year (2021) the peak pasture yield was greatest at the Brigalow softwood scrub C site, however, a similar peak pasture yield and the highest N yield was reached at the Brigalow blackbutt A site (Table 1). Peak pasture production during the 2021 growing season was broadly reflected in the similar or lower sward N yields compared to the drier year.

Site calibration

The GRASP model was used to simulate pasture production at the four buffel pasture sites through calibration using GRASP Calibrator and the adjustment of parameter values to achieve the ‘best fit’ between model and site data. Calibration commenced using the Queensland Government’s Brigalow blackbutt and Brigalow softwood scrub land type parameters used in the FORAGE online system (Zhang and Carter 2018).

The average annual rainfall at the four buffel pasture sites during the study (2020-2022) was in the long-term 60-100th percentile for all sites (Table 1). The four calibrated buffel pasture models when compared with observed (measured) data were a good to very good fit for pasture yield (Total Standing Dry Matter, TSDM kg ha^{-1}, Fig. 1 & Table 2), fair to moderate fit for soil water, with none to moderate agreement for N yield in TSDM (Table 2).

Long-term median annual pasture growth was highest at the Brigalow blackbutt B site, with pasture growth at the other sites being 2% (D), 6% (A) and 10% (C) less than site B (Table 2). The long-term median pasture growth for the calibrated models was higher than the respective FORAGE Brigalow blackbutt land type models but lower than the respective FORAGE Brigalow softwood scrub land type models (Table 2).

Discussion & Conclusions

Detailed pasture production data collected at the Brigalow blackbutt and Brigalow softwood scrub buffel grass pasture sites was successfully used to calibrate the GRASP model. Model calibration included adjustment of the Queensland Government's Brigalow blackbutt and Brigalow softwood scrub land type parameters values to achieve the 'best fit' between model and site data.

Table 1. Annual rainfall, average % Gayndah buffel grass composition of total pasture yield, average Grass Basal Area (%GBA), peak pasture yield Total Standing Dry Matter (TSDM) and pasture sward nitrogen content for peak yield (kg N ha^{-1}) for the paired GLM Brigalow blackbutt ('A', 'B') and Brigalow softwood scrub ('C', 'D') land type buffel (*Cenchrus ciliaris* cvv. Biloela, Gayndah) pasture sites.

GLM Land type	Site annual rainfall mm (Percentile annual rainfall 1889-2024)			Average Gayndah buffel composition total yield (%)	Average Grass Basal Area (%GBA)	Peak yield TSDM (kg ha^{-1})			**Sward nitrogen for peak yield (kg N ha^{-1})	
	2020	**2021**	**2022**			**2020**	**2021**	**2022**	**2020**	**2021**
Brigalow blackbutt sites										
***A**	631 (60)	1367 (100)		96	17	2686	4317		29.9	30.2
B	598 (60)	787 (90)	853 (100)	98	13	3314	3062	3178	33.8	19.0
Average				97	15					
Max						3314	4317	3178	33.8	30.2
Brigalow softwood sites										
***C**	588 (60)	923 (100)		98	22	2742	4343		24.4	26.1
D	576 (60)	725 (90)	849 (100)	69	12	2484	3708	3452	27.8	23.0
Average				84	17					
Max						2742	4343	3452	24.4	26.1

*Only first 2 years data **2022 data being analysed

The four buffel calibrated models produced reasonably good fits (R^2 0.84 – 0.92) to observed TSDM data, aligning with the R-squared (R^2 0.92) achieved for a model calibration of buffel grass site near Moura, central Queensland (Peck et al. 2017). Poor to moderate agreement of the four calibrated models to soil water (R^2 0.15 – 0.70) and N yield of standing dry matter (R^2 0.0 – 0.66) were achieved during this study. Discrepancies between observed and predicted values of soil water are likely to be due to difficulties accessing sites during the wet periods and sampling dry, crumbly soils, rather than any site-specific impediment. The poor to moderate fits of modelled data to measured N yield at the three of the four Gayndah-dominant buffel pasture sites (A, B, D) were worse than that achieved for the calibrated Brigalow softwood scrub buffel grass model (R^2 0.57) at Moura where Gayndah buffel contributed only 22% of pasture yield (Peck et al. 2017). The higher observed than predicted N yields achieved during this study could be due to the ability of Gayndah buffel to respond quickly to rain and flower early whilst the flowering plant continues to produce extra N-rich leaves and new shoots. GRASP has a relatively simple calculation of N limitation so both the limitations of soil fertility and climate can be represented in simulations of pasture growth. The observed high N yields as an indicator of pasture quality are also an important driver of animal production. Further work is required to develop a dynamic N sub-model in GRASP that will enable representation of buffel grass species that exhibit high N yields in simulations of pasture growth and animal production.

The long-term (1890 – 2024) median pasture growth for the four calibrated buffel grass models (4739 – 5022 DM kg ha^{-1}) was slightly higher than the simulated long-term (1995 – 2014) annual pasture growth (4166 DM kg ha^{-1}) of grazed buffel grass pasture near Moura (Peck et al. 2017). The long-term median pasture growth for the calibrated buffel grass pasture models were approximately 10% more than FORAGE Brigalow blackbutt buffel but 30 – 35% less productive than the FORAGE Brigalow softwood scrub buffel model. Further consideration of site-specific characteristics and the adequacy of the study sites to represent the broader Brigalow softwood scrub and Brigalow blackbutt buffel pastures in central Queensland is required.

This work has provided an opportunity for a senior researcher to successfully transfer their knowledge and experience in modelling grazing systems to a new researcher, and demonstrate the value of the traditional, resource-intensive site data to calibrate buffel pasture GRASP models to inform and improve the FORAGE modelled estimates of buffel grass pasture productivity in central Queensland.

Table 2. Linear relationships (R-squared) between observed and predicted Total Standing Dry Matter (TSDM kg ha^{-1}), soil water for layers 1 (0 – 10 cm), 2 (10 – 50 cm) and 3 (50 – 100 cm), and nitrogen yield (kg N ha^{-1}) for the four Brigalow blackbutt and Brigalow softwood scrub buffel pasture calibrated models. Long-term (1876 – 2024) annual (1 Oct – 30 Sep) seasonal analysis 'All Years' median pasture growth (kg ha^{-1}) simulated for each calibrated buffel site model and for FORAGE Brigalow blackbutt and Brigalow softwood scrub land type models.

GLM Land type	**TSDM (kg ha^{-1}) R^2**	**Soil water layer R^2**			**N Yield (kg N ha^{-1}) R^2**	**'All Years' median annual pasture growth (kg ha^{-1})**	**'All Years' median annual pasture growth for FORAGE Brigalow blackbutt and Brigalow softwood scrub (kg ha^{-1})**
		1 (0-10 cm)	**2 (10-50 cm)**	**3 (50-100 cm)**			
Brigalow blackbutt sites							
***A**	0.92	0.51	0.33	No data	0.29	4739	4430
B	0.84	0.44	0.30	No data	0.0	5022	4600
Brigalow softwood sites							
***C**	0.92	0.30	0.47	0.70	0.66	4515	6970
D	0.86	0.27	0.15	0.56	0.56	4928	7028

*Only first 2 years data

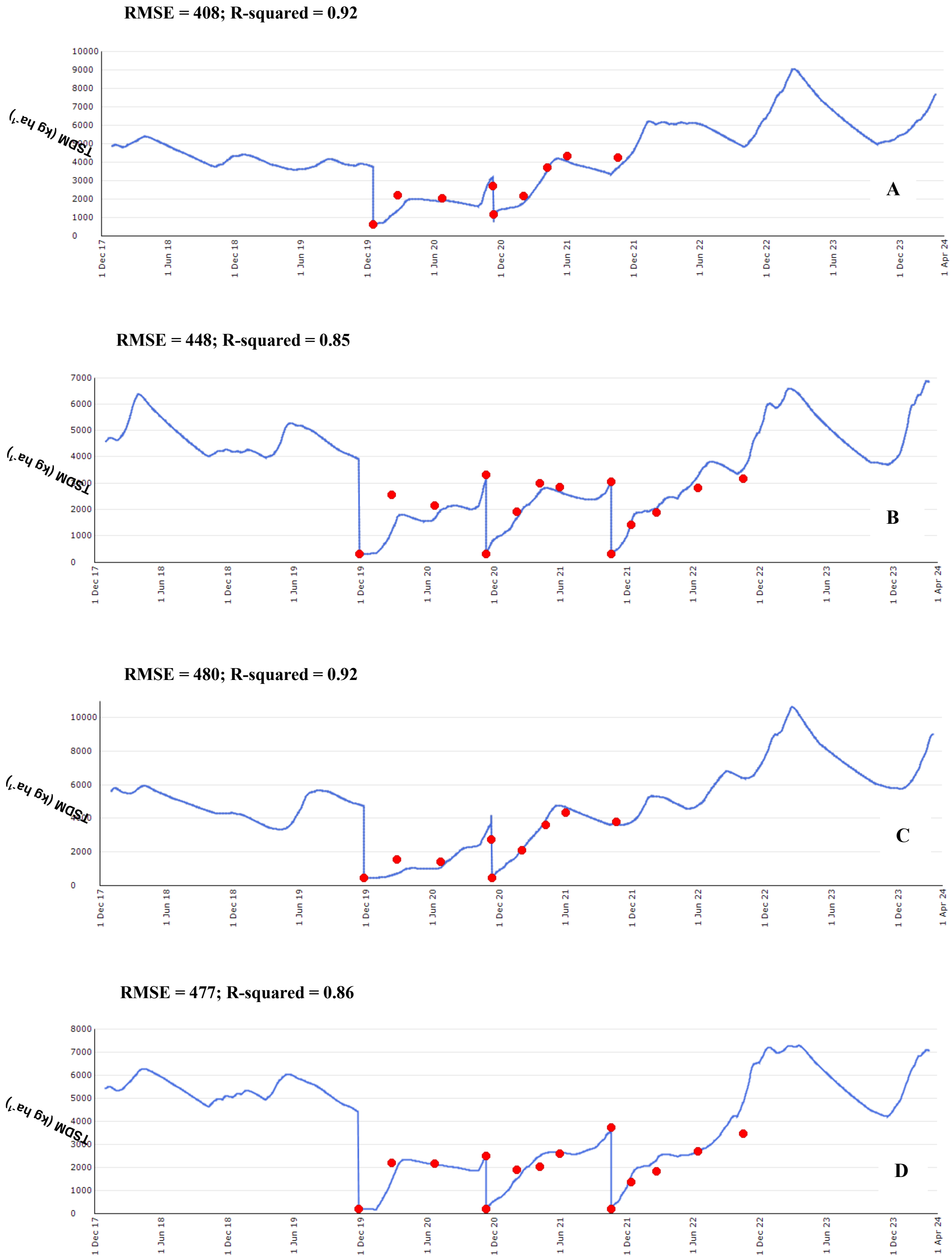

Figure 1. Time series for Total Standing Dry Matter (TSDM) kg ha^{-1} (observed red circles and predicted blue line) for the GRASP calibrated Brigalow blackbutt ('A' and 'B') and Brigalow softwood scrub ('C' and 'D') buffel pasture sites. X axis December 2017 to April 2024. Y axis TSDM (kg ha^{-1}). Linear regression

statistics (R-squared and root mean square error (RMSE)) are provided. Note: Only the first two years of data used in model calibration for 'A' and 'C' sites.

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On-animal sensors: measuring grazing cattle behaviour under two different supplement strategies

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Key words: protein supplements; on-animal sensors; monitor behaviour

Abstract

Protein supplements are a common approach to address nutrient deficiencies in rangeland cattle. On-animal sensors have emerged as an alternative for measuring individual cattle behaviour, including supplement intake, in near real-time without human intervention. This study aimed to study the combination of on-animal sensors to monitor behavioural changes in response to varying levels of individual supplement consumption.

Fourteen Droughtmaster heifers were fitted with a wireless ear tag (WelfareTag™ HerdDogg), GPS collar (i-gotU GT-600), and rumen bolus (SmaXtec® Classic Bolus). They co-grazed a 10-ha paddock from 20/9/22 to 13/12/22. In two consecutive periods, they were offered different supplementary high-protein diets, expected to vary in palatability. During period one (days 1-42), heifers received 300 g/d of a low-intake supplement (26% CP, 5% Urea), and during period two (days 43-85), they received 1000 g/d of a high-intake supplement (30% CP, 4% Urea). Data were analysed using R (version 4.3.1) and RStudio with a linear mixed-effects model ('lmer'), each parameter was considered individually.

During period 2, heifers spent 1.7 times more time at the feed trough than in period 1 ($p<0.001$), suggesting increased supplement consumption. Grazing activity was not significantly higher in period 1 than in period 2 ($p<0.1$). Resting time in period 1 decreased ($p<0.1$) but travelling times increased ($p<0.01$). Rumen temperature and rumination index were lower in period 1 ($p<0.05$, $p>0.1$), while oestrus index was higher in period 1 compared to period 2 ($p<0.001$). Counts of water-drinking events were higher in period 2 ($p<0.001$).

In conclusion, behavioural differences were detected by on-animal sensors associated with greater supplement intake. The adoption of sensors for continuous monitoring enhances nutritional, grazing, and reproductive management in extensive rangelands, supporting better decision-making about target supplement intake and improving grazing behaviour and pasture utilisation.

Introduction

The Australian beef production operations are predominantly pasture-based, with grazing cattle facing challenges such as fluctuating pasture quality and quantity during the dry season, mineral deficiencies in the soil, and unpredictable rainfall that affects forage availability. To address these challenges and minimize production losses, supplemental feeds are often provided during the dry season to supply essential proteins, minerals, and energy (Bowman & Sowell, 1997). However, the effectiveness of supplementation relies on animals consuming the target amounts. In recent years, precision livestock management has emerged, allowing producers to monitor the health, welfare, and productivity of animals in near-real-time. On-animal sensors are central to this approach, enabling continuous, remote monitoring of livestock behaviour 24/7. These sensors, attached directly to the animal, can record a range of behaviours, offering valuable insights for managing extensive cattle systems. This study aims to integrate three types of on-animal sensors—a wireless ear tag, a rumen bolus, and a GPS tracking collar—to monitor behavioural changes in grazing cattle in response to varying levels of individual supplement intake. We hypothesize that these sensors can detect behavioural adaptations to different supplementation levels.

Methods

The study was conducted from September 20 to December 13, 2022, at the University of Queensland, Gatton, Australia. Fourteen Droughtmaster heifers, aged 11-13 months (average weight: 268 ± 32.7 kg, range: 194-320 kg), were allocated to a 10.11 ha paddock with unimproved pasture African star grass *(Cynodon nlemfuensis Vanderyst)* at 85% coverage and Queensland blue grass (*Bothriochloa pertusa*) and provided mineral and protein supplements for 12 weeks. The experiment was divided into two periods. During period 1 (days 1-42), heifers were offered a low-intake supplement (target: 300 g/head/day) containing 12% crude protein, 5% urea, and 5 MJ/kg energy (PBA Feeds, Toowoomba, Qld). In period 2 (days 43-85), they received a high-intake supplement (target: 1000 g/head/day) with 19% crude protein, 4% urea, and 8 MJ/kg energy (PBA Feeds, Toowoomba, Qld).

Each heifer was fitted with three on-animal sensors: 1) Wireless ear tags (WelfareTag™, HerdDogg) with Bluetooth technology recorded the animal's presence and the received signal strength indication (RSSI). A threshold of ≥ -50 dBm was used to predict time spent at the feed trough, based on prior studies(reference if appropriate); 2) GPS tracking collars (i-gotU GT-600) recorded the heifers' positions at 10-second intervals to monitor grazing patterns and classify heifers' activity; and 3) Rumen boluses (SmaXtec® Classic) recorded temperature, oestrus index, rumination rate, and water intake, with a temperature drop below 38°C indicating drinking events. The classification of cattle activity into three different categories – grazing, resting, and travelling – was based on the criteria established by Augustine and Derner (2013). Data were collected over 85 days. A linear mixed-effects model ('lmer') in R (version 4.3.1) was used for statistical analysis of the longitudinal data with repeated measures.

Results

Wireless ear tag

During period 2, heifers spent an average of 8 minutes at the feed trough, compared to 4.5 minutes in period 1, representing a 1.7-fold increase ($p < 0.001$). This indicates a significant increase in supplement consumption during the second period (Table 1).

GPS tracking collar

Grazing activity was higher in period 1 (21.37%) than in period 2 (17.37%), but this reduction in grazing time was not statistically significant (Table 1, $p > 0.1$). When comparing the two different periods, it was found that the resting time in period 1 (69.18%) was lower than in comparison period 2 (77.62%), however that difference was not significantly different (Table 1, $p > 0.1$). Travelling time was increased in period 2 (3.57%) compared to period 1 (2.85%), this difference was significantly different (Table 1, $p < 0.01$). Additionally, there was a statistical difference in travel time between the two periods ($p < 0.01$), with heifers in period 2 travelling 0.54% more than during period 1.

Rumen bolus

The results showed that there was a significant (Table 1, $p < 0.05$) increase in the heifers' reticulo-rumen temperature by 0.12°C in period 2 compared to period 1. During period 1, the average reticulo-rumen temperature was 39.08°C, while in period 2 it was 39.17°C. The rumination index of heifers showed no significant difference in response to the two different supplement target intake (Table 1, $p > 0.1$). Although the average rumination index in period 1 was 26,6540 and in period 2 it was 27,734, it was found that the increase between the two periods was not statistically significant ($p > 0.1$). The oestrus index had a significant influence on the two different periods. The results showed that heat index increased significantly (Table 1, $p < 0.001$) from period 1 to period 2. In period 1, the average oestrus indicator was 3.19 units, while in period 2 it decreased to 2.35 units. The heifers in period 1 had a higher oestrus index on the day of oestrus than in period 2. In Period 2, heifers under the higher supplement intake had a lower average of oestrus index. The results for the cumulative number of water-drinking events per day showed a significant increase of 1.64 in period 2 compared to period 1 (Table 1, $p < 0.001$). During period 1, the average cumulative water drinking events per day was 3.17, while in period 2 it increased to 5.23.

Table 1 contains detailed data on the difference in measured behaviours: time spent at the feed trough, grazing time, resting time, travelling, rumen temperature, rumination index, heat index and counts of water drinking events, between the two periods.

Table 1 Difference in measured behaviours using on-animal sensors between the 2 periods.

Behaviours measured	Period		SEM	P-value
	1	2		
Time spent at the feed trough (min)	4.5	8.0	0.46	<0.001
Grazing time (%)	20.37	17.37	1.07	0.08
Resting time (%)	69.18	77.62	1.05	0.09
Travelling time (%)	3.06	3.60	0.09	0.002
Rumen temperature (°C)	39.08	39.17	0.02	0.015
Rumination index[1]	26654	27734	721	0.29
Oestrus index[2]	3.19	2.35	0.15	<0.001
Counts of water-drinking events	3.17	5.23	0.27	<0.001

[1]Measures rumination times every 10 minutes. [2]Dectects heifer on oestrus based on behaviour changes.

Discussion

Supplemental feeding is a common strategy to enhance the performance of grazing beef cattle. However, traditional herd-based monitoring of supplement intake often overlooks individual variability in consumption and may not account for animals that do not consume the supplement (Bowman & Sowell, 1997). Precision livestock management can provide continuous near-real-time monitoring on an individual animal basis, rather than via herd-based information (Aquilani et al., 2022). In this study we combined the use of three on-animal sensors to continuously monitor 14 heifers, revealing significant insights into cattle behaviour and supplement intake.

The wireless ear tag recorded the predicted time spent at the feed trough, with cumulative counts of RSSI ≥ -50 dBm indicating that time at the trough increased by 1.8 times during the second period, which featured a more palatable supplement. This second supplement had nearly double the metabolisable energy (8 MJ/kg vs. 5 MJ/kg) and a higher protein content (30% vs. 26%), which likely contributed to its enhanced palatability and voluntary intake (Launchbaugh et al., 1997; McDowell, 1996). Previous research (Imaz et al., 2020, p. 8; Nkrumah et al., 2007, p. 2388; Oliveira et al., 2018, p. 634) has demonstrated that time spent at the feed trough has a strong positive correlation with feed intake. Our results are consistent with the previous work cited above and show that as the palatability of the supplement increases, the voluntary intake and predicted time spent at the feed trough also increase.

Our results showed that increased time at the feed trough corresponded with a reduction in grazing time, particularly during the second period, when the supplement provided an intake target of 1 kg/day per head. This decrease in grazing time is consistent with literature indicating that high-protein supplements can reduce grazing activity (Bargo et al., 2003). This effect is likely due to the substitution effect, where providing a higher amount of supplement reduces pasture intake and, consequently, grazing time. Bargo et al. (2003) reported that for each kilogram of supplement offered to grazing dairy cows, there was a reduction of 12 minutes in grazing activity.

The heifers averaged 72.44% and 77.62% resting time during periods 1 and 2, respectively, supporting previous observations that grazing cattle often exhibit significant inactivity (Swain et al., 2008). Additionally, we noted a statistically significant increase in travel time during the hotter second period, likely due to the heifers seeking shade, which was located 400 m from the feed trough. Period 2 was, on average, 4°C hotter than period 1, with maximum temperature ranging from 21.3°C to 37.6°C. The heifers displayed higher reticulo-rumen temperatures during period 2 (39.18°C) compared to period 1 (39.06°C). This increase may result from the animals' inability to dissipate sufficient metabolic heat (Becker et al., 2020) and the higher energy content in the feed, which also contributed to the increased rumen temperature in period 2. Kurihara (1996) also observed an increase in body temperature and respiration rate in dairy cows when comparing a low to a high-quality diet.

During the trial, the heifers were in oestrus for five days out of 50 in period 1 and two days out of 35 in period 2. Notably, predicted time spent at the feed trough decreased during oestrus ($p < 0.001$), corroborating findings by Reith et al. (2014) that report a 14.6% reduction in intake on oestrus days. The cumulative number of water drinking events also significantly increased by 1.64 times in period 2 ($p < 0.001$), suggesting that the heifers were compensating for heat stress by increasing water intake. Ahlberg et al. (2018) found that the water intake in feedlot steers increased when they were exposed to temperatures above 28.06°C. Weather conditions, particularly maximum temperature, significantly impacted the time spent seeking shade. The heifers spent an average of 18.42% of their time in the treed area during period 2, compared to only 6.18% in period 1.

In summary, this study confirmed the efficacy of on-animal sensors in monitoring individual cattle behaviours that affect supplement intake. The combined use of these technologies facilitated a nuanced understanding of how supplement consumption, grazing time, and environmental factors interact. Future research with larger herds and varying supplement types is recommended to further validate the applicability of on-animal sensors in pasture-based systems.

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A quick meal plate index and its use as a decision-making tool for ranchers

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Key words: grass allowance, forage balance, extensive production systems, livestock management

Abstract

In Uruguay, the forage base that feeds our herds and flocks is natural grassland. Research in the last 20 years has shown the importance of working with a greater proportion of grass to improve animal performance and make our systems more resistant and resilient to climate change. However, to date there has been no tool that allows for simple grass budgeting that can be used by livestock ranchers without major complications. With this objective, an index called the "Meal Plate Index" (MPI) has been developed in collaboration with ranchers, which, by estimating forage availability by measuring it with a ruler and comparing it with forage requirements by category, objective and season, allows us to know how well we are doing with grass in relation to the productive objectives we are trying to achieve. In practice, the difficulty is in making the grass field measurements. For this reason, and to move towards general application, a simplified version has been developed which, by means of visual estimation with self-calibration of the height of the sward and calculation of the stocking rate of the farm, can quickly and easily provide an estimate of how full the feed plate is that the animals need. The MPI tool, in both its regular and "quick" versions, was compared against external information provided by a national ranchers' network. The tool was adjusted to account for average and extreme forage conditions (both scarcity and excess) during its development and testing phases. The impact of using this simplified tool will improve the performance of ranching systems and for our national herd.

Introduction

Uruguayan livestock farming is one of the main economic and land use activities (Paparamborda et al. 2023). The primary source of food for livestock on ranches is the native grassland, which is a heterogeneous resource, both in the seasons of the year (e.g. forage species and grazing management) and between years, due to climatic effects (Modernel et al. 2016). In this context, the Instituto Plan Agropecuario (IPA 2024) is the national extension agency for extensive producers, where it works with ranchers and other stakeholders on relevant issues for livestock production systems (Durate & Dieguez 2023). The IPA's activity is focused on extension activities, workshops and projects with producers and training activities on relevant topics for livestock production. Particularly, it is of interest to work in a participatory manner with the forage assignment at native grasslands in livestock production systems (Durate & Dieguez 2023). This issue is more relevant in open-air systems, dependent on variable and extreme weather conditions. Adaptive management (Darnhofer et al. 2010) is important in a context of climate change, to enhance production systems resiliency in participative processes (Dumont et al. 2020). Likewise, it is of interest of IPA to generate quick tools for diagnosing of feed offered and required to help decision making about the actual and projected stocking rate and animal allocation. The estimation of forage availability and animal demand, as key factor of system productivity (Paparamborda et al. 2023), are crucial issues that can be implemented with the use of new information and communication technologies local and international impulse (MGAP 2024, UN 2024). In this work is presented a methodology which the "Meal Plate Index" (MPI) was participatively developed, and further development for a "quick MPI", as prototype of an online decision-making tool.

Methods

The MPI tool was developed within IPA participative project, where 18 ranches participated in 8 field workshops by farm (one by season in a 2-year period). The MPI consists of the ratio between forage allowance and animal requirements (Duarte & Dieguez 2023).

In the first version of MPI, a spreadsheet with inputs like animals' number by category to calculate dry matter requirements, and paddocks grass height (GH) was developed. The GH was converted to DM offering by hectare using seasonal constants (250, 220, 250 and 215 kg DM/cm/ha for autumn, winter, spring and summer respectively; Duarte & Dieguez 2023). In those sessions training of farmers to data gathering, GH measurement skills, data input and results interpretation was carried out. To define cattle requirements, average forage availability was established according to the category and season (see Table 1). Also Stocking Rate (SR) was calculated using national definition of Gross Unit by hectare (GU/ha), being 1 GU the requirements of DM of a breeding cow with 380 kg of LV, that weans a calf by year (Berreta & do Nascimento 1991).

Table 1: Average forage allowance for cattle category by season expressed in kg DM by kg of liveweight (LW; Do Carmo et al. 2019).

Category	Autumn	Winter	Spring	Summer
Growing cattle (<300 kg LW)	3	3	2	3
Fattening cattle (>300 kg LW)	5	9	5	5
Breeding cows	5	4,5	6	5

In workshops instances, animals, paddocks and feed management information was discussed with stakeholders, according to MPI values. Some relevant workshops activity included the discussion with focus group of ranchers, analyzing together a particular farmer case, to achieve the adjusted SR (farm carrying capacity; Paparamborda et al. 2023) to cope climatic issues like drought episodes. To visualize results of MPI, ranges were defined values like a traffic light where values less than 0,6 had red color, ranges between 0.6 and 0.8 had yellow color, ranges between 0.8 and 1.2 had green color, and ranges more than 1.2 had brown color. These traffic light colors represent forage availability, but last range (>1.2) reflect a forage surplus with loss of quality, linked with pasture digestibility. In field workshops, ranch owners received other farmers in those activities, where seasonal field GH measurements, SR and MPI calculations were made, and finally discussions round were held to clarify grass and cattle management options to improve MPI, particularly in situations with values < 0.8. In other cases, where MPI was acceptable, success factors that explain results were also discussed inside focus group.

As a benchmark for tool use, MPI results were compared with external data from the farmers' information-sharing network, which provides monthly updates on grass availability, climate conditions, and cattle status (RING 2024).

Since, in the development and validation processes some issues were detected on data gathering (mainly pasture objective measurements with a ruler), further development was made towards an easier decision-making tool. A "quick MPI" was developed using a two-entry table, presented in the next section.

Results

Table 2 presents MPI values for autumn and for breeding cows. Since several categories and paddocks combinations can be considered, infinite tables can be presented. Table 2 must be read as an example of a particular situation.

Table 2: MPI values for breeding cows in autumn in a double-entry table format.

	SR (GU/ha)							
GH (cm)	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2
2	0.6	0.5	0.5	0.4	0.4	0.3	0.3	0.3
3	1	0.8	0.7	0.6	0.5	0.5	0.4	0.4
4	1.3	1.1	0.9	0.8	0.7	0.6	0.6	0.5
5	1.6	1.3	1.1	1	0.9	0.8	0.7	0.7
6	1.9	1.6	1.4	1.2	1.1	1	0.9	0.8
7	2.2	1.9	1.6	1.4	1.2	1.1	1	0.9
8	2.5	2.1	1.8	1.6	1.4	1.3	1.2	1.1
9	2.8	2.4	2.1	1.8	1.6	1.4	1.3	1.2

During project execution, farms with a "yellow" zone had lower forage supply than required and reduced their SR (e.g., selling culled cows) to transition to the "green" zone. Farms in the "green zone" could retain animals, sell tactically, and reserve paddocks while maintaining their status. Farms with a "brown light" used strategies like fattening culled cows and excluding paddocks for autumn reserves to transition to the "green" zone. However, these conditions, typical of prior spring-summer seasons, have been absent in several regions for years. In 2022/2023, a severe drought caused very low forage availability by autumn 2023 (INIA-GRAS 2024). Farms reduced SR (0.5–0.7 LU/ha), pasture heights rarely exceeded 4 cm, and MPI values were in "red" and "yellow" zones. Key tactical measures included selling animals, leasing land, and importing feed. Autumn paddock reserves for winter were not feasible, creating a winter forage deficit despite rainfall recovery. In 2023/2024, abundant rainfall (INIA-GRAS, 2024) led to record pasture growth in spring-summer and high forage availability by autumn 2024, with pasture heights of 7–10 cm and most MPI values in "brown" and "green" zones. Farms increased SR through animal retention, grazing sparse paddocks, and early protein supplementation. Strategic autumn reserves were unnecessary, as pastures maintained high heights, ensuring favorable winter forage conditions.

Discussion and Conclusions

Forage allowance is a key factor in improving the productive performance of systems (Do Carmo et al. 2019). In Uruguay, technical options to enhance productive and reproductive efficiency are well-known, a recent study by Paparamborda et al. (2023) indicates that producers often do not adopt these technologies due to various reasons. Molina & Álvarez (2009) argues that non-economic factors are associated with decision-making and determine technological changes. In this context, participatory work with producers is an appropriate and well-valued tool, where peer-to-peer knowledge exchange is productive (Do Carmo et al. 2019, Paparamborda et al. 2023). Furthermore, according to evaluations conducted during workshops in this study, the objective of peer exchange was achieved through the development and application of the MPI. This index, which is easy to implement, facilitates pasture monitoring and forage allocation for livestock. During workshops where MPI was applied, discussions extended beyond production objectives, encompassing the broader goals of the family-farm system. Various technical alternatives were outlined to improve outcomes and achieve specific goals. The MPI's design aligns in some aspect with the co-innovation approach (Paparamborda et al. 2023), encompassing three domains: social learning, monitoring and evaluation dynamics, and complex adaptive systems.

On the other hand, Carballo & Severi (2024) highlight that even forage is crucial for livestock production systems, pasture measurement is not a common practice among producers. This motivated the creation of a Quick MPI, where training the eye to estimate pasture height, alongside SR estimation, simplified situational diagnostics. MPI is a situational index where low values may result from below-normal pasture growth in previous seasons (e.g., due to lower rainfall) or from excessive forage demand caused by overstocking. Identifying the "why" is the first step in discerning potential solutions.

The MPI tool, in both its regular and “quick” versions, was compared against external information provided by a national ranchers' network called RING (RING, 2024). The tool was adjusted to account for average and extreme forage conditions (both scarcity and excess) during its development and testing phases.

The workshop environment facilitated the development of MPI, reflection, identification of alternatives, actions, and learning. This space for co-creation of knowledge accelerated adaptation processes for managing in uncertain and changing environments. In this regard, the MPI tool enhances group discussions by situating participants in the real-world context of their situation. When producers recognize they have a problem, it initiates technical change dynamics as they seek more information, plan alternatives, and select a course of action. Currently, a mobile application for Quick MPI is being developed, featuring simple data input (e.g., category, number and weight of animals, and pasture height by paddock). The goal is to scale this tool to a broader audience.

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Quantifying ecosystem services: A conceptual framework for regenerative agriculture in Western Australia's rangelands

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Key words: Ecosystem services; net primary productivity; remote sensing; machine learning; InVEST model

Abstract

Rangelands and pastoral systems play vital roles in biodiversity conservation, carbon sequestration, and supporting livelihoods. However, their vast and heterogeneous landscapes pose significant challenges for assessing and managing ecosystem services (ES). This study aimed to develop a comprehensive framework to quantify the impacts of regenerative agriculture (RA) practices within these ecosystems, focusing specifically on Western Australia's rangelands. These practices offer a sustainable approach to enhancing ecosystem resilience, yet their effects on ES remain underexplored. The framework integrates the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model, remote sensing technologies such as high-resolution satellite imagery, and machine learning (ML) techniques. These methodologies systematically map and assess key ecosystem services across different spatial scales, including provisioning (e.g., net primary productivity (NPP)), regulating (e.g., water dynamics), cultural (e.g., habitat quality), and supporting services (e.g., soil health). Using field and climate data from 2000 to 2023, along with satellite indices (NDVI, LAI), were used to calculate Photosynthetically Active Radiation (PAR) and Fraction of PAR Absorbed (FPAR), which are crucial for estimating Net Primary Productivity (NPP). Advanced ML algorithms, including Random Forest and Neural Networks, are employed to predict key ecosystem services. The framework supports the simulation, evaluation, and optimization of regenerative agriculture practices, thereby enhancing ecosystem resilience and promoting sustainable rangeland resource management. Forecasting ecosystem values in monetary terms, especially under regenerative agriculture scenarios, equips policymakers with tools to assess policy outcomes and advance sustainable land management in rangelands and pastoral systems. Despite its capabilities, persistent challenges such as data availability, the nuanced and context-specific nature of regenerative agriculture scenarios, and ethical considerations—such as community involvement in data collection—are critical for successfully implementing the framework.

Introduction

Rangelands, which cover approximately 40% of Earth's terrestrial surface, provide essential ecosystem services (ES), including biodiversity conservation, carbon sequestration, water regulation, food, and livelihood support for an estimated 200–500 million pastoralists worldwide (Alkemade et al. 2013; Maestre et al. 2022). In Australia, these vast arid and semi-arid landscapes support Indigenous communities, livestock grazing, and industries such as mining and tourism. However, rangeland ecosystems are increasingly threatened by overgrazing, invasive species, soil erosion, and climate variability, resulting in significant degradation (Gemechu and Dalle 2023). For example, 44% of grazing lands in northern Australia show signs of degradation, which compromise their ecological and economic functions, including the capacity to sustain biodiversity, store carbon, and maintain soil and water quality (Nielsen et al. 2020).

Regenerative agriculture (RA) presents a promising solution for restoring degraded rangelands (Khangura et al. 2023). Practices such as rotational grazing, greater tactical adjustment of carrying capacity (e.g. livestock sales, use of irrigated pasture systems), and landscape rehydration aim to restore soil health, improve water retention, and enhance biodiversity by fostering more diverse and resilient ecological systems (Jayasinghe et al. 2023; Lal 2020). However, assessing the impacts of RA on ES—such as carbon sequestration, biodiversity enhancement, and water retention—is complex due to the spatial and temporal variability inherent in rangeland ecosystems. Traditional assessment methods, including low-resolution remote sensing and qualitative surveys, lack the precision and scalability needed for effective evaluation (Kabir et al. 2020).

This study aimed to develop a conceptual modelling framework that integrates remote sensing (RS), Geographic Information Systems (GIS), and machine learning (ML), to assess the impacts of RA practices on ecosystem services in Western Australia's rangelands. By incorporating models such as Carnegie-Ames-Stanford Approach (CASA) and Integrated Valuation of Ecosystem Services and Trade-offs (InVEST), the framework facilitates precise, scalable, and localized assessments of ecosystem services. This approach provides detailed spatial and temporal data tailored to the unique conditions of rangeland ecosystems, addressing critical gaps in current methodologies. Ultimately, this research will offer actionable insights for sustainable rangeland management, enabling land managers and policymakers to make informed decisions that promote the long-term ecological and economic sustainability of rangelands.

Methods

A literature review identified key ES relevant to rangelands, such as soil organic carbon (SOC), water retention, and biodiversity, which were selected for their ecological and practical significance (Mashizi et al. 2019). These ES were chosen to assess the effects of RA practices, including rotational grazing, tactical stocking adjustments, landscape rehydration, and soil management (Jordon et al. 2022). Western Australia's rangelands were selected for their ecological importance, challenges related to land degradation, and representation of arid and semi-arid climates, enhancing the broader applicability of the framework. The framework applies RS, GIS, ML algorithms, and biophysical models to assess ES and link them to RA practices:

Ecosystem services assessment: High-resolution satellite indices (e.g., NDVI, LAI), combined with field data (e.g., soil properties, vegetation biomass), are used to monitor spatial and temporal variations in key ES indicators. The CASA model estimates Net Primary Productivity (NPP) to quantify vegetation growth and carbon fluxes. The InVEST model, in conjunction with ML algorithms, assesses carbon sequestration, water retention, biodiversity, and soil health. ML algorithms, and biophysical models (e.g., CASA, InVEST). All datasets are., RS data from Sentinel-2 and MODIS, harmonized for spatial and temporal consistency, serve as the foundation for ES mapping across rangelands.

Linking RA to ecosystem services: The effects of RA practices, such as rotational grazing and landscape rehydration, on ES are quantified using GIS and biophysical models. Changes in SOC, soil health, and water retention resulting from RA practices are mapped and analysed.

Model validation: Model outputs are compared with field-measured data (e.g., vegetation biomass, SOC), while uncertainty is assessed using Monte Carlo simulations and sensitivity analysis. This iterative process ensures robustness and adaptability to varying management practices and climatic conditions.

Results

The conceptual framework was developed to quantify key ES and assess the impact of RA practices on Western Australia's rangelands (Figure 1). The case study region will be selected based on its ecological significance and the ongoing implementation of RA practices. This approach highlights how RA practices, such as rotational grazing and landscape rehydration, contribute to the enhancement of ES and the resilience of ecosystems. The framework is currently in the conceptual stage, with full implementation planned for future studies.

Ecosystem service quantification

Carbon sequestration is estimated through both aboveground and belowground biomass, with NPP serving as the basis for SOC estimation (Lal 2004). RA practices, like rotational grazing, are expected to improve carbon storage by increasing SOC. Water retention is evaluated using a soil water balance model, integrating InVEST-driven evapotranspiration and water availability (Su et al. 2020). Improved soil health through RA practices like soil rehydration enhances water retention, which contributes to ecosystem resilience. Biodiversity is assessed using diversity indices (e.g., Shannon and Simpson), which are linked to NPP and floral density (Pla et al. 2011). RA practices are anticipated to increase biodiversity by promoting diverse plant communities. Soil health is evaluated by measuring soil organic matter, nutrient cycling, and improvements in soil structure (Doran et al. 1994). Soil health is a key indicator of RA’s success in promoting sustainable land management. Soil erosion is modelled using the Revised Universal Soil Loss Equation (RUSLE) (Renard 1995), while pollinator activity is inferred from NPP-driven floral density (Tylianakis et al. 2008). Greenhouse gas (GHG) mitigation is quantified by CO_2 sequestration and reductions in CH_4 and N_2O emissions (Joyce et al. 2013). GHG mitigation is enhanced by RA practices that improve carbon sequestration and reduce emissions from soil disturbance.

Visualization and trend analysis

The InVEST model and ML algorithms, including Random Forest (RF) and Convolutional Neural Networks (CNN), are employed to upscale ES metrics across larger spatial and temporal scales. High-resolution satellite imagery, in conjunction with field surveys, improves the accuracy of predictions and captures spatial heterogeneity (Burke et al. 2021). Tools such as Google Earth Engine and ArcGIS are used for spatial mapping and trend analysis to evaluate seasonal and long-term ES dynamics under varying climatic conditions.

Current status and future work

While still in the conceptual phase, the framework is designed to enable the spatial and temporal mapping of ES, allowing for future scenario evaluations and sensitivity analysis.

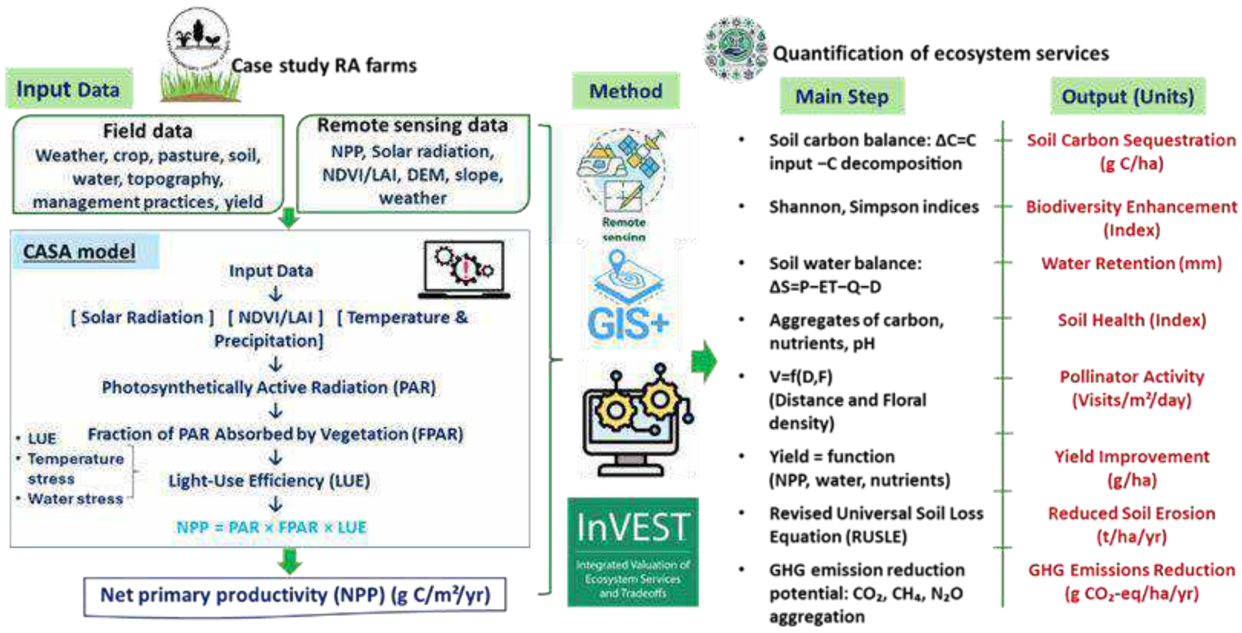

Figure 1. Conceptual framework for evaluating ecosystem services of regenerative agriculture in rangeland systems

Discussion

This study proposed a novel framework for assessing the impact of RA on ES in Australia's rangelands. By integrating RS, biophysical models, and ML, the framework enhances precision compared to traditional methods by accounting for regional variability and enabling scalability across landscapes (Kabir et al. 2020).

The selected ES—SOC, water retention, and biodiversity—are essential for ecological stability and effective land management. SOC plays a critical role in soil fertility and climate mitigation, while water retention contributes to climate resilience. Biodiversity, assessed through diversity indices, supports habitat quality and pollinator populations, both of which are vital in rangeland ecosystems (Lal 2004; Su et al. 2020; Pla et al. 2011). Previous studies (e.g., (O'donoghue et al. 2022; Jayasinghe et al. 2023) confirm the relevance and quantification potential of these services in RA systems, providing a strong basis for their inclusion in this framework. The framework directly informs RA decision-making by quantifying the impact of interventions on key ES. For example, rotational grazing can be evaluated for its effect on SOC and biodiversity through changes in NPP and species diversity indices. Tactical adjustments to carrying capacity, such as managing stocking rates or utilizing irrigated pastures, can be assessed for their influence on water retention and carbon storage across varying climatic and land-use scenarios. Landscape rehydration practices can also be linked to water retention improvements via soil moisture dynamics analysis from high-resolution remote sensing data.

The framework employs NPP to quantify carbon sequestration and link it to broader ecological processes. The CASA model estimates NPP using satellite and field data, providing regional estimates and addressing local variability (Zhu et al. 2017). This allows for region-specific customization, improving ES prediction accuracy by accounting for local environmental and land-use variability. The integration of ML algorithms, such as RF and CNNs, enhances the model's ability to capture complex, non-linear relationships, addressing landscape heterogeneity. These techniques have proven effective in ecological monitoring (Liu et al. 2018).

By integrating these tools, the framework helps land managers prioritize RA interventions based on their benefits and trade-offs, maximizing ES outcomes while considering landscape variability and resource availability. It can guide decisions on rotational grazing, soil health, and water retention strategies tailored to local conditions.

While the framework offers significant advantages, challenges remain, particularly regarding data quality and model uncertainty. Reliable field data is critical for model calibration, while uncertainty analysis—incorporating sensitivity and Monte Carlo simulations—addresses potential sources of error (McFarland et al. 2008). Successful implementation of the framework also hinges on collaboration with land managers and policymakers to ensure its practical applicability across diverse rangeland ecosystems. Despite these challenges, the integration of high-resolution data, advanced modelling techniques, and stakeholder engagement positions this framework a powerful tool for sustainable land management. It provides a solid foundation for evaluating RA interventions and enhancing ecosystem services in rangeland environments, offering valuable insights for land managers and policymakers.

Conclusion

This study proposed a comprehensive framework to assess the impact of RA on multiple ES in Western Australia's rangelands, including SOC, water retention, biodiversity, soil health, soil erosion, and pollinator activity. The framework integrates RS, biophysical models (CASA, InVEST), and ML techniques to quantify these services with high precision and scalability. It uses NPP as a key input in the InVEST model to estimate other ES. Despite challenges related to data quality, model calibration, and uncertainty, the framework provides valuable tools for optimizing RA practices, supporting sustainable rangeland management, and enhancing ecosystem resilience.

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Predicting drought using remotely sensed vegetation cover

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Key words: Drought; Destocking; Decision Trigger; Groundcover.

Abstract

In Australia, land degradation caused by wind erosion and dust storms often occur during drought when vegetation cover is low. Destocking early is a critical management action that can reduce soil erosion; however, predicting drought to inform producer decisions regarding destocking is a complicated task. In Australia, drought is determined by several indicators, such as rainfall deficiencies, soil water, pasture growth, water availability, agricultural production, and community impact. Many of these indicators influence total vegetation cover (denoted as cover), which includes photosynthetic and non-photosynthetic cover.

This study uses a 22-year record (2001-2022) to investigate if a "trigger point", i.e., the month and cover level, can be identified that would potentially inform destocking four to six months before a drought cover (<20th percentile minimum monthly cover in summer) is reached. Twenty-four properties in western NSW rangelands were evaluated to determine the trigger month and trigger cover. The trigger month was August for 83% of properties. The drought cover ranged from 60% to 25%. The trigger cover ranged from 70% to 35%. Over the 22 years, 22% of years recorded drought cover. The method correctly predicted 80% of years with drought cover, i.e. those years below the trigger cover that had drought cover the following summer. The method failed to predict drought in six percent of years. In six percent of years, it predicted drought, but no drought occurred. The study demonstrates the practical application of a new tool to help land managers prepare for drought.

Introduction

Degradation of soils and vegetation is highly undesirable (Duniway *et al.* 2019). According to the United Nations Convention to Combat Desertification definition, land degradation can be caused by both human and climate factors (UNCCD 1994). Drought alone does not cause land degradation; the major cause is carrying too many animals for too long (McKeon *et al.* 2004). Maintaining cover is key to avoiding land degradation. Pasture production is low in drought, and ground cover declines, especially when stock numbers exceed the forage available and soil erosion increases. It has long been recognised that preventative early warning before the onset of drought would help land managers reduce livestock and unmanaged herbivore numbers before total vegetation cover (denoted as cover), which includes photosynthetic and non-photosynthetic cover, is reduced to levels that enable soil erosion (Childs 1973; McKeon *et al.* 2004; O'Reagain 2011). McKeon et al. (2004, p.22) state, "it is hard to imagine that any manager, if forewarned of a potential degradation event, would take the risk of animal losses, financial cost, and environmental damage by not reducing stock numbers early". However, knowing when to destock, referred to as a decision trigger, is a significant challenge that many authors have identified (Ratcliffe 1938; Condon 1992; McKeon *et al.* 2004; Hacker *et al.* 2010).

Accurately predicting the onset and termination of droughts is a major deficiency in drought prediction (Mishra and Singh 2011) because drought is a continuum (Van Loon *et al.* 2024). Several drought monitoring services exist in Australia, each providing information to assist decision-making. The Bureau of Meteorology (BoM) website has an interactive Australian Water Outlook tool (https://awo.bom.gov.au) with information on soil moisture, runoff, evapotranspiration, deep drainage, and precipitation. It also has a dedicated Drought page (http://www.bom.gov.au/climate/drought/) with information on rainfall deficiencies, soil moisture, water, and rainfall forecasts.

In New South Wales (NSW), the Department of Primary Industries and Regional Development (DPIRD) publishes an interactive tool called the Combined Drought Indicator (https://edis.dpi.nsw.gov.au/). It utilises the Rainfall Index (RI), Soil Water Index (SWI), Pasture Growth Index (PGI), and Drought Direction Index (DDI) with a multi-index approach. It tracks the onset (e.g. drought affected (intensifying)), duration and retreat of large drought events.

In the United States, the U.S. Drought Monitor (USDM) (https://droughtmonitor.unl.edu/) provides weekly maps of normal conditions, abnormally dry (D0), showing areas that may be going into or are coming out of drought, and four levels of drought: moderate (D1), severe (D2), extreme (D3) and exceptional (D4). It uses multiple data sources of streamflow, reservoir levels, temperature and evaporative demand, soil moisture, and vegetation health and blends this with drought impacts, field observations and local insight from a network of more than 450 experts.

This study aims to reduce soil erosion and land degradation by using satellite fractional vegetation cover data as a metric to set a decision trigger month and estimate the trigger cover (TC) level below which destocking should be considered for grazing properties in western NSW. Decision triggers (trigger) are designed to link cover data in this paper to a management action, i.e., consider destocking (Cook *et al.* 2016). Two triggers are presented: 1) the time of the trigger so management can be adapted, and 2) the cover threshold, i.e. a visual cue for the trigger, four to six months ahead of the drought.

Methods

Cover changes every month, and the ranges in cover change from property to property. As a result, each property is assessed for 1) which winter month is the best trigger, i.e. correlates with the following summer cover, 2) how many times the drought cover, that is, the cover measured in previous droughts since 2001 and defined as the 20th percentile of the 22-year monthly time series (DC) and how many times TC was recorded for the property over the 22 years, and 3) how many years were both TC and DC observed.

For 24 properties in the semi-arid rangelands of western New South Wales, Australia, a 22-year time series of monthly green (photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV) and total vegetation cover (cover) for each property at 500m resolution was extracted from GEOGLAMM RaPP (hereafter called RaPP) (CSIRO 2024).

Drought cover, rounded to the nearest 5%. This coincided with the Millennium Drought (2002-2009) and the Tinder-box drought (2017-2020). The DC level was determined for each of the 24 properties. The trigger month, i.e., the month in winter that can predict DC the following summer, was determined using linear regression (E 1) for each winter month (June/July/August) cover (WC) against the month with the minimum summer cover (December/January/February) (MSC).

MSC= a WC – b
(1)

Where a is the slope and b intercept of El 1.

The TC, i.e., the level of cover in the trigger month below, which predicts DC the following summer, was determined using a regression equation for August for each property to calculate the DC (Eq 2).

TC= DC -b) / a
(2)

Using the exact rounded TC, e.g., 65%, and DC, e.g., 50%, ignores errors in the estimates of the values. In determining if TC or DC occurred in any month, we added a tolerance of 2.5%. This value was chosen because it is half the possible rounding error. For example, if the measured WC was 67% and the TC was ≤ 65%+2.5%, the TC was said to have occurred. Similarly, if the MSC was 51%, and DC was ≤ 50%+2.5%, the TC was said to have occurred.

Years with DC and TC were counted for each property. The 'Prediction of Drought" model (PoD) was said to work when the TC and DC conditions were met. PoD performance was calculated by counting PoD years and dividing by the DC years (Table 1). Errors in the model were assessed as follows: yearly counts of no trigger measured, but DC occurred in summer, and the trigger was measured, but no DC occurred.

Results

The results of the fractional cover time series analysis successfully identified the DC, the TC, and the TC month for each property. The values were different for each property. August had the highest coefficient of determination (R2), with 83% of properties, July 12%, and June 4%. For simplicity, August was chosen as the trigger month for all properties. TC ranged from 35 to 75%, and DC ranged from 25 to 60%. The cover declined, i.e., the difference between TC and DC, 10 to 20%. Properties with low differences were stoney or had tree cover. Properties with large differences were either treeless or sandy country with scattered trees and shrubs.

On average, across the 24 properties, 33% of years between 2002-2022 experienced DC in summer months, while the PoD model predicted DC for 27% of years (Table 1). The primary test was to evaluate if the model could predict TC and DC for a year when DC occurred. To evaluate this test, we divide the years when the PoD model worked (27%) by the DC years (33%). The method correctly predicted 82% of years that recorded DC. The method failed, i.e. no trigger was measured, but DC occurred in six per cent of years; similarly it failed in six percent of years when a trigger occurred, but DC did not.

Table 1. The results for the 22 years, 2002-2022, of the 24 properties in western New South Wales. Results expressed as a percentage of 22 years

	Years when drought cover was recorded (DC) (%)	Prediction of droughts (PoD) (%)	No trigger was measured, but DC occurred next summer (TnDCy) (%)	The trigger was measured, but no DC occurred (TyDCn) (%)
Minimum	23	14	0	0
Maximum	64	64	23	32
Average	**33**	**27**	**6**	**6**

Discussion [Conclusions/Implications]

Remote sensing and modelling are widely used to estimate drought (Mishra and Singh 2011; Vicente-Serrano *et al.* 2020; Fleming-Muñoz *et al.* 2023; Guillory *et al.* 2023). Drought forecasting plays a significant role in risk management and drought preparedness (Mishra and Singh 2011). Landholder discussions have revealed that it is difficult to know when drought is coming because it can be a slow process of change (Van Loon *et al.* 2024). This contributes to the difficulty of recognising the onset of drought and is one reason we have sought to set objective trigger months and cover levels.

This study defines a property-based decision trigger point for when to destock. The aim was to have a month for the decision and a trigger cover level that would indicate that the cover level will likely be lower than that previously measured in drought during summer. The trigger would link to destocking management action to avoid soil erosion. Land managers in western NSW rangelands utilise a range of triggers for destocking, including drought forecasts produced by various agencies, cumulative rainfall, and visually assessing pasture biomass and cover. Some managers have specific months to decide stocking rates based on past experiences and risk determination. The results of this study build on this concept to provide objective property scale metrics.

We calculated the triggers using cover as the metric because cover is closely related to soil erosion. Other drought indices, e.g., rain and soil moisture, are related to vegetation growth and cover but do not describe the cover. Using the cover metric, the analysis found that 32% of years had cover dropping to below DC levels. When PoD is expressed as a percentage of years with DC, the model worked 82% of the time. Increasing the tolerances, currently 2.5%, for TC and DC could improve the PoD model.

Averaged across the 24 properties, DC was measured in 32% of years, and PoD worked in 27% of the 22 years. Of those years when DC was measured, 82% had a predicted TC, and the cover level went to DC levels; that is, the model worked. In this study, destocking too early would have occurred 6% of the time because a trigger was measured, but the cover did not drop to DC levels the following summer. Destocking, in this case, would mean forfeiting production. When discussing the model results with producers in western NSW, one manager said, “You have to own your decision”, and pointed out that this scenario would result in the country getting a rest. The opposite situation of having no trigger and DC occurring the next summer means the model failed to predict the upcoming DC levels, and no management action would be taken. This would result in an increased risk of erosion.

This project demonstrates a trigger method that improves the clarity and transparency of management decisions. The approach can also be applied to paddocks or individual landforms. Cover can be used as an early warning before the onset of drought, which helps maintain cover going into drought.

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A tool for guided state and transition model development based on ecological theory

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Key words: ecosystem dynamics; land degradation assessment; monitoring

Abstract

State-and-transition models (STMs) are ideally suited to provide management and restoration guidance as well as site-specific benchmarks for land degradation monitoring and measurement, monitoring, reporting, and verification for ecosystem service markets. STMs, however, have been difficult to produce with sufficient consistency, utility, and accessibility to serve these functions. To address these problems, we developed the State Transition Classifier and State Transition Atlas tools that guide users through the production of STMs featuring 1) guidance for defining land units based on the maximum spatial extent of an STM, 2) menus for attributing each STM component (i.e. states and elements of transition narratives) with standard, logic-based classes, 3) guidance for structuring STM narrative portions in an efficient and consistent way, 4) guidance for inclusion and interpretation of quantitative indicators and benchmarks, and 5) an online storage and display solution (the Atlas). These tools support collaborative development of STMs at a variety of scales and can be adapted to different classification systems used on rangelands globally. The Classifier and Atlas can facilitate a broad understanding of rangeland ecosystem dynamics by developers, users, and the public at large.

Introduction

Evaluation of land degradation supporting land health and sustainable development goals is an ongoing global challenge (Cowie et al. 2018). There is vast heterogeneity in potential ecosystem conditions and their responses to global change drivers. Unrecognized heterogeneity can lead to incorrect assessment of land degradation and counterproductive responses. For example, afforestation of naturally treeless grasslands, based on the assumption that open ecosystems were deforested at some time in the past, is symptomatic of misidentified land potential (Briske et al. 2024). Furthermore, misidentification of ecological constraints to recovery in true instances of ecosystem transition can accelerate, rather than reverse, land degradation. For example, use of fire or physical removal of woody plants to recover historical grassland degradation in some circumstances can trigger increased soil erosion and worsen land degradation (Karban et al. 2022).

State and transition models (STMs) provide a means to organize scientific information about causes and management of ecosystem transitions according to variations in land potential (e.g. via ecoregions or ecological sites). STMs are used globally for evaluating, mapping, and managing ecosystem services

(Eastburn et al. 2017; Han et al. 2022; Jones et al. 2023; Peinetti et al. 2019; Sato and Lindenmayer 2021). By classifying land areas to discrete states based on ecosystem processes, STMs provide mappable benchmarks for land evaluation. STMs can house qualitative and quantitative information about the consequences of state transitions for ecosystem services. Thus, STMs can play central roles in the measurement, monitoring, reporting, and verification of carbon storage and other processes for ecosystem service markets and climate commitments. Furthermore, STMs can guide restoration investments. Restoration successes and failures can be predicted by variation in soil, climate, and the characteristics of existing vegetation states (Brudvig and Catano 2024).

While many STMs have been developed, the unorganized body of models has several critical limitations, including 1) lack of consistency and accuracy, 2) lack of spatial coverage, 3) vague or incorrect application to specific land areas, and, consequently, 4) limited utility for decision making. Systematic development of STMs is a requirement for databasing STM information and helps to create logical consistency and scientific credibility.

We developed two tools, the State Transition Classifier and State Transition Atlas. The Classifier is a web-based tool to develop STMs using a consistent model structure and choice lists for each STM component. The Atlas is a global database for building and storing STMs linked to spatial data and related information for different ecoregions that is useable by the public.

Methods and Tools

The guided STM format, called the State Transition Classifier, was developed from literature review using terminology for STM components including states, triggers, resilience management (actions affecting the ability of triggers to cause a transition), feedbacks reinforcing alternative state after transitions occur, and restoration practices to overcome specific feedbacks (Bestelmeyer et al. 2017; Suding and Hobbs 2009). Each component is associated with a drop-down list of potential categories, also derived from the STM literature. When logically constructed, this format creates an STM "class" or syndrome. Options for descriptive narratives and data tables are also included for most components to provide region-specific details.

Two web applications were developed. The State Transition Classifier (https://webapps.jornada.nmsu.edu/transition-classifier) is accessible to anyone interested in exploring STM development through an interactive interface. This application encourages users to catalog the changes that can occur within an ecosystem of interest. It displays transitions graphically and lets users assign Classifier categories to diagram components using point-and-click features. Once a set of transitions has been created, users are able to connect these transitions to form a complete STM. Classifier attributes are incorporated into STM diagrams and providing a concise visual summary of the mechanisms that lead to (and potentially reverse) ecosystem transitions.

The Classifier is meant to be a temporary repository of ecological information. It is a place where users can think through ideas about STMs in a non-committal way. Transitions created with the tool are saved in an IndexedDB database on the user's device so that users can return to their work at a later time. Aside from exporting STMs from the tool as JSON documents and graphics (Fig. 1), however, users have no way to share the STMs they create with a broader audience.

We developed a second web application to extend the functionality of the Classifier and facilitate more effective information sharing. With the State Transition Atlas, users can create and characterize ecosystem transitions just as with the Classifier application. In addition, the Atlas provides a place where uses can archive STMs indefinitely, map regions where STMs are applicable, and share STMs with a global audience. Users must register with the Atlas project to publish information to the platform. Published STMs can be either public (i.e., accessible to everyone) or private (accessible only to a group of invited users). Users invited to the platform can be assigned read-only, read-write, or administrative access. Whereas the Classifier is a single-page web application served as a static website, the Atlas requires more sophisticated system architecture. It includes a website, server application, and supporting document database. STM documents exported from the Classifier can be imported seamlessly into the Atlas application. The structure of the Atlas enables future integration with monitoring and other key rangeland management datasets (McCord et al. 2023) to support streamlined assessment and management decision making.

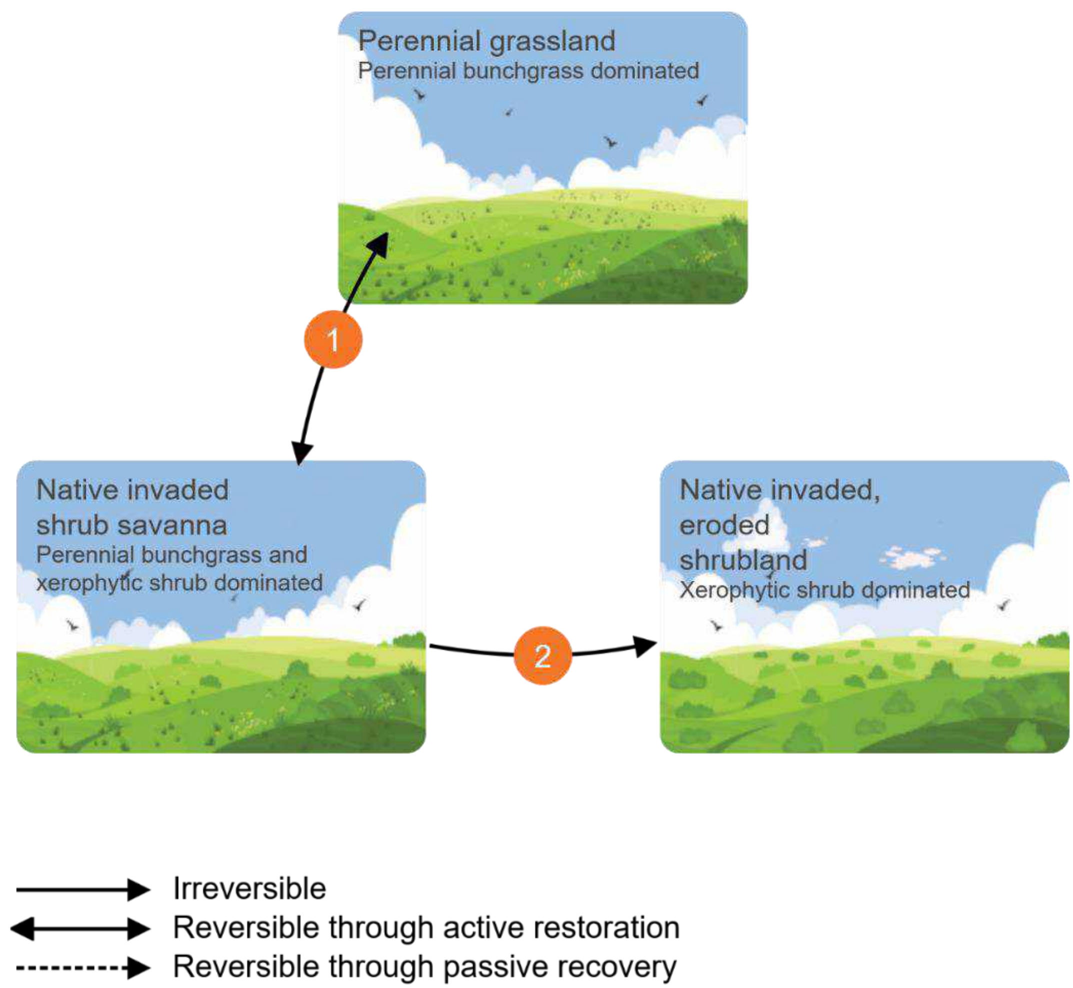

Figure 1. A simplified example of the Ecosystem Transition Sandbox graphical format. State and transition details can be added.

Discussion

The Classifier and Atlas have undergone preliminary testing and refinement and will undoubtedly be refined further. Regarding the Atlas, the governance of a body of STMs that can be produced by multiple users is a challenging problem. Even with the structure provided by these tools, logically inconsistent and conflicting models can be produced by different users. Thus, we are developing a strategy involving the production of global STM "syndromes" based on ecological mechanisms in the scientific literature as a first step for the Atlas, followed by national-scale application of the syndromes and adding details and benchmarks as a second step carried out by vetted, inclusive, collaborative groups. Participatory development of STM information is essential for their practical use in managing communal natural resources (Knapp et al. 2011). Separating development of syndromes as a first step from details and benchmarks as a second step in effect separates arguments about the ecological mechanisms underpinning STMs from values and experiences in local to national land management. This approach, we hope, will simplify the production of STMs and accelerate their use for the science-supported monitoring and evaluation of rangelands. We expect that such revised approaches to STM development will improve the accessibility, consistency, and quality of information to pastoralists and the institutions seeking to promote rangeland resilience.

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Rangeland mapping technologies and tools

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Mapping depleting aquifers in drylands and the impact on net primary productivity

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Key words: Carbon Dynamics; Gravimetry; Groundwater; Remote Sensing

Abstract
The Gravity Recovery and Climate Experiment (GRACE) satellite can measure changes in the height of the water table within 1 cm, unfortunately, GRACE has a horizontal pixel resolution of 40 km X 40 km. We selectively applied a GRACE-based downscaling approach to model the change in the height of groundwater from 2003 to 2017 within distinct groupings of hydrographic basins. We determined that the existence of distinct hydrographic systems at spatial scales smaller than the scale of GRACE pixels does not appear to preclude this downscaling methodology. We then compared this change in the height of the water table over the entire state of Nevada to a net primary productivity (NPP) disturbance map of the frequency of drought on the landscape. We found no significant correlation between disturbance frequency and the modeled change in water table height, implying that aquifer overdraw is not predictive of a reduced ability for the landscape to resist disturbance.

Introduction
Researchers have increasingly turned to NASA's GRACE and GRACE-FO gravimetric missions to address longstanding difficulties in monitoring Earth's groundwater resources. The major limitation of these instruments is the extremely coarse spatial resolution of the data they produce (40-km pixels, Wiese et al, 2016). Numerous research teams have developed methodologies to compensate for this limitation by integrating GRACE data into empirical models alongside finer-resolution climatological and geographic data, that effectively allow for GRACE data to be downscaled to more useful spatial resolutions.

However, many of the most widely-cited GRACE downscaling studies have trained, applied, and validated their empirical models over relatively straightforward topographies (Miro and Famiglietti 2018, Chen et al 2019). There is a need for additional work to refine our understanding of what spatial scales GRACE downscaling methods can be applied and what landscape factors affect the validity of these methods.

The goals of this experiment were:

1. Determine whether GRACE downscaling methods are valid when the study area contains hydrographic basins where no in-situ training or validation method is available.

2. Determine whether trends in downscaled GRACE data correlate with observed anomalies in landscape productivity.

Methods

The study area for this experimentation was the U.S. state of Nevada, chosen because it is 98% Dryland, and its complex basin-and-range topography maximizes the density of distinct hydrographic systems within the footprint of each GRACE pixel. The GRACE downscaling method we utilized for this experiment was a linear regression from least squares (Vishwakarma et al 2021), which was chosen because this experiment was a sensitivity analysis more so than an attempt to maximize model accuracy. The modeled variable was the flux of the height of the water table, with the interannual period resetting in March rather than January due to the greater availability of in-situ well measurements. March is also the beginning of the growing season for Nevada's primary dryland crops.

The in-situ data for this experiment were compiled from records maintained by the Nevada Division of Water Resources (NDWR 2024). The majority of these records were drawn from private agricultural and industrial users, with great variation in the quality and consistency of record-keeping. Because of the inconsistencies within these data, we applied GRACE downscaling to the overall trend of the water table from 2003 to 2017 rather than to an interannual time series. Applying GRACE downscaling methods at decadal rather than interannual timescales has some precedent in the literature (Scanlon et al, 2018).

We addressed our first research goal by utilizing two different methods of organizing training/validation data from in-situ records. We also leveraged the set of hydrographic basins delineated by past surveys (USGS, 1971). To produce our first dataset, we simply withheld 20% of the available site records for validation purposes, and otherwise used the available training data irrespective of location or site type. We refer to this as **the basin-inclusive method**.

To produce our second dataset, we chose a subset of hydrographic basins from within the study area and used in-situ records from these as training data. We then chose a second subset of hydrographic basins from within the study area to use as validation data. These basins were non-contiguous, meaning that the validation data were both spatially and hydrographically discontinuous from the training data. We refer to this as **the basin-exclusive method**.

The two methods cannot be directly compared because of the differing distribution and amount of training and validation data available in each case. However, we reasoned that if the second training/validation approach produces a respectable accuracy, we may have some confidence that the aquitards between hydrographic basin do not invalidate GRACE downscaling approaches applied over areas that contain multiple distinct hydrographic systems.

We addressed our second research goal by applying our downscaling approach to the entire State of Nevada and then compared this to a raster representation of the frequency of drought disturbance on vegetation in the landscape. This raster represented drought "disturbances" as events where the annual net primary productivity NPP (Robinson et al, 2019) decreased 20% or more relative to the time-series mean. We reasoned that since most of Nevada's waterways are groundwater-dependent, consistent aquifer overdraw may be reflected in the landscape's resilience to disturbance. We tested this hypothesis by testing for spatial correlation between this disturbance frequency and the modeled change in water table height.

Results

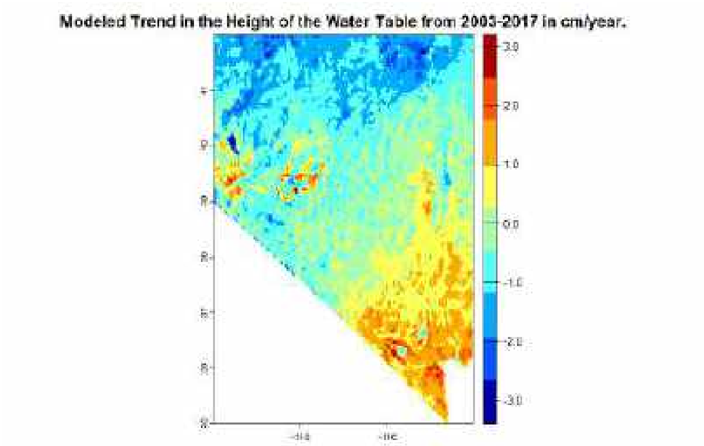

Figure 1: The state of Nevada model output based on the basin-inclusive training/validation dataset. The set of predictor variables include the flux in precipitation (mm), the flux in mean annual temperature (*C), the soil water content at field capacity at 200 cm depth, the soil bulk density (kg/m^3) at 200 cm depth, and elevation (m). These variables were retrieved via Google Earth Engine (Earth Engine Data Catalog, 2024). The target resolution for this method was the 4km resolution of the PRISM precipitation dataset (Daly et al, 2008). This model had a RMSE of 2.8 cm/year and a normalized RMSE of 0.15.

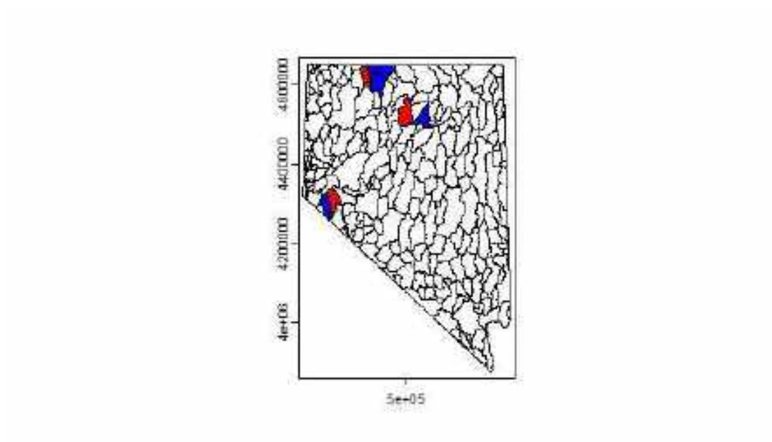

Figure 2: The basins chosen for the first, basin-selective training/validation dataset. Basins in blue contained points used for training, basins in red contained points used for validation. The model was trained using the basin-exclusive training/validation dataset and had a RMSE of 1.8 cm/year and a normalized RMSE of 0.15, indicating that the model is somewhat less reliable than the one produced using the basin-inclusive data.

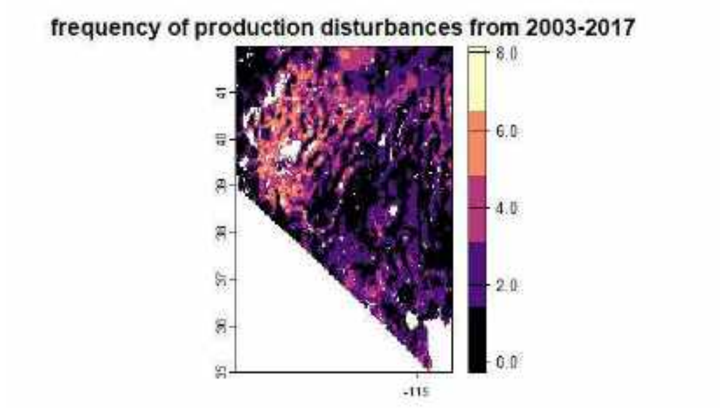

Figure 3: The drought disturbance net primary productivity (NPP) frequency raster was used to test whether there was an observable relationship between the GRACE modeled change in the water table height and the resilience of groundwater-dependent ecosystems. We observed no significant spatial correlation between these variables ($p = 0.17$).

Discussion

These experiments revealed a considerable need for further investigation. The basin-exclusion method for investigating the effects of aquitards on the downscaling methodology shows promise, but could be refined by more carefully curating the excluded basins to control for underlying geology and dominant land-use type.

The lack of correlation between groundwater levels and disturbance frequency could have several causes, and likewise indicates a need for more refined investigation. This could indicate that the groundwater model performs unreliably in areas between or far away from training/validation points, or the correlation could be thrown off by the behavior of agricultural water users, who account for a majority of groundwater usage and may be maintaining artificial "islands" of stable landscape production at the cost of aquifer overdraw. Controlling for land use in future iterations of this experiment should allow us to isolate which of these explanations is more likely.

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Accurate modelling of photosynthetic light responses of C_3 and C_4 species

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Abstract

Industry-oriented research innovations during the past decades have significantly contributed to the productivity, profitability and sustainability of pastoral industries. Key examples of these innovation efforts include (1) sensor, IoT and machine learning technologies facilitating automation of data collection, data integration and model simulation towards digital decision tools for farmers, and (2) simulating the consequences of changed environment and/or management practices on rangeland and pastoral systems through integrating biological, physical and digital properties and processes across leaf, whole-plant and paddock levels. However, there are fundamental physiological processes which are not well reproduced by models, partly due to the challenge of bridging the advancement of cross-disciplinary knowledge. This paper reviewed recent experiment-modelling-integration efforts towards the accurate model representation on light-response of photosynthesis, in particular: the performances of two models – the most widely used non-rectangular hyperbolic model (NH model) and a more recently developed mechanistic and nonasymptotic model (Ye model) – in reproducing plant photosynthetic light response across light-limited, light-saturated and photoinhibitory light intensity levels. The accuracy of Ye model, and its consistency of model framework, in reproducing the light responses of concurrent photosynthetic functions (i.e., photosynthesis, electron transport rate, stomatal conductance and water use efficiency), make it ideal to be adopted by the current and future experiment-modelling-integration efforts on global rangeland, pastoral and/or broadacre production systems.

Introduction

Plants growing in natural or semi-natural systems experience fluctuating light environments over time scales extending from seconds to hours, largely due to cloud movements and self-shading. Accurate characterization of light-response curve of photosynthesis at leaf scale is fundamental for quantifying crop light relations at whole-plant and community scales. An accurate model should be robust in reproducing light-response curve of photosynthesis (PN–I curve) over light-limited, light-saturated and photoinhibitory I levels, and ideally returning key quantitative traits defining the curves, including initial slope of increase (α), dark respiration rate (RD), the maximum net photosynthetic rate (PNmax) and the corresponding saturation intensity (Isat).

A few models have been developed to characterize the light response of photosynthesis of higher plants, including biochemical models, rectangular and non-rectangular hyperbolic models, negative exponential equations, and nonasymptotic function models. The non-rectangular hyperbolic model (NH model) is the most widely used (Holley, 2022).

The FvCB model (Farquhar, von Caemmerer and Berry, 1980) has been widely used to characterize leaf gas exchange. In the FvCB model, the NH model is a sub-model to characterize the light response of electron transport rate (*ETR*–*I* curve, using the same function as the above P_N–I model) besides estimating the maximum electron transport rate (ETR_{max}) (Farquhar & Wong, 1984). Unavoidably, due to its asymptotic function, the NH model overestimates ETR_{max} when the model is fitted against observations. Besides, since early years, the NH model has been reported on its failure in reproducing the *ETR*–*I* curve at photo-inhibitory *I* levels (Ögren & Evans, 1993).

This paper reviewed recent studies comparing the performances of two different models (NH model and Ye model) in reproducing the light response curves of *ETR and* P_N.

Methods

NH model on the light response of photosynthesis and electron transport rate

The NH model describes the P_N–I function as below (Thornley 1976, Ögren and Evans 1993, Thornley 1998):

$$P_N = \frac{\alpha I + P_{Nmax} - \sqrt{(\alpha I + P_{Nmax})^2 - 4\theta\alpha I P_{Nmax}}}{2\theta} - R_D \quad (1)$$

where P_N is net photosynthetic rate, P_{Nmax} is the maximum net photosynthetic rate, α is the initial slope of curve, *I* is light intensity, θ is the curve convexity (dimensionless), and R_D is the dark respiration rate.

ue to its asymptotic function, the NH model can only indefinitely approach to, but never reach, a maximum net photosynthetic rate (and thus cannot return the corresponding saturation *I*). This means that (1) the P_{Nmax} generated by fitting the NH model will be unavoidably overestimated, and (2) the NH model cannot reproduce the curve section at and after the saturation *I* (where photoinhibition occurs).

The non-rectangular hyperbolic model has been mainly used to fit the *ETR*–*I* curves of plants, and it has been a sub-model in the FvCB model when irradiance is below the saturation level. In the NH model, the dependence of *ETR* on *I* can be expressed as follows:

$$ETR = \frac{\alpha' \times I + ETR_{max} - \sqrt{(\alpha' \times I + ETR_{max})^2 - 4\theta \times \alpha' \times I \times ETR_{max}}}{2\theta} \quad (2)$$

where α' is defined as the initial slope of the *ETR*–*I* curve, θ is a degree of curvature, and ETR_{max} is the maximum *ETR*. Because the first derivative of Eqn. 2 is always greater than zero, we cannot use Eqn. 2 to estimate the saturation *I*.

Ye model on the light response of photosynthesis and electron transport rate

The Ye model describes the P_N–I function as below (Ye 2007; Ye *et al*. 2013):

$$P_{\mathrm{N}} = \alpha \frac{1-\beta I}{1+\gamma I} I - R_{\mathrm{D}} \quad (3)$$

where α is the initial slope of P_N–I curve, R_D is the dark respiratory rate, and β and γ are the photoinhibition coefficient and saturation coefficient, respectively (Ye *et al*. 2013). Due to its nonasymptotic function, Ye model can calculate the actual P_{Nmax} and the actual corresponding saturation I (I_{sat}).

According to Ye *et al*. (2013), the photosynthetic electron transport rate (*ETR*) via PSII can be described as:

$$ETR = \alpha_e \frac{1-\beta_e I}{1+\gamma_e I} I \quad (4)$$

Since Eqns. 3 and 4 are of the non-asymptotic function, they have the first derivative. When the first derivative equals to zero, the maximum net photosynthetic rate (P_{Nmax}), the maximum electron transport rate (ETR_{max}) and their corresponding saturation intensities (I_{sat}) can be calculated.

Results

Ye model can accurately characterize the *ETR*–*I* curves (Figure 1) for various C_3 and C_4 species across light-limited, light-saturated and photoinhibitory *I* levels. Its robustness and accuracy in reproducing P_N–I curves are consistent at different temperature and CO_2 concentration levels (Figure 2).

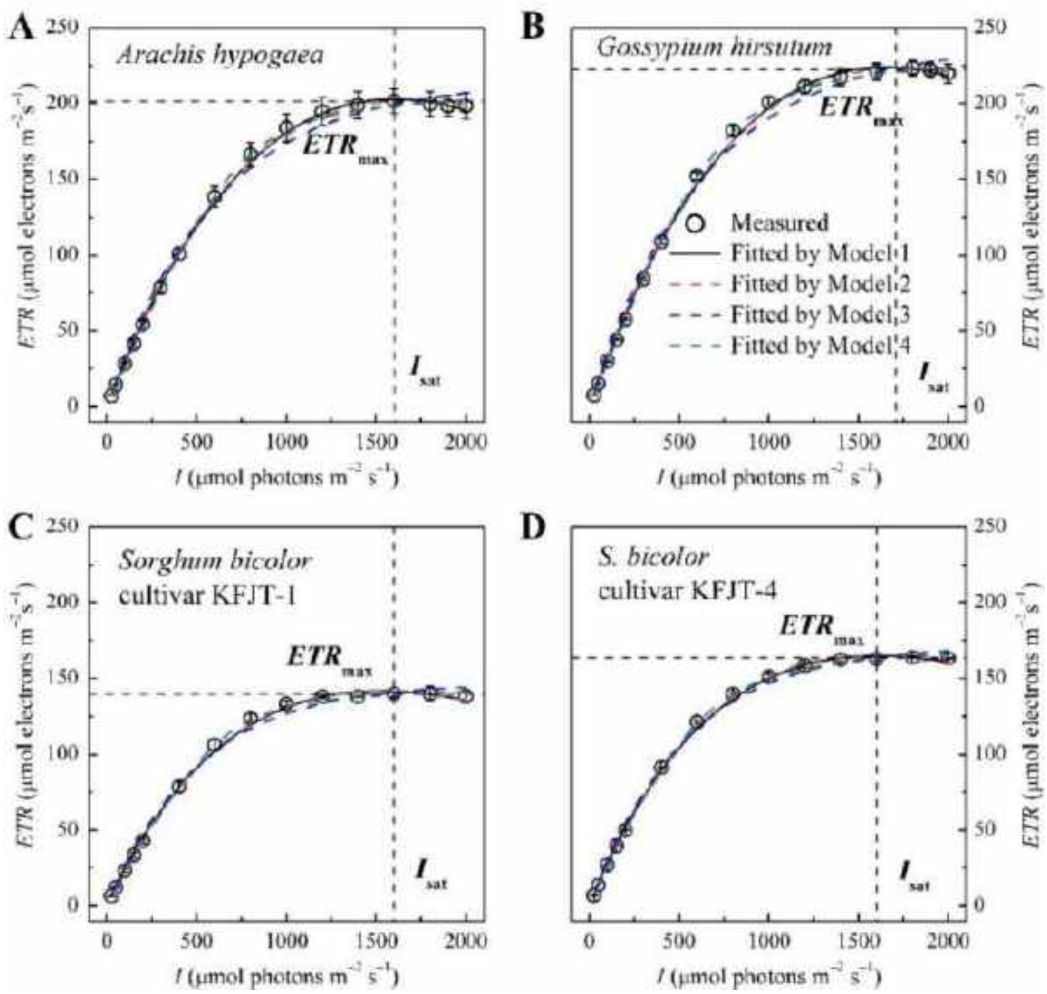

Figure 1. Light-response curves of the electron transport rate (*ETR–I*) for *Arachis hypogaea* (**A**), *Gossypium hirsutum* (**B**), *Sorghum bicolor* cultivar KFJT-1 (**C**) and *S. bicolor* cultivar KFJT-4 (**D**). The curves were simulated by Model 1 (Ye model), Model 2 (negative exponential function), Model 3 (exponential function), and Model 4 (non-rectangular hyperbolic model). A black horizontal dashed line represents the observed value of ETR_{max}, and a black vertical dashed line represents the observed value of I_{sat}. Data is sourced from Yang et al. (2025).

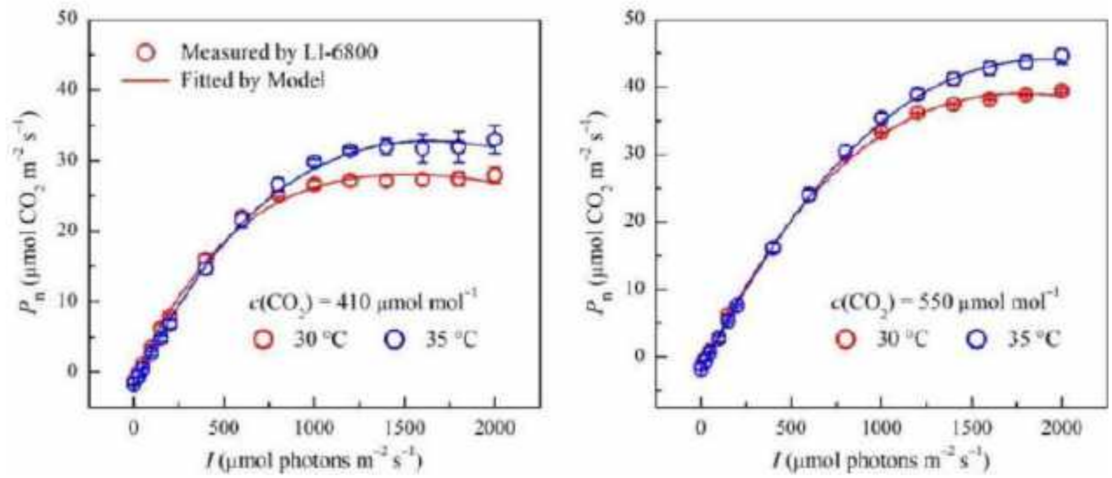

Figure 2. Photosynthetic light response curves fitted by the Ye model for leaves of sweet sorghum under different temperature and atmospheric CO_2 levels (410 and 550 mmol mol^{-1}) and air temperatures (30 and 35°C). Data is sourced from Yang et al. (2024).

Discussion and conclusion

Using an experiment-modelling-integration approach, Ye et al (2021) highlighted that Ye model can well address the limitations of NH model such as (1) underestimation of dark respiration rate (2) overestimation of the maximum net photosynthetic rate and (3) failure in reproducing the photoinhibitory response over both low *I* levels (i.e., 0–50 µmol m^{-2} s^{-1}) and photoinhibitory *I* levels (i.e., when *I* surpassed the cultivar-specific saturation light intensity). Using a consistent model framework as the P_N–I model, Ye et al (2020) reported Ye model can accurately reproduce the *ETR–I* curve, while the NH model significantly overestimated the maximum electron flow for carboxylation but not that for oxygenation, highlighting the reason underlying why the NH model would overestimate P_{Nmax} and ETR_{max}.

This paper reviewed recent research efforts using the experiment-modelling-integration approach to address the long-standing limitations of asymptotic models, and highlighted the long-lasting limitations of the most widely used non-rectangular hyperbolic model (NH model) such as (1) NH model led to underestimation of dark respiration while overestimation of the maximum net photosynthetic rate, and (2) NH model failed in reproducing the photoinhibitory response when light intensity surpassed the species-specific saturation intensity. The more recently developed mechanistic model (Ye model), attributed with its nonasymptotic function, addressed the above limitations of NH model extremely well.

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Accounting for carbon stock change in Australia's rangelands – a hybrid approach using remote sensing and empirical modelling

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Key words: greenhouse accounts; remote sensing; biomass

Abstract

Australia's rangelands are under varying types of land-use and management, including cattle grazing, Indigenous fire management, and activities encouraging regeneration of native vegetation to restore biomass and earn carbon credits. Despite the typically sparse vegetation, the vast area of the rangelands (almost 6 million km^2) is a substantial stock of land sector carbon. Changes in these stocks, whether due to management or wet - dry climate fluctuation, are thus a major contributor to Australia's overall carbon fluxes. Improving estimates of greenhouse emissions and sinks in the rangelands is thus essential to fulfil Australia's climate change treaty obligations, and also to account for land management effects in carbon credit schemes.

Here we present a new approach to account for land-sector carbon, targeted principally at the rangelands. Recent work has quantified the relationship between canopy cover and above-ground biomass (AGB) across Australia's rangelands. We extend the widely-used Full Carbon Accounting Model (FullCAM), using a time-series of remotely-sensed woody cover to estimate changes in AGB through time. This time series is integrated with the FullCAM model, to combine observed changes in woody cover with the effects of fire, litterfall, decay and soil respiration, to account for greenhouse emissions and sinks through time.

We introduce and demonstrate this approach for rangeland areas. Once this approach, informed by satellite monitoring of woody cover, is scaled up, it is anticipated that FullCAM will reduce model uncertainty by integrating empirical biomass estimates with a process-based modelling framework.

Introduction

Rangelands occupy approximately 40% of the global surface and provide critical ecosystem services, such as forage for livestock, soil stabilization, biodiversity habitat and climate change mitigation. Given their vast extent, even minor changes in carbon stocks can have significant impacts on the global and national carbon budgets. Woody biomass is a key component of the carbon cycle in these environments, with increasing woody vegetation associated with benefits including enhanced carbon sequestration.

Estimating and monitoring woody biomass in Australia's rangelands is challenging due to diverse vegetation types, complex disturbance regimes (grazing, fire, drought) and associated high spatial and temporal variability. Australia's National Greenhouse Accounts (Australian Government, 2024) use the Full Carbon Accounting Model (FullCAM; Richards and Evans, 2004; Forrester et al., 2024), to monitor and report carbon emissions and sequestration from the land sector. The FullCAM framework estimates accumulation of tree biomass using an empirical growth relationship known as the Tree Yield Formula, with parameters including maximum above-ground biomass (AGB), age of maximum growth, and importantly, stand age. This approach to estimating biomass, and thus carbon, depends on the date from which a given stand began to grow. In rangeland systems where vegetation dynamics may be dominated by diffuse cycles of biomass increase and decrease in response to factors such as climate, grazing and low intensity fire, this approach has limitations.

Canopy cover is strongly correlated with AGB, and remote sensing (including Landsat and Sentinel time series) has been broadly adopted to map vegetation cover, including for aiding the estimation of AGB at large spatial scales (Allred et al., 2021; Jones et al., 2021; Kearney et al., 2022). Modelling AGB directly from time-series estimates of canopy cover may provide an alternative to generalized growth models to better estimate AGB change, and thus carbon flux, in sparse and diverse vegetation, such as Australian rangelands.

This study presents a novel prototype, a variation of the FullCAM model that combines a process-based model of vegetation carbon cycling, with remote-sensed observation of vegetation change, to improve estimation of carbon stocks and flows in the rangelands. By integrating dynamic carbon cycle processes with satellite-derived observations of vegetation cover, this model aims to capture the spatial and temporal variability in rangelands, offering a tool more applicable for carbon accounting and vegetation carbon sequestration projects in these more arid areas. In this paper, we outline the integrated workflow and share the preliminary results.

Methods

We mapped carbon stock for woody vegetation in a rangeland area, through a process with three main stages. The first, a satellite derived time-series of the proportion of woody cover tracked changes in vegetation extent and density. Second, AGB was inferred at each location through time. The ABG was based on woody cover and vegetation structure relationships, previously calibrated over an extensive program of fieldwork. Third, the inferred AGB was incorporated into a model adapted from the Full Carbon Accounting Model (FullCAM; Forrester et al., 2024; Richards and Brack, 2004) alongside other carbon cycling processes such as litterfall and decay, to simulate movement between carbon pools, and overall carbon stock change in the woody component of rangeland environments. These steps are now described in more detail.

Remote-sensed woody cover

The FullCAM framework estimates spatial and temporal regeneration of AGB using a stand-age based empirical growth relationship (Tree Yield Formula, TYF; Paul & Roxburgh, 2020). In rangeland systems where vegetation dynamics are typically dominated by more diffuse cycles of increasing and decreasing biomass in response to factors such as climate, grazing and low intensity fire, this approach has limitations.

The current standard for estimating fluxes of greenhouse gasses related to vegetation change in Australia's Greenhouse Accounts (DCCEEW, 2024) is the national forest and sparse woody vegetation data (Furby, 2002; DCCEEW, 2023) which uses Landsat satellite data for the period since 1988 to derive an annual classification of Australia's vegetation cover into 3 categories: woody vegetation (forest, >= 20% tree cover), sparse woody vegetation (5% to <20% cover), and non-woody (<5% cover). This dataset tracks changes through time in the extent of forest, particularly for well-defined changes such as clearing of forest, and the establishment of new or restored forest areas, but is not sensitive to changes in cover within those categories. Thus its use in carbon accounting relies on growth and recovery functions to simulate biomass accumulation through time (Forrester et al., 2024), calibrated to empirical datasets.

In this study we trialled a new remote sensing approach to capture the full range of variation in woody cover, enabling direct observation of changes in woody cover to be translated into time-specific estimates of above-ground biomass and carbon pools. This approach to estimate cover (Chia et al., 2024) partitions Landsat multi-spectral reflectance into multi-variate proportions (MVP) for four ground-cover classes: woody, dry grasses, green grasses and soil (bare) based on spectral unmixing algorithms described by Berman et al. (in prep). The timing of images is selected to provide a yearly value representing permanent woody cover, typically during the dry season (July for northern and northeastern Australia, and January for central and southern Australia). The time series covers the period 1988 to 2022 at 0.00025 degree (~25 m) resolution. Annual cover values were interpolated to monthly by assuming linear change between observed values and extrapolated to use the earliest observed value for years prior to 1988.

Cover to biomass

Our 'cover-to-biomass' model is based on the quantitative relationship between canopy cover and AGB which Pasut et al. (in press) derived from an extensive dataset of field measurements. These measurements, collected from 431 field sites across the Australian rangelands, included live AGB and standing dead AGB, with sites stratified to represent the region's variability. The resulting log-linear relationship between woody cover proportion and above-ground biomass, is expressed here as:

$$AGB = e^{b\,ln(C)} * B_f \qquad \text{Eq.1}$$

where AGB is above-ground biomass; b is the scaling factor for cover; C is the percentage of woody cover; and B_f is the Baskerville correction factor.

The model was calibrated for three broad vegetation structural types, *shrub-dominant*, *Acacia-dominant* and *tree-dominant*, with values of b and B_f for each vegetation structural type.

Integrated land carbon model

We adapted the FullCAM model framework to estimate AGB using remotely sensed cover data. For detail on the FullCAM framework see Forrester et al. (2024). The existing FullCAM uses a growth curve in which the annual increment in living tree biomass depends on parameters including tree-stand age (dated to detection of new forest cover) and time since disturbance. The cover-to-biomass model however, ties changes in AGB to continuous vegetation change, estimating AGB from annual observations of cover, rather than a growth curve.

Other model components follow the existing FullCAM approach, where the vegetation class at each location is defined from the National Vegetation Information System (NVIS) Major Vegetation Groups. AGB is allocated among living carbon pools (stem, bark, branches, leaves) using FullCAM proportions for allocation of live biomass which are specific to each vegetation class, with below-ground tree biomass similarly assigned to fine and coarse root carbon pools in proportion to AGB. Turnover (such as litterfall of leaves and bark to debris) and decomposition of debris are predicted using an exponential decay model that quantifies the rate at which carbon moves between pools. Fire events were not directly simulated in this study, although the effects of fire on loss of woody biomass and its subsequent recovery, are included where they affect observed woody cover. Non-CO_2 greenhouse gasses are not included at this stage.

Flux of carbon between land and atmosphere occurs in this model in two ways. First, during the decay of non-living biomass, a proportion of the carbon is released as CO_2, while the rest of the lost carbon moves to another pool, for example, soil carbon. Second, changes in site carbon mass, primarily due to changes in AGB indicated by the cover-to-biomass function, are treated as direct carbon removals from, or emissions to, the atmosphere, corresponding to increases or decreases in AGB.

In summary, the prototype cover-to-biomass model in this study is a hybrid, combining process-based modelling of carbon transitions / transformation between pools, with an observation-driven component where changes in biomass at each pixel are directly linked to satellite-detected variations in woody cover.

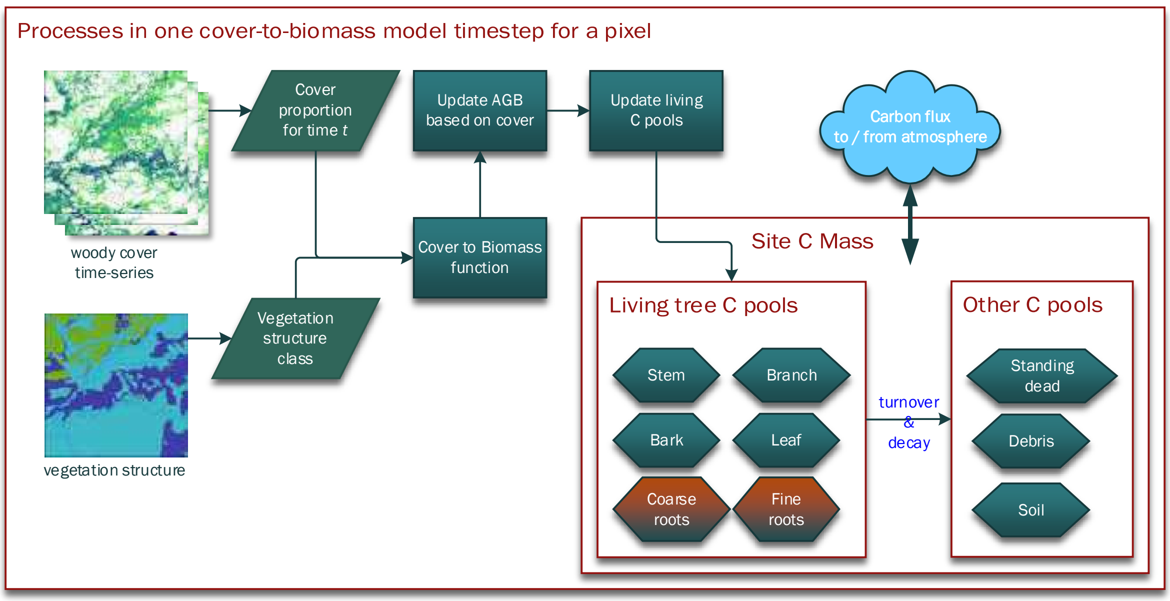

Figure 1. Main processes in the cover-to-biomass model per time-step, for one pixel. Vegetation structure and remote-sensed woody cover percentage for each timestep inform the cover-to-biomass function to update living biomass pools. Turnover and decay processes then populate the debris and soil carbon pools. Atmospheric carbon flux is inferred from changes to site carbon mass.

Results

Results from running the prototype model for an area of 6 million ha (96 million pixels at 25 m resolution) in inland northern New South Wales and southern Queensland, returned values for aboveground living tree C mass ranging from 0 to 79 t C ha^{-1}, and for total stand C mass ranging from 22 to 170 t C ha^{-1}. As expected, results were strongly reflective of local topography and drainage as important drivers of C density, and of patterns of agricultural land-use. Figure 2 shows in detail the estimates of woody cover and of carbon pools for an area along the Barwon River east of Bourke, NSW for the year 2020.

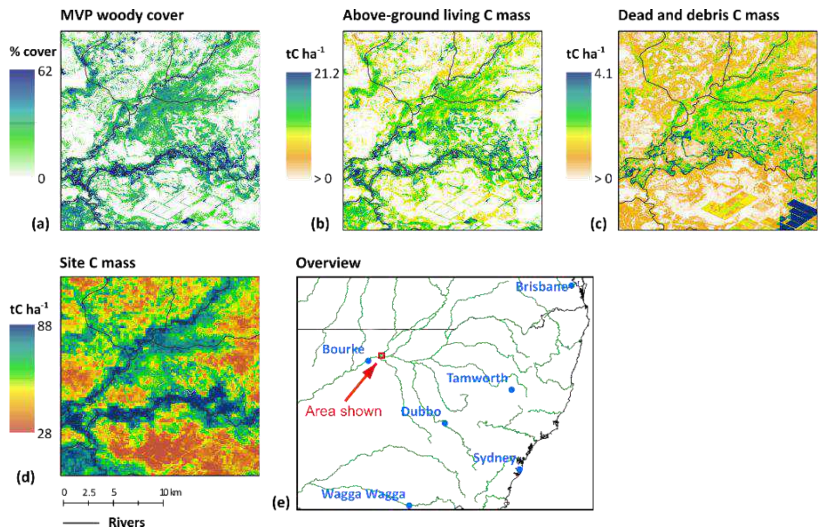

Figure 2. Example model outputs for 2020 along the Barwon River east of Bourke, New South Wales at 25 m resolution, showing a) % of woody cover from the multivariate proportion (MVP) model; b) carbon in aboveground tree biomass; c) carbon in debris and standing dead trees; d) total C mass, including above and belowground tree components, standing dead, debris and soil organic carbon; and e) overview map. The effects of floodplains on biomass are clear, as is irrigated agriculture near the south end of the area.

Discussion

The method and results presented here illustrate the potential of a new approach to estimating land sector C stocks, and subsequently emissions and sinks, in rangeland environments where methods based on stand-level, growth curves may not reflect typical growth trajectories. They introduce an approach based on observed changes in woody cover through time, combined with modelled turnover and decay, which with further development, aims to improve to C accounting across Australia's vast rangelands. A comprehensive accounting approach will also need to include emissions of non-CO_2 greenhouse gasses, especially due to fires, to manage inter-annual variability in cover inferred from remote-sensed cover, and to demonstrate model performance across diverse rangeland environments in comparison to currently used approaches.

Acknowledgements

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Assessment and mapping of rangeland health in East Africa and globally

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Abstract

Rangelands across eastern Africa are in need of urgent interventions to restore rangeland health and build resilience to climate change. Drylands cover nearly half of the global land surface and harbor high biodiversity, yet they remain understudied and undervalued. The compounding effects of climate change and land degradation currently represent a major threat to drylands in general, and rangelands in particular. There are substantial gaps in the evidence base for land restoration with a significant bias towards the Global North and forest ecosystems. This research aims to address key gaps in East Africa around (1) the role of restoration interventions that consider and manage plant-soil-water feedbacks in accelerating the recovery of key ecosystem functions and related ecosystem services, (2) the link between above-ground and below-ground interactions, including biodiversity and (3) how such interventions can be scaled to improve restoration outcomes. The project builds on long-term and robust data collected in the field across a range of rangeland systems in East Africa using the Land Degradation Surveillance Framework (LDSF). We systematically assessed the impact of woody and non-woody vegetation (species, structure, cover, above-ground biomass, diversity), soil inherent properties (soil texture, pH), and land management (grazing and browsing intensity) on ecosystem functioning and the delivery of key ecosystem services, including erosion control, water regulation (soil infiltration capacity), and carbon storage, We present grass, forb and woody species diversity in 11 – 100 km^2 LDSF sites across East Africa, as well as maps of soil organic carbon, soil erosion and herbaceous cover. We will present the use citizen science to enhance the participation of local communities, and in particular women and youth, increasing transparency and inclusion in the various phases of rangeland restoration. These methods can be applied globally and fill key knowledge gaps around rangeland health and the impact of inventions on the ground.

Introduction

Rangelands are vital systems, covering 40-50% of the earth's terrestrial surface, providing essential goods and services such as livestock forage, biodiversity habitats, and carbon sequestration (Sala et al., 2017). In East Africa, these landscapes support pastoral livelihoods, harbour high biodiversity, and play critical roles in regulating regional and global climate systems (Little, 1996; Mgalula et al., 2021). However, they are currently under threat from a combination of pressures, including climate change, unsustainable land management, and socioeconomic factors (Otieno & Kinyamario, 2018). A systematic study of soil erosion prevalence, using the LDSF database, highlighted that drylands were more susceptible, including the vegetation classes of bushland and shrubland. (Vågen and Winowiecki, 2019). This degradation, evidenced by reduced productivity, soil erosion, and decreased biodiversity, demands targeted restoration interventions that are locally relevant, scalable, and informed by robust data. Restoration interventions require both a focus on vegetation recovery, but an understanding of complex plant-soil-water interactions, ground-truthing data, and participatory approaches with local communities. Yet, despite their importance, substantial knowledge gaps around effective, locally applicable and scalable restoration practices in rangelands systems (Boyd & Svejcar, 2009). A pressing need is to develop integrated protocols and tools that capture on-the-ground conditions, produce practical insights, and support locally relevant restoration efforts at meaningful spatial scales.

Our work integrates field data from the Land Degradation Surveillance Framework (LDSF)—a robust field data collection protocol designed for systematic, repeatable environmental assessments of soil health, rangeland health, land degradation and vegetation diversity (Vågen and Winowiecki, 2023; Vågen et al., 2012)—with spatial modelling tools and a citizen science data collection platform. By combining rigorous plot-based data, geospatial remote-sensing analyses, and community-led monitoring through mobile apps, this approach aims to fill critical knowledge gaps and enhance the evidence base for rangeland restoration interventions. We focus on East Africa as a case study region, reviewing both the protocol and the emerging results, and discuss how these methods can scale to inform rangeland restoration interventions more broadly, and be integrated into monitoring, evaluation and adaptive management frameworks.

Methods

The LDSF is a comprehensive field data collection protocol for assessing soil and land health (Vågen and Winowiecki, 2023). It provides guidance and methods for designing and implementing robust sampling strategies across broad, heterogenous landscapes along with tools to sample vegetation dynamics (cover, structure, and function), key soil physical properties, evidence of soil degradation, and historic land use change. The LDSF includes a specific rangeland module tailored to rangeland systems and employs accessible, practical, and affordable methodologies that can be implemented in remote areas with limited technical resources. Data collected through the LDSF support a rangeland health and indicator framework, enabling assessments of soil organic carbon stocks, soil infiltration, soil erosion, vegetation cover and density, species composition and diversity, and overall land degradation status and risk.

The nested, randomized sampling design of the LDSF framework facilitates the evaluation of the indicators at multiple scales, capturing both within- and between-site variability. Moreover, the LDSF integrates effectively with earth observation (EO) data, allowing assessments to span broader spatio-temporal scales. By combining field-derived indicators with medium-resolution (10 – 30m) EO data from Landsat and Sentinel, and applying advanced machine learning modelling pipelines, we can predict indicators of rangeland condition across landscapes at 10 – 30m spatial resolution and through time. This approach supports the development of historic baselines and the evaluation of areas lacking extensive field data availability. In this study we present results from 11 LDSF sites, eight in Kenya, one in eastern Rwanda and two in northern Tanzania, with 1760-1000-m^2 sampling plots. In each plot, there were four subplots each of 100m2, where erosion was scored, tree and shrubs were identified and measured and soil samples were collected. In addition, across each plot, two-15m transects are laid (N-S, E-W) where perennial and annual grasses, forbs and woody vegetation under 1 m tall are assessed.

Integrating field with EO products also improves long-term monitoring of restoration and degradation trends. To enhance the assessment of management and restorations interventions we incorporate a citizen science smart-phone application—The Regreening App (*The Regreening Africa App User Guidelines*, 2022)—which includes a rangeland module. This tool enables smallholder ranchers and land managers, to record the timing, location, and nature of specific interventions. By merging this localized, site-specific information with medium-resolution predictions of rangeland condition indicators, we can produce more robust and context-relevant assessments and evaluations of rangeland restoration initiatives.

Results

As shown for the sites surveyed as part of the GCF-Twende project in Figure 1, they covered a strong gradient in terms of SOC and land degradation status, the latter expressed here as soil erosion prevalence. Sites in the northern parts of the study area are generally lower in SOC (median <5 g/kg) and have higher soil erosion prevalence than sites in southern Kenya, although there are relatively high levels of degradation in all sites. The sites also represented a wide range of management types, including private conservancies, private pastoral land, and communal pastoral land. Species diversity of annual and perennial grasses varied strongly between sites, as well as the types of species present. For example, Mbalambala had very few grass species present and a high proportion of bare ground, as well as presence of invasive species such as *Prosopis juliflora*. In contrast, Mbirikani had higher species diversity and no invasive species were observed. Results from the surveys in northern Tanzania show high levels of bush encroachment in some districts, as well as high rates of conversion of rangelands into agriculture. In West Pokot there has been a transition from communal pastoral systems to private land tenure over the last three decades, resulting in higher levels of fragmentation and hence variability in terms of land use was also high in the Chepareria site.

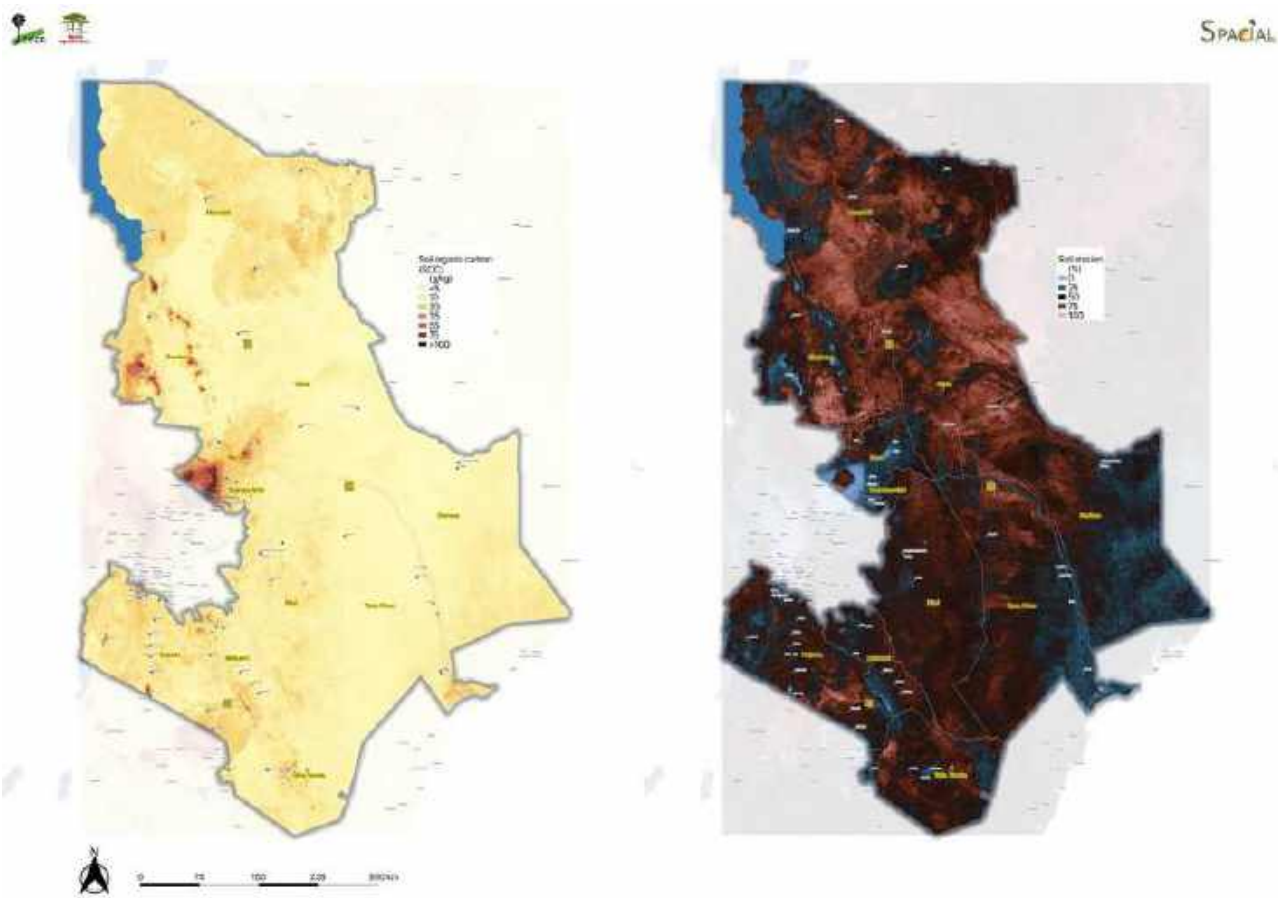

Figure 1: Maps of soil organic carbon (SOC) (left) and soil erosion prevalence (right) across southern and (north)eastern Kenya, within the GCF-Twende project.

Discussion [Conclusions/Implications]

Despite their immense ecological, economic, and cultural significance, rangeland systems remain challenging to monitor and assess due to their inherent spatio-temporal variability. This complexity has often hindered the development of robust, scalable frameworks for evaluating rangeland health, restoration progress, and management effectiveness. By integrating standardized field protocols, remote sensing data, participatory approaches, and advanced modeling techniques, our work contributes to overcoming these longstanding barriers. The approaches outlined here help establish reliable pipelines for data collection, analysis, and interpretation, ensuring that locally relevant interventions can be scaled to broader landscapes. Ultimately, this convergence of methods and tools provides a critical foundation for enhancing adaptive management practices, improving restoration outcomes, and ensuring that rangeland systems continue to sustain both livelihoods and ecosystems well into the future.

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Mapping the condition of Queensland's grazing lands

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Key words: land condition; LCAT; ABCD framework.

Abstract
Grazing land condition is the ability of grazing land to convert rainfall into useful forage and is determined by changes in pasture, soil, and woodland condition. The Grazing Land Management framework defines four condition classes (A, B, C or D), indicating maintenance of 100%, 80%, 50% and 20% of productive potential respectively. The Queensland Government is currently funding a six-year program to map grazing land condition in key Great Barrier Reef catchments. The work incorporates assessment of thousands of grazing land sites using the Land Condition Assessment Tool (LCAT), modelling the ABCD land condition class at those sites and generating modelled land condition maps across the targeted regions. Modelling and mapping land condition across large areas presents some significant challenges. For example, land condition is a multidimensional outcome that can be hard to mathematically fit to a unidimensional scale like ABCD, and spatial data that might predict some of these dimensions is either absent or limited. This has led the project to investigate and trial a number of approaches to delivering land condition mapping. This paper outlines the project's progress and some of our key learnings so far. These include an outline of LCAT sampling to date, an overview of the modelling and validation process and details around the planned rollout of the mapping.

Introduction
One of the key threats to the Great Barrier Reef (GBR) is soil sediment runoff from the GBR catchments, and grazing lands have been identified as a significant contributor to this threat (State of Queensland 2018). The Queensland government currently funds a suite of research and extension projects aimed at protecting the GBR. The Land Condition Monitoring Program is one of these and is tasked with developing maps of grazing land condition for GBR catchments.

Grazing land condition is an established framework for quantifying how well a grazing ecosystem is functioning and is defined as the capacity of grazing land to respond to rain and produce useful forage (Chilcott et al. 2003). Under this framework, sites are classified in one of four classes A (good), B (fair), C (poor) or D (very poor) based on the pasture, soil and woodland condition. Sites in A, B, C and D condition are respectively considered to have maintained about 100%, 80%, 50% and 20% of their original capacity to convert rainfall into useful forage. The system has been used widely in Queensland research, development and extension projects, and has proven a useful tool for engaging land managers around landscape health and productivity.

The Land Condition Monitoring Program involves several activities including upgrading the VegMachine.net website and developing a field guide for identification of important Queensland pasture species. This paper focusses on the land condition mapping component of the program. We outline the process to date for developing land condition layers and discuss several key issues around the work including future directions.

Methods

The project area includes three key Great Barrier Reef Natural Resource Management (NRM) regions (NQ Dry Tropics, Fitzroy Basin Association and Burnett Mary Regional Group). These cover a combined 351 000 km^2. Collection of land condition data in this area began in 2020 and is currently funded to June 2026.

All land condition data in the study were collected using LCAT (Land Condition Assessment Tool (Hassett et al. 2021)), a simple phone / tablet survey tool embedded in the ESRI survey 123 app. LCAT users include field staff of most Queensland NRMs as well as research and extension staff of the Queensland Department of Primary Industries. All users receive LCAT training prior to field use. LCAT users evaluate one hectare grazing land sites, recording data on variables including ground cover, primary pasture species, pasture density, pest species and abundance, woody cover and erosion. The LCAT algorithm then generates a variety of site summaries on-the-fly including a land condition rating (A, B, C or D). These data and summaries are then uploaded to cloud storage where they can be made available for land condition modelling.

The modelling process largely follows that of Scarth et al (2020). The study area is first segmented into polygons with common long term ground cover and woody cover histories. Summary values are then extracted from a large number of existing spatial layers for each segment to serve as the predictors for the land condition model. Where LCAT sites intersect a segment, the summary values for the segment are used in a random forest model to predict the land condition class of the intersecting site. The modelling process generated 30 potential models with varying parameterisations, and a single model was selected by evaluating fit to both holdout and cross-validation data as well as expert evaluation of the mapping on familiar client properties. The final selected model was then used to predict condition in all segments, and these segments were mapped with their predicted land condition class to create the land condition map.

Results

The current iteration of modelling incorporated 4233 land condition assessments, composed of (916, 1268, 1592 and 457 A, B, C and D condition sites respectively. Ten percent of these were randomly assigned to holdout validation data and the remainder used for model training. The final model incorporated multiple spatial predictors, but the most influential related to long term Dynamic Reference Cover Method value (Bastin et al. 2012), historical rainfall, temporal trend in woody vegetation cover, topography and historical ground cover. Table 1 shows the fit of the model to the holdout data. The ordered Kappa statistic for this fit (suitable for ordinal data) was $\kappa=0.52$, indicating moderate agreement between observed and predicted land condition class. The model predicts C and D condition relatively well, but fewer A and B condition sites are correctly assigned. Figure 1 shows an example section of the imagery.

Table 1. Confusion matrix for numbers of predicted vs observed land condition classifications from final land condition model for 423 sites in the holdout dataset.

Observed \ Predicted	A	B	C	D
A	49	20	20	1
B	12	63	41	4
C	8	24	134	8
D	3	4	8	24

Discussion

LCAT has proven a highly effective tool for collecting and collating land condition data in this project. Its key advantage is that it provides a wide set of users with a common set of criteria and rules for consistent assessment of land condition, and the wide user base maximises data available for exercises such as this project. This is a significant improvement on previous land condition studies (e.g. Karfs et al. 2009, Beutel et al. 2021) that relied on multiple datasets from multiple studies, many of which used different methods to arrive at their land condition assessments.

It's worth noting that LCAT data are collected for a number of purposes depending on the collecting organisation. As well as modelling land condition, these purposes include site monitoring, evaluation of sites applying for public remediation funding and assessment of impact by extension providers. This wide use demonstrates the utility of LCAT, but also highlights an important point – that the full LCAT dataset is not a random sample of the landscape. As such the collated points may not represent the true proportion of each condition class in the landscape. This underlines the importance of developing land condition layers that can adequately estimate those proportions for all parts of the landscape.

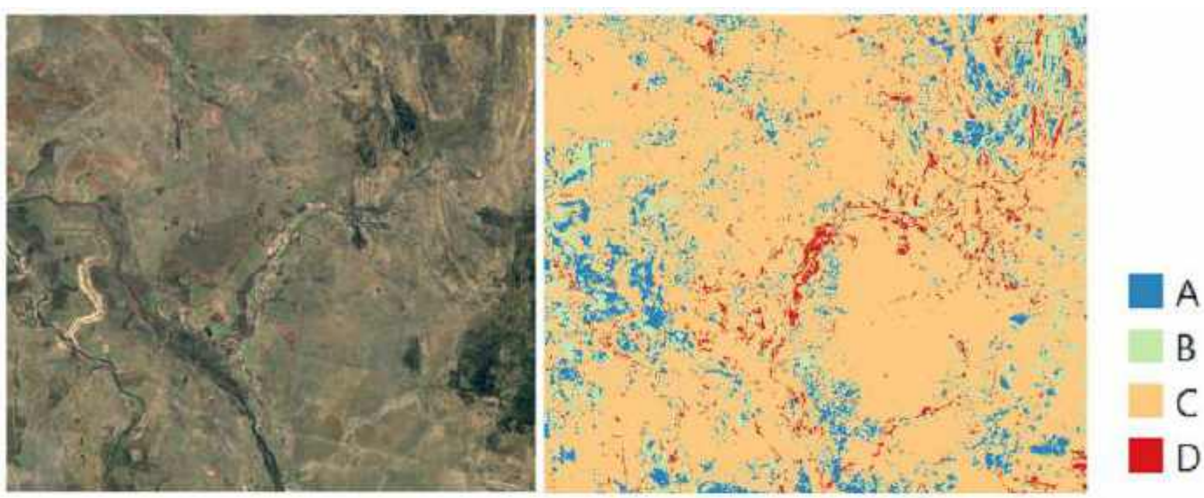

Figure 1. Example section of the current iteration of land condition mapping for a section of the Burdekin region (right) and corresponding RGB image of same area (left).

Table 1 shows the predictive precision of the most recent version of land condition mapping across the entire landscape (we have not yet analysed prediction in subset areas such as individual land types, but work is planned on this topic). While the current model improves on the previous year's iteration (not shown) it also highlights a significant challenge in modelling land condition, and that is the difficulty of correctly detecting high (A and B) condition sites. The current model relies heavily on ground cover related predictors (above), but high ground cover does not necessarily imply good land condition. For example, high coverage of the grass *Bothriochloa pertusa* will produce a C condition rating, at best. We think the model's reliance on ground cover data limits its capacity to distinguish condition classes when cover is relatively high. Conversely poorer condition sites have generally less ground cover than good condition sites, and so the model distinguishes C and D condition sites quite well.

In response to this challenge, we have begun work to model and map the distribution of major pasture species like *B. pertusa*. LCAT surveys include identification of the dominant pasture species so provide a ready data source to map where particular species dominate. If we can map the distribution of such species, these layers could assist in the differentiating condition classes in high cover areas by providing data to the model about pasture composition.

Some of the predictors in our current land condition model are long term (>30 year) ground cover and climatic summary data. These were selected for their predictive capacity, and our thinking is that they may be capturing some of the inherent characteristics of the landscape that have no other surrogates in the predictor set (e.g soil types, climatic zones). Currently it's unclear how long-term predictors will impact our capacity to monitor temporal change in land condition. If these long-term variables mostly describe the context of invariant aspects of the landscape, and shorter-term (≤ 5 years) predictors capture change in condition then its possible long-term predictors will play a useful ongoing role. Ultimately though, the best test of any land condition model's predictive skill is detailed analysis of where and when it does and doesn't predict land condition well, and this is part of the longer term project planning.

The current iteration of the land condition mapping was distributed to a limited audience of extension officers and graziers. These users are providing additional feedback about the mapping. The goal for this work is to publicly distribute future iterations through channels like VegMachine.net once a review of the mapping demonstrates an acceptable level of accuracy and suitable support documentation for users.

Acknowledgements

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Rangeland monitoring models and techniques

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Structural diversity in rangelands: a framework for quantifying what makes a functional rangeland

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Key words: ecosystem function, landscape monitoring, sagebrush steppe, unoccupied aerial systems

Abstract

Rangelands across the globe are threatened by factors such as climate change, altered fire regimes, and annual grass invasion, often leading to simplified vegetation structure and reduced ecosystem function. Restoring degraded rangelands to their original state is not always possible given socially acceptable levels of financial and capacity commitment. Whether the goal is to reestablish historically occurring flora and fauna or to mitigate some of the negative impacts of a degraded system, managing and restoring these ecosystems requires knowledge of what makes rangelands multifunctional systems (e.g., grazing, wildlife habitat, recreation) and what causes declines in these ecological functions following degradation. Structural diversity metrics can be used as an indicator of ecosystem function and are now possible to continuously measure across landscapes with remote sensing. Recently, the use of structural diversity from 3-dimensional (3D) spatial datasets has been proposed as a flexible method to measure ecological functions in forested systems but has yet to be applied to rangeland management. We propose using structural diversity to monitor rangeland ecosystem function with two case studies. First, we measure structural diversity across a series of ecological states in semiarid rangelands, from intact shrub and native bunchgrass communities to invasive annual grass-dominated sites and multiple phases of juniper (*Juniperus* spp.) encroachment. Second, we compare structural diversity between paired grazed and ungrazed landscapes. We found that structural diversity differs across ecological states, demonstrating a potential way to assess ecosystem function. With the recent increase in the availability of high-resolution 3D structural data from low-cost unoccupied aerial systems (UAS), structural diversity could be used to help managers rapidly assess the ecological function of rangelands.

Introduction

Recent advances in technologies, such as more widely available LiDAR and low-cost unoccupied aerial systems (UAS or drones) bring new opportunities to understand structure—function relationships (Anderon and Gaston 2013). Researchers in forested ecosystems have begun to explore these relationships, suggesting a theoretical framework focusing on the vertical structuring and niche partitioning seen in these systems (Atkins et al. 2018; LaRue et al. 2023), and linking some of these metrics to ecosystem functions such as productivity (LaRue et al.

2019), but little work has been done in rangelands (see Zaiats et al. 2024), despite demonstrated linkages between structural heterogeneity and ecosystem function using other methods (Maestre et al. 2016). Besides estimating structural contributions to biodiversity, structural diversity could assess fire resilience (e.g., patch arrangement of woody fuels), recovery from disturbances (e.g., post-fire, agricultural abandonment), wildlife habitat, and management treatment longevity. Compared to forested ecosystems, rangelands have less vertical stratification, and therefore different metrics and spatial scales should be considered.

In this study, we provide two case studies demonstrating a framework (Fig. 1) for applying structural diversity metrics to management of rangelands: 1) three ecological states representing intact shrub steppe, invasive annual grass invasion, and juniper encroachment; and 2) a long-term grazing exclosure study (88 years) comparing six sets of paired grazed and ungrazed pastures.

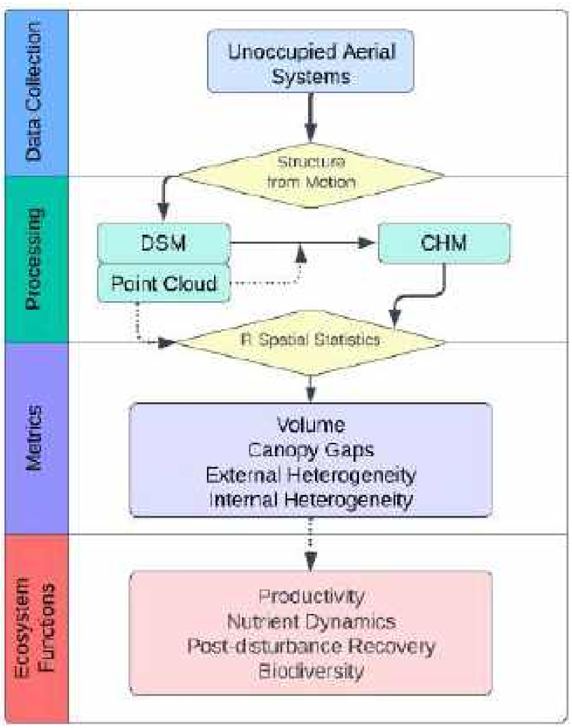

Figure 1. Workflow for generating structural diversity metrics with unoccupied aerial systems (UAS) structure from motion to generate digital surface models (DSM) and canopy height models (CHM).

Methods

We conducted our research at two study areas in southeastern Oregon, USA. The first case study was in the Stinkingwater Mountains (43.63°N, 118.38°W), which contains a range of vegetation communities and ecological states from intact shrub steppe dominated by *Artemisia tridentata*, to post-fire landscapes invaded by medusahead (*Taeniatherum caput-medusae*), to conifer (*Juniperus* sp.) encroached shrublands. The second case study was a long-term grazing exclosure study at the Northern Great Basin Experimental Range (NGBER, 43.48°N, 119.71°W), with pastures covering a range of elevations and vegetation communities with *A. tridentata* dominating the lower elevations and *J. occidentalis* woodlands dominating the higher elevations, but little annual grass invasion compared to the Stinkingwater Mountains.

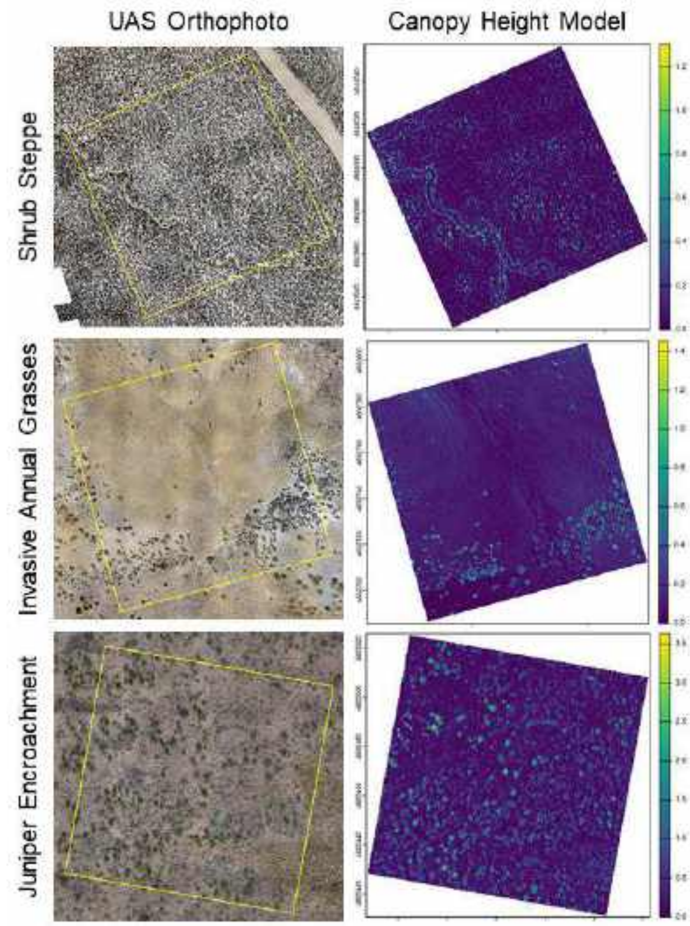

Figure 2. Unoccupied aerial system (UAS) high-resolution orthophotos and canopy height models for three sites in Oregon, USA representing healthy shrub steppe, annual grass invaded, and juniper encroached ecological states. Yellow boxes represent the 100 x 100 m (1 ha) assessed in this study.

We collected imagery with a Freefly Astro (Freefly Systems, Woodinville, WA, USA) UAS equipped with a 61 MP camera. We flew the UAS at 40 m altitude above ground level, with a nadir flight and a 30-degree offset flight with a cross-grid pattern resulting in ~1-cm pixel resolution. We processed the UAS imagery with Open Drone Map (ODM version 3.3) on USDA's SCINet supercomputer Atlas with 48 cores and 320 GB of RAM. ODM parameters were feature-quality and pc-quality set to 'ultra,' min-num-features of 40,000, and orthophoto-resolution and dem-resolution set to 0.01 to obtain the highest pixel resolution from the data. We generated digital surface models (DSM) using structure from motion photogrammetry (Cunliffe et al. 2016; Olsoy et al. 2018). To standardize our structural diversity metric comparisons, we clipped a 100 x 100 m (1-ha) region out of each image for testing purposes. We generated a canopy height model (CHM) by subtracting a ground surface (minimum height on a 1-m moving window) from the digital surface model generated by ODM (Fig. 2). We calculated structural diversity metrics related to volume, openness (gaps), and heterogeneity (internal and external) (LaRue et al. 2019) at a 1-m spatial scale in R version 4.4 (R Core Team 2024) with the terra package (Hijmans 2024). Volume was summed across the 1-ha plot. We calculated the percent of canopy gaps (pixels with less than 15 cm vegetation height) aggregated to 1 m and then averaged across the 1-ha plot. Heterogeneity was calculated as the standard deviation of vegetation heights, with external structural heterogeneity representing the average standard deviation across the 1-ha plot, and internal structural heterogeneity calculated as the standard deviation of the standard deviation of height across the 1-ha plot (LaRue et al. 2019). For the grazed-ungrazed sites (n = 6 pairs), we used paired t-tests to assess differences in structural diversity metrics.

Results

Ecostates

Unsurprisingly, volume was highest in the juniper site with 3610 m^3ha^{-1} compared to both the shrub steppe site (1046 m^3ha^{-1}) and the invasive annual grass site (1480 m^3ha^{-1}). Structural heterogeneity metrics were lowest in the invasive annual grass site (external = 0.046, internal = 0.055) compared to the shrub steppe site (external = 0.096, internal = 0.072) and the juniper encroached site (external = 0.201, internal = 0.151).

Grazing

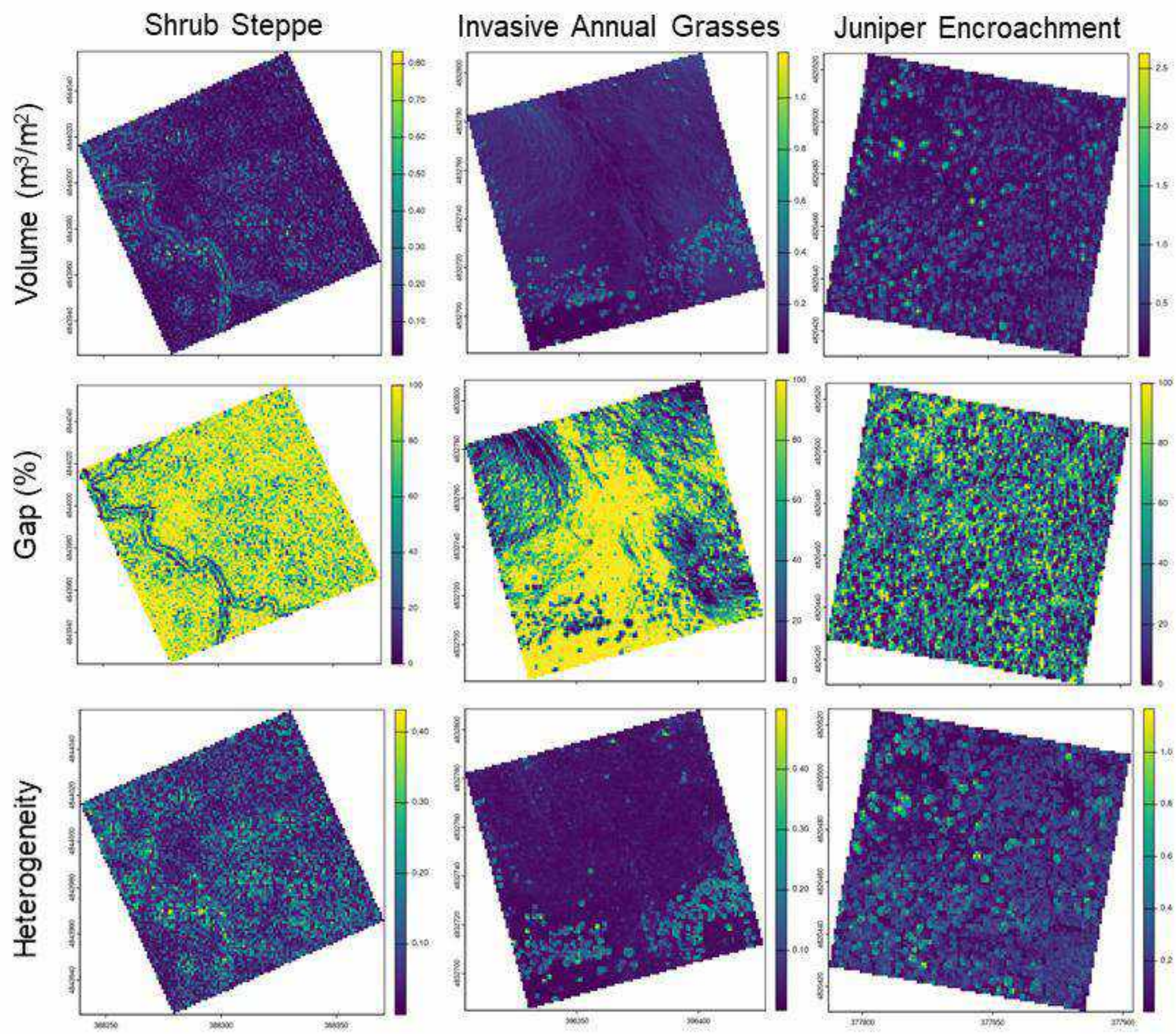

Figure 3. Structural diversity metrics for three sites representing distinct ecological states in Oregon, USA.

We did not find any statistical differences in structural diversity metrics between grazed an ungrazed plots at NGBER. Volume was 4508 m^3ha^{-1} in grazed and 4690 m^3ha^{-1} in ungrazed plots (t_5 = -0.36, P = 0.733). Gap percent was marginally significant with 56% gaps in grazed and 49% in ungrazed plots (t_5 = 2.45, P = 0.058). External heterogeneity was 0.19 in both grazed and ungrazed plots (t_5 = -0.05, P=0.96) and internal heterogeneity was 0.23 in both grazed and ungrazed plots (t_5 = -1.21, P = 0.28). Variability was higher between sites than treatments, for example, the site with the most juniper had 15,458 m^3 volume, while the non-juniper pastures had between 1147 and 1767 m^3 volume. Percent gaps also ranged from 0.1% at the juniper site to over 80% at two of the grazed non-juniper sites.

Discussion

Structural diversity metrics differed across ecological states, with juniper encroached sites having higher volume and less canopy gaps. However, we did not detect structural diversity differences in grazed pastures compared to long-term grazing exclosures, perhaps due to the small sample size (n = 6). The light to moderate grazing at the site could explain our results, which did not lead to differences in species composition (Copeland et al. 2021). The scale we used to calculate structural diversity metrics (1 m) could also be wrong for the ecological process (Levin 2000). The relative contribution of different plant functional types and species to structural diversity is unknown and could shed light on differences in biodiversity and occupied niches, which are undetected when looking at site-level structural diversity metrics. For example, the volume and canopy connectivity seen at the invasive annual grass invaded site is due to large mats of medusahead and indicate high wildfire fuel loading within a degraded system, while similar volume and connectivity in the shrub steppe ecological state represents high shrub cover with less connectivity of fine fuels. Selecting metrics that quantify these differences in wildfire risk and biodiversity is vital (Levin 2000; Ellsworth et al. 2020). Rangelands likely have differences in useful spatial scales (Zaiats et al. 2024) and less emphasis on vertical structural diversity than forests, particularly semiarid rangelands which tend to have lower productivity. However, more productive rangelands such as African savannas or the central plains of USA could demonstrate some of the vertical stratification and utilize the wealth of structural diversity metrics already developed for forested systems.

Future research could explore how metrics change across different scales and seek to directly link structural diversity metrics with ecosystem functions. A few examples of future work are landscape prioritization for fuels management, assessing resistance and resilience after disturbances, and developing workflows and tools to ease the implementation of these across broad landscapes and ease administrative burdens for land management agencies.

Acknowledgements

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Assessing woody plant health in rangeland ecosystems: implications for estimates of aboveground biomass

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Key words: Standing dead; Tree health; Plant functional types; Allometry; Rangelands

Abstract

Rangelands are subject to episodic droughts, regular fires and grazing pressure, all of which impact woody plant (tree/shrub) health. Consequently, standing dead and senescent woody plants are key components of these ecosystems. Stand-level, woody aboveground biomass (*AGB*), an important component of the terrestrial carbon budget, is typically scaled using individual-based allometric relationships with predictor variables such as stem diameter or crown area measured through on-ground inventories of woody plants. Current data are lacking to allow assessment of the influence of woody plant condition on allometry and subsequent scaling of *AGB*. To address this, we undertook field measurements across 431 Australian rangeland sites to improve understanding of the variation in the condition of woody plants across rangelands, including how condition of different plant functional types affects overall stand condition, and how stem diameter-crown area allometry varies with condition and plant functional type. Field measurements included stem diameter, crown width and vigour, and health scores of live and standing dead woody plants. Over one-quarter of individual woody plants were either dead or senescing across all sites. Stem diameter-crown area allometric relationships differed among plant functional types, with those found for trees differing from those of shrubs and multi-stemmed acacias. For a given stem diameter, allometry-predicted crown area declined as health score decreased. Our findings suggest that if traditional allometric relationships developed for live, healthy woody plants are applied to predict *AGB* in these ecosystems, substantial over-estimations may result, particularly for stands with a relatively high proportion of woody plants of poor condition. Results will inform ongoing improvements to the accuracy of stand-level biomass estimates in rangelands.

Introduction

Stand-level aboveground biomass (*AGB*) is a key component of the terrestrial carbon budget and typically scaled using allometric relationships with predictor variables such as stem diameter (Paul et al. 2016) or canopy area (Suganuma et al. 2006; Chieppa et al. 2020) measured through on-ground inventories of woody plants. However, most allometric relationships have been developed using young, healthy woody plants (Baker et al. 2004), and there is a paucity of data available to assess the influence of plant condition on this allometry and subsequent scaling of stand-level *AGB*. Uncertainty in *AGB* estimates will result when variance in condition of woody plants within a population to which the allometric relationship is being applied differs from that within the population of woody plants upon which the relationship was originally developed. This leaves a potential over-prediction bias in *AGB* when typical allometric relationships are applied to a population of woody plants containing relatively high proportions of over-mature, or dead woody plants.

In Australia, rangeland ecosystems encompass a broad range of woody vegetation types that are increasingly being monitored to assess the impact of changed climate and management on provision of ecosystems services through estimating changes in *AGB* (Fensham et al. 2011). Further, rangelands are subject to episodic droughts, regular fires and grazing, all of which impact woody plant health (e.g., Fensham et al. 2003; Fensham 2005; Cook et al. 2020). Rangeland ecosystems therefore provide a good case study for exploring implications of health of woody plants on allometry-predicted biomass and subsequent scaling of stand-level *AGB*.

The objectives of this study were to: (i) develop a protocol to quantify plant condition and apply this to extensive plot-based inventories to quantify typical proportions of woody plants that are senescent or dead, (ii) assess how health condition of individual woody plants influences their biomass to inform how allometry-predicted biomass may be adjusted based on condition of woody plants of different types and sizes, and (iii) explore implications of health condition of woody plants on allometry-predicted biomass and subsequent scaling of stand-level *AGB*.

Methods

A total of 431 sites (each 90 m × 90 m) from 51 properties across Australian rangelands were selected to cover a range of rangeland vegetation types. We measured 278,478 individual woody plants for health score of the stem (H_S) and crown (H_C) of live woody plants, or health score of standing dead woody plants (H_D) (Table 1) and recorded plant functional type (PFT, as per Paul et al. 2016), including Shrubs, Multi-stemmed acacia trees, *Eucalyptus* and *Corymbia* (Eucalypt) trees, Mallees, and Other trees of relatively high wood density. Live aboveground biomass of individual woody plants ($AGBi_{Live}$) was estimated from the application of PFT-based allometric relationships described by Paul et al. 2016. Standing dead aboveground biomass of individual woody plants ($AGBi_{Dead}$) was estimated using theoretical PFT-based allometric relationships developed for standing dead woody plants (Paul and Roxburgh 2024), noting that these allometrics were representative of an H_D score of 1. Stand-level total aboveground biomass (AGB_{Total}, Mg DM ha^{-1}) was calculated from the sum of all $AGBi_{Live}$ and $AGBi_{Dead}$ divided by site area.

For each individual tree/shrub, stem diameter (*D*) was measured at either 130 cm (*D130*; trees) or 10 cm (*D10*; shrubs), and the width and length of the crown was measured at the smallest and longest diameters of the crown, respectively. Measurements of crown width and length were used to estimate the crown area of the individual woody plant (*CAi*, m^2), assuming an ellipse.

Influence of condition on crown cover of individual woody plants

Crown vigour of the *CAi*, defined as the percentage of the *CAi* occupied by branches and/or leaves (Table 1), was visually assessed for 1,201 individuals of varying PFT and health score, excluding stumps, across 45 sites covering a range of vegetation types and site conditions. The effect of health score on *CAi* of a given *D* was tested, where *D* is a surrogate of aboveground woody biomass of individual trees/shrubs currently used in existing allometric relationships. Separate relationships were developed for different groupings of PFT, starting with the five PFTs, and further grouping into broader life-forms of 'Trees'

(Eucalypt, Other trees, Mallee) and Shrubs/Multi-stemmed acacias. Analysis of variance was used to test whether crown vigour differed significantly between health scores and life-forms.

D-CAi allometric relationships were developed with the form:

$$CAi = aD^{b} \qquad \text{Eqn 1}$$

where *CAi* was individual crown area (m^2), *D* was *D130* for trees and *D10* for Shrubs and Multi-stemmed acacia, constant *a* was a scaling factor and constant *b* was the exponent, determining rates of growth. Dead woody plants with H_D scores of 4 and 5 where there was no crown were excluded.

Sensitivity of stand-scale allometry-predicted woody biomass to plant health

Sensitivity of allometry-predicted AGB_{Total} to variations in plant condition were assessed by comparing 'uncorrected' *AGB* derived from application of existing allometric equations as described above, with alternative estimates of *AGB* where downward 'corrections' for different health scores based on assumed typical reductions in *AGB* components (stem, branch and foliage) were applied (Table 1). Due to the paucity of information on typical reductions in these components associated with differing health, these corrections were informed using published data on typical allocations to different biomass components (e.g., Forrester et al. 2024; Paul and Roxburgh 2024), and then proportionally reducing all or part of different components in line with the health scores as described in Table 1.

Table 1: Description of health scores applied to crown and stem components of live woody plants and to standing dead woody plants, and assumed corrections for downward adjustment of allometry-predicted biomass used in sensitivity analyses.

Health Score	Description	Assumed corrections[1]
	Live woody plants: Crown (H_C)	
1	Crown very healthy; almost no dead branches	1.00
2	Crown fair; some small dead branches	1.00
3	Crown poor; most small branches dead	0.50[2]
4	Crown very poor; most small branches dead and one or more large dead branches	0.40[2]
5	Crown nearly dead; most small and large branches dead	0.30[2]
	Live woody plants: Stem (H_S)	
1	Stem live, bark intact	1.00
2	Stem live, bark breached/shallow scars but still intact	1.00
3	Stem live, bark breached/deep scars and heartwood exposed	0.30[2]
4	Stem live, but heartwood extremely hollowed or stem mostly dead	0.20[2]
	Standing dead woody plants (H_D)	
1	Dead, with small canopy branches	1.00
2	Dead, with only large canopy branches	0.80[3]
3	Dead, main bole and few large branches remaining	0.50[3]
4	Dead, only main bole remaining or most of stem height	0.10[3]
5	Dead, more than half of main stem missing	0.05[3]

[1] assumptions for downward adjustment of *D*-based allometry-predicted biomass used in sensitivity analyses. Note: A value of 1 indicates no correction and a value of 0.5 indicates a reduction of 50%.

[2] assumptions for H_C and H_S were only applied for for large (*D130* >55 cm) highly-senescent (H_S of 3-4 and/or H_C of 3-5) Euc trees.

[3] assumptions were only applied for dead woody plants (H_D 2-5).

Results

Characteristics and condition of woody plants in rangelands

Across all stands, over one-quarter of individuals were either dead or senescing (mean ± SD: 26.1 ± 23.3%). The proportion of dead individuals averaged 15.9 ± 18.3%; 10.6 ± 16.0% were standing dead (with branches remaining, H_D scores of 1 or 2), and 5.3 ± 9.5% were stumps (only the main stems remaining at various heights, H_D scores of 3-5). The distribution of data for the proportion of dead was strongly positively skewed with only one-third of sites having >16% of individuals being dead.

Influence of condition on crown cover and biomass of woody plants

Crown vigour of individual woody plants significantly (F = 49.12, P<0.001) increased as condition increased. For live trees, crown vigour increased from a mean of 32% at an H_C score of 5, to a mean of 69% at an H_C of 1, and for Shrub/Multi-Ac, increased from a mean of 68% to 88% as condition score improved from an H_C of 5 through to an H_C of 1. Similarly, vigour of standing dead (dead woody plants with branches remaining) increased from 20% to 43% as condition increased from H_D 3 to 1. Within the broader groupings of 'Tree' and 'Shrub/Multi-stemmed acacia', there were no statistical differences (P>0.05) between PFTs.

D-CAi allometric relationships varied between broader life-form groupings of Trees and Shrubs/Multi-stemmed acacias (data not shown). For both live and dead Trees, *D-CAi* allometric relationships differed with condition (Fig.1). For a given *D*, allometry-predicted *CAi* declined as condition declined. Model efficiency (*EF*) of *D-CAi* allometric relationships decreased with decreasing condition (H_C 1-5: EF = 0.63 to 0.32; H_D 1-3: EF = 0.52 to 0.25), largely attributable to differences in sample size for live Trees (H_C 1-5: N = 22,746 to 123), but not dead Trees (H_D 1-3: N = 821 to 1,201).

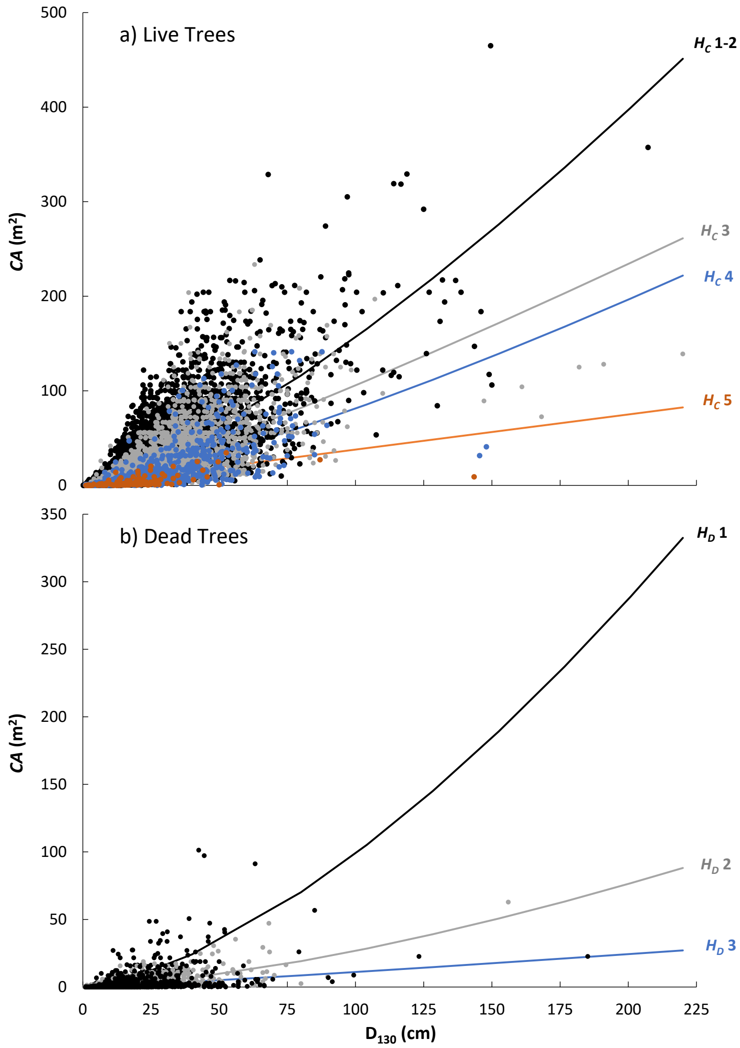

Figure 1. Allometric relationships between stem diameter (*D*) and crown area (*CA*) corrected for crown vigour for the Trees grouping representing the Eucalypt, Other hardwood tree and Mallee plant functional types: (a) live Trees and b) dead Trees. Lines represent fitted power functions. Health scores for live (H_C 1-5) and dead (H_D 1-5) trees are defined in Table 1.

Across all sites (N = 431), allometry-predicted AGB_{Total} was on average 9 ± 12% (but up to 72%) lower when multipliers were applied to account for standing dead and, where present, large senescing Eucalypt trees, relative to existing allometric equations (Fig. 2a). These corrections had a particularly high influence on sites of relatively high biomass (AGB_{Total} > 100 Mg DM ha^{-1}; N = 22), where allometry-predicted AGB_{Total} was on average 34 ± 19% lower after applying the recommended corrections. By comparison, when only considering sites where there were no large senescing Eucalypt trees (N = 317), allometry-predicted AGB_{Total} was on average 5 ± 8% (but up to 50%) lower when multipliers were applied to account for standing dead (Fig. 2b).

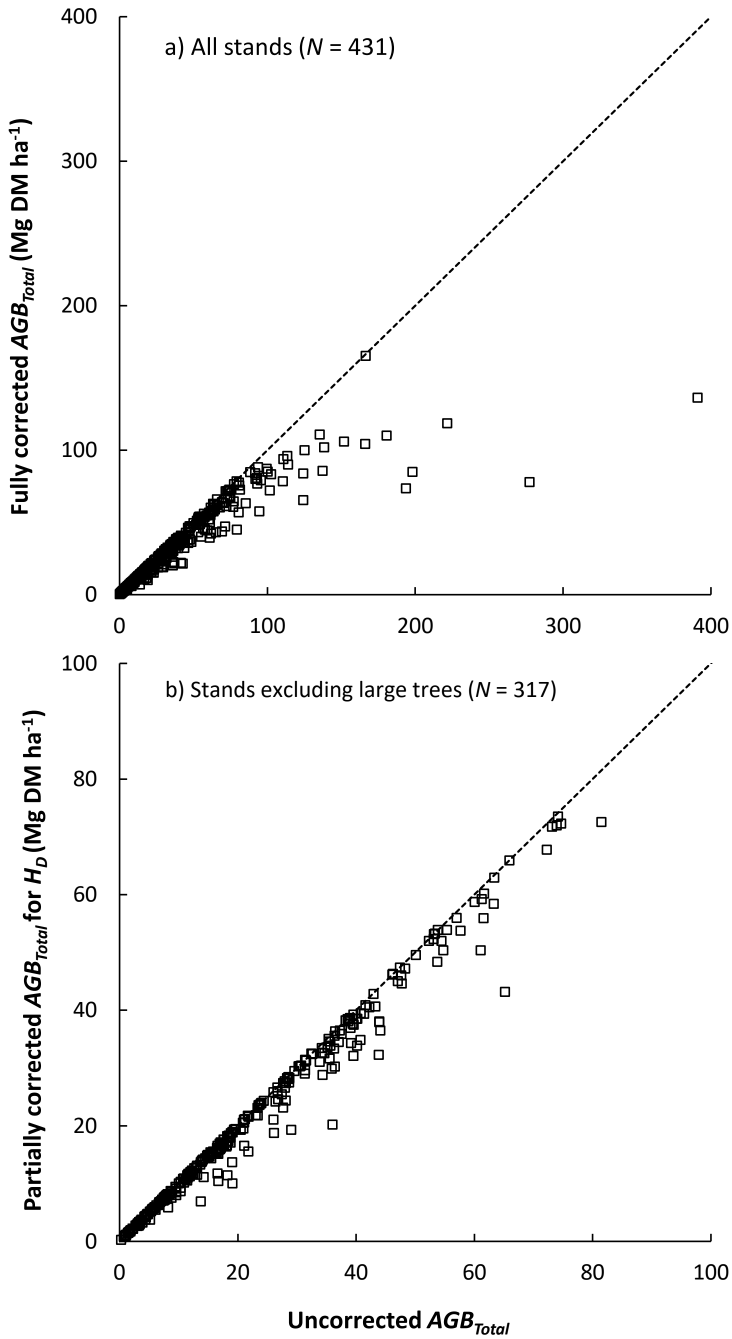

Figure 2. Relationship between uncorrected stand-level allometry-predicted total aboveground biomass (AGB_{Total}, Mg DM ha^{-1}) and AGB_{Total} where a) full corrections were applied to account for H_C, H_S and H_D scores, and where present, large senescent Euc trees, for all of the 431 rangeland sites, and b) AGB_{Total} where partial corrections were applied to account for H_D scores for 317 rangeland sites where there were no large trees (*D130* >55 cm). Corrections are provided in Table 1.

Discussion

A key finding of this study was that across the 431 measured sites, around 16% of individuals were standing dead. A review found in Australian woodlands that 8.1-23.0%, and in dry sclerophyll forests, 0.2–4.5% of total biomass was standing dead (Woldendorp et al. 2002). Mortality events in rangelands tend to be episodic, for example, Fensham and Holman's (1999) survey suggested that ~25% of live basal area was converted to dead standing wood during 5 years of intense drought over a large area of Northern Queensland. Cook et al. (2020) reported that standing dead was 9.6% of total biomass in savannas subjected to regular fires.

This is the first study in rangelands to provide evidence of the influence of health condition of woody plants on their *AGB* – both directly via a significantly lower *D* (and hence, *AGB*) for a given *CAi* (Fig. 1), and indirectly via a significantly decreased *CA* with decreased canopy vigour. Our results suggest that the condition of individual woody plants within rangelands are likely to influence the observed canopy cover of the stand.

Assuming these 431 diverse rangelands stands were representative of Australian rangelands more broadly, these results suggest that if traditional *D*- or *CA*-allometric relationships developed for healthy live trees or shrubs were applied to these ecosystems to predict *AGB*, substantial over-estimation may result, particularly for stands with a relatively high proportion of trees of relatively poor condition. The fact that there was decreasing efficiency in the *D*-*CAi* relationship with decreasing health score of woody plants (Fig. 1) indicated that not only will condition impact the relationship required to predict *AGB*, it will also impact the precision of that relationship. This may be expected because a poor health score is qualitative and will likely encompass varying effects on *AGB* given it will not accurately account for the extent of stem hollowing. Internal hollows within the stem and large branches are typically not visible to the on-ground observer seeking to provide a health score, yet these hollows are likely to substantially influence the actual *AGB*.

Conclusions/Implications

This study provides improved understanding of the variation in woody plant condition across a wide range of rangeland vegetation types, and its impact on allometric relationships, which are critical for predicting woody biomass. To avoid substantial over-prediction of total stand *AGB*, corrections to existing allometric relationships derived from predominantly healthy woody plants are required to account for differences in *AGB* of dead woody plants, and a decline in *AGB* of live woody plants, particularly as they age and over-mature. The results inform improved accuracy of stand-level woody biomass estimates in rangelands.

Acknowledgements

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DAVE-Grass: a process-based model for herbaceous vegetation dynamics

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Key words: dynamic vegetation model; C_3/C_4 vegetation; elevated CO_2 concentrations; elevated temperatures

Abstract

Process-based vegetation models are invaluable tools for understanding and predicting vegetation responses to changes in climate and land management. However, many existing models were developed decades ago and do not incorporate our latest knowledge of plant and ecosystem functioning. Here we present DAVE-Grass, a new dynamic and process-based model of herbaceous vegetation function with a focus on Australian grasslands. The model integrates our latest empirical and theoretical understanding of processes considered to be critical for predicting rangeland responses to changes in climate and management: photosynthesis, growth, carbon allocation, phenology, establishment, persistence, water and nutrient dynamics as well as fire behaviour. It represents C_3 and C_4 plants as well as annual and perennial growth forms which compete for resources such as light and water. The model has been evaluated against data from manipulative experiments, land-atmosphere fluxes, biomass, as well as phenology from phenocams and satellites. In this presentation, we showcase early applications of the model with a focus on the current and projected distribution of C_3 and C_4 vegetation across Australia under different climate change scenarios. The process-based nature of the DAVE-Grass model provides insights into the mechanisms underlying observed changes in vegetation cover and composition. By combining these features with its applicability from site to continental scales, the model promises to be a critical tool for guiding effective management and adaptation efforts in rangelands.

Introduction

Grasslands, including managed pastures, rangelands, and savannas, cover approximately 40% of the global ice-free land surface, act as significant C storage, and fulfil a wide range of ecosystem services (Petermann & Buzhdygan, 2021; White et al., 2000). However, many grasslands are at risk from climate change and intensifying land use and land management globally large areas of grasslands have been identified as degraded to some extent (Bardgett et al., 2021). The increasing pressure on grasslands highlights the need for reliable tools to predict their responses to changes in climate and to identify sustainable management options.

Process-based vegetation models are primary tools to understand ecosystem processes and to predict their functioning under a changing climate (Fisher & Koven, 2020). However, existing process-based models are not well suited to investigate many real-world applications. Dynamic vegetation models often oversimplify crucial processes such as phenology, senescence, and plant persistence (De Kauwe et al., 2017). In addition, these types of models often ignore management routines.

Pasture and grass growth models do account for many management activities, but often oversimplify plant physiological processes. In addition, these types of models were often developed for a specific pasture type and are not applicable across larger spatial scales (Ma et al., 2019).

Here, we present the grassland model DAVE-Grass, a newly developed model that aims to overcome these critical limitations of existing models. We give a short overview of key processes represented in the model and showcase its ability at a grassland site in southern NSW.

Methods

Model description

DAVE-Grass is a dynamic, process-based vegetation model that incorporates key physiological, phenological, and plant demographic processes of herbaceous vegetation. Management routines including grazing, mowing, and irrigation, are currently under development. The model is embedded into the widely used LPJ-GUESS dynamic vegetation model (Smith et al., 2014).

The key processes represented in the model are illustrated in Fig. 1. The model uses absorbed radiation by the canopy to calculate photosynthesis in different canopy layers using the Farquhar et al. (1980) model for C_3 vegetation and the von Caemmerer (2000) model for C_4 vegetation. Plant respiration is calculated as in LPJ-GUESS. The resulting net primary productivity (NPP) is used for either growth or kept as storage in the form of non-structural carbohydrates. The carbon (C) used for growth is allocated to different plant components depending on environmental conditions and plant growth stage. Similar processes govern the plant turnover (senescence) rates. These processes are modulated by competition between plant types, disturbances such as fire, as well as nutrient and water availability. Long-term plant survival and dynamics are represented in the form of mortality and establishment processes.

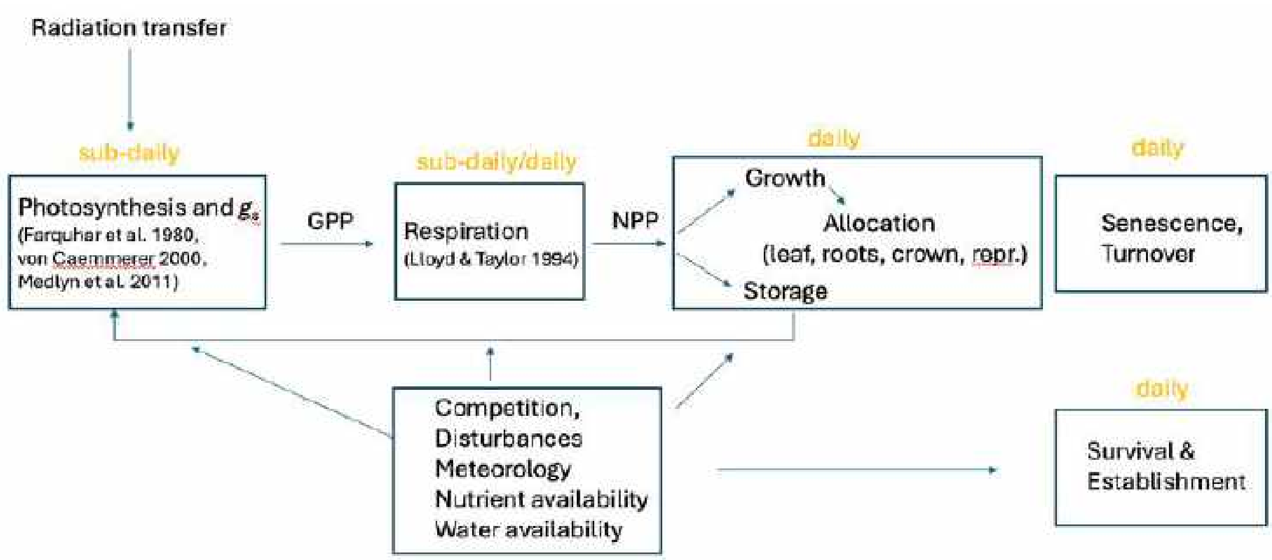

Figure 1: Schematic diagram of the DAVE-Grass model including the most important processes and their interactions.

Site-level application

We present a site-level application of the model at Yanco, an extensively managed, semi-arid grassland site in the western plains of the Murrumbidgee Catchment in southern NSW (latitude: -34.9893, longitude: 146.2907). Mean annual precipitation at the site is ca. 450 mm. More information on the site can be found in Yee et al. (2015). The type or species of grass as well as the grazing intensity are not reported. Meteorology as well as land-atmosphere fluxes of carbon dioxide, water vapour, and heat are measured at the site using an eddy covariance system. Gross primary productivity (GPP) was derived from measured net ecosystem exchange using the SOLO machine learning algorithm.

The model was forced with meteorology measured at the site from 2014 to 2021. In addition to the simulation using measured meteorology (hereafter 'control'), we performed three factorial experiments to analyse ecosystem responses to the main climate change drivers CO_2 and temperature: 1) elevated CO_2 concentrations of +200 ppm ('eCO2'), 2) elevated temperatures of 2 °C above ambient, assuming an unchanged constant relative humidity ('eTair') and 3) a combination of +200 ppm CO_2 and +2 °C temperature ('eCO2_Tair'). All experiments started 8 years before the simulation period in 2006 and were implemented as a step change. Prior to that, the model was spun up using recycled meteorology according to standard model procedures.

Results

Observed and simulated GPP

The daily average measured meteorology of the site is shown in Fig. 2a. At the sub-daily time scale, temperature reaches extremes of >40 °C in summer and < 0 °C in winter. Precipitation is distributed relatively evenly throughout the year. The 2018 - 2020 period is characterised by drier-than-average conditions.

Fig. 2b shows the derived GPP from the flux tower in comparison to simulated GPP by the DAVE-Grass model. Observed GPP shows largely irregular temporal dynamics. While peak GPP occurs mostly in spring, productivity is clearly linked to available soil moisture and the ecosystem can be productive in summer if moisture conditions allow. The model reproduces these flux dynamics moderately well ($r^2 = 0.45$). Notable disagreements between simulations and observations occur in summer and autumn 2016, where the model underestimates GPP. Closer examination revealed that biases in available soil moisture are the primary cause for this discrepancy.

The simulations further indicate that the site is C_3-dominated (Fig. 1c). C_4 vegetation is scarcely present and contributes negligibly to GPP in the summer months.

Climate Sensitivity Experiments

The climate sensitivity simulations revealed that elevated CO_2 concentrations had overall positive effects on both C_3 and C_4 vegetation (Figure 2d). C_3 vegetation achieved higher GPP throughout most of the simulation, though not consistently. Periods of high growth and therefore high water use may lead to subsequent phases of reduced water availability compared to the control simulation, limiting productivity in certain time periods.

Elevated air temperatures had positive effects foremost for C_4 vegetation, which contributed a notably higher proportion to overall GPP in a warmer climate (Figure 2e). C_3 vegetation benefited from elevated air temperatures in some periods but showed declined productivity in others.

The combination of elevated air temperatures and elevated CO_2 concentrations (*eCO2_eTair*) had a strong positive effect on C_3 vegetation during most time periods (Fig 2f). However, as in the *eTair* scenario, productivity declined during a few short time periods compared to the control simulation. This is evident in early summer 2018, when drier conditions occurred compared to the control simulation due to increased water use from autumn to spring 2018. In this scenario, C_4 vegetation remains almost unchanged compared to the control run, likely due to strong competition by C_3 plants.

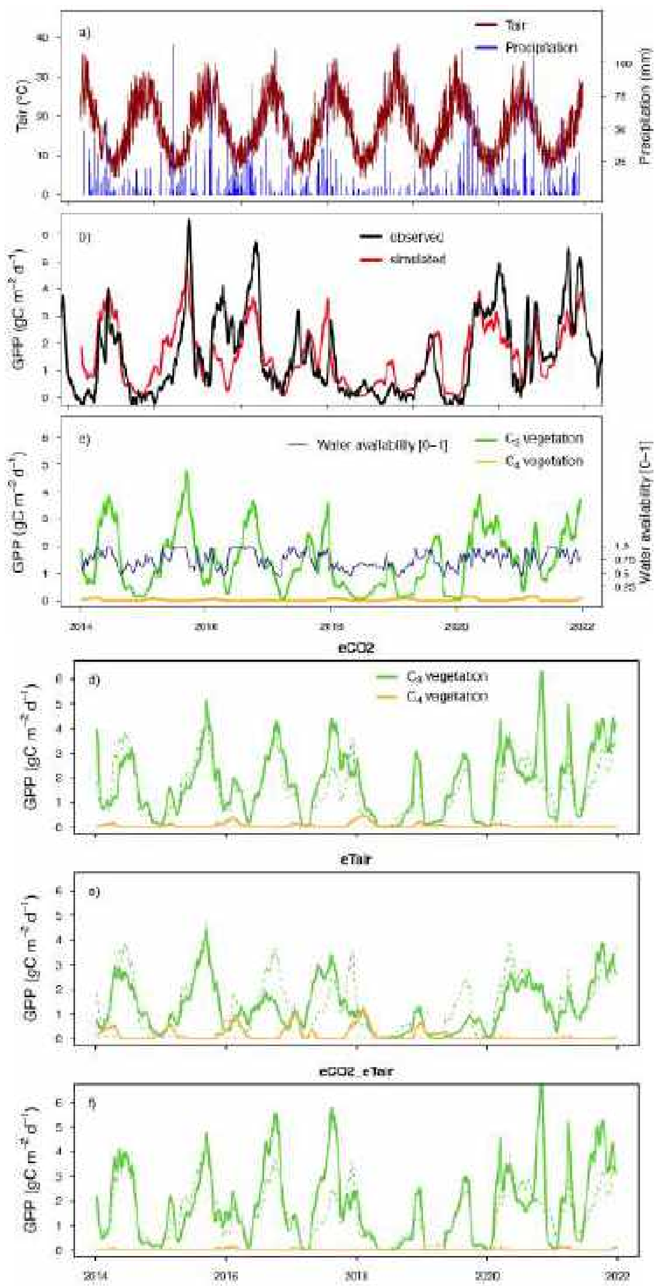

Figure 2 a) Measured average daily air temperature and precipitation at the Yanco site. b) Observed and simulated (control experiment) of gross primary productivity (GPP). c) simulated GPP divided into contributions from C_3 and C_4 vegetation. Shown is also simulated plant available soil water content as a scalar from 0 to 1. Panels d) to f) show the climate sensitivity experiments: d) elevated CO_2

concentrations (+200 ppm), e) elevated air temperatures (+2 °C), and f) a combination of elevated CO_2 concentrations (+200 ppm) and air temperatures (+2 °C). The dashed lines denote the control simulations as shown in panel c.

Discussion

We present a brief overview of the DAVE-Grass model, a newly developed process-based model of herbaceous vegetation functioning. The model includes physiological, phenological, and plant demographic processes that were informed by the latest theory and data and that are commonly ignored or oversimplified in current dynamic vegetation models, especially for herbaceous vegetation (De Kauwe et al., 2017; Wilcox et al., 2023).

The application of the model to the Yanco site, a semi-arid grassland in southern NSW, demonstrates that the current model version can broadly capture the irregular patterns of ecosystem productivity at this location. Nonetheless, further model development is needed to improve the dynamics of vegetation productivity. Improvement should focus on hydrological processes such as soil evaporation and percolation, as well as the sensitivity of vegetation processes like photosynthesis and leaf senescence to water stress.

The climate sensitivity scenarios illustrate that the model predicts beneficial effects of higher CO_2 concentrations for both C_3 and C_4 vegetation. This is likely due to direct CO_2 fertilisation effects for C_3 plants as well as water savings effects due to stomatal closure for both C_3 and C_4 plants (Ainsworth & Rogers, 2007; Morgan et al., 2011). As expected, higher air temperatures benefited C_4 plants (Yamori et al., 2014), whereas a combination of these two factors benefited C_3 plants more than C_4 plants. In all cases, the simulations reveal strong legacy effects, meaning that the past state of vegetation influences its current state.

In summary, this case study offers a foundation for understanding the factors driving vegetation distribution and predicting how these patterns may shift in a future climate.

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Harnessing Landsat fractional cover time series to monitor dryland ecological integrity at multiple scales

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Key words: vegetation structure complexity; satellite remote sensing; non-photosynthetic vegetation; bare soil; elastic net model

Abstract

Inadequate environmental management in drylands can have serious consequences shifting ecosystems into alternate stable states where key ecosystem services are compromised. Open access Earth observation data can provide continuous and consistent measurements globally, thus providing valuable information on remote dryland locations. The most widely employed remote sensing indicators are spectral indices of vegetation greenness, such as the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) and are not specifically fit for drylands where background soil has a strong influence and senescent vegetation often dominates. Methodological advances in the past decade now allow the quantification of vegetation fractional cover (VFC) into three categories: photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV) and bare soil (BS). Although monitoring applications have been derived from this product, significant knowledge gaps remain regarding the relationships between vegetation cover fractions and descriptors of ecosystem condition. Our work addressed these gaps at regional and continental scale. At the regional scale we explored links between VFC time series statistics and field measurements of woodland ecosystem quality (soil health and vegetation structure complexity) and elastic net regression to assess combinations of fractional cover statistics for predicting ecosystem quality. We found that time series statistics were robust predictors of soil health and vegetation structure complexity. At the continental scale we demonstrated how vegetation structure components (i.e. woody and herbaceous cover) can be accurately predicted by VFC time series statistics (RMSE<14.75%). Moreover, we found links between field-measured vegetation structure complexity metrics (i.e., growth form and height class diversity) and different combinations of cover-fraction time-series statistics depending on vegetation type and climate.

Introduction

Drylands are vulnerable to degradation due to inadequate land management practices and climate change (D'Odorico et al. 2013). Monitoring methods that enable access to these large and remote areas are needed to inform more sustainable land management practices that can adapt to a changing climate. Multi-spectral satellite remote sensing can be a suitable technique to systematically collect information in dryland ecosystems. A large majority of the methods employed so far relied on vegetation greenness as an indicator of ecosystem health (Soubry et al. 2021). However, drylands are often dominated by senescent vegetation that is hard to separate from soil signals in terms of visible and short infrared wavelength reflectance (Roberts et al. 1993). Moreover, vegetation in this state can still provide crucial functions in drylands such as protecting the soil from erosion (Ludwig et al. 2005), and forage and habitat provision (Moore et al. 2004; Zou et al. 2016). Methods have been developed in the past decade that estimate vegetation fractional cover (VFC) i.e., the proportion of photosynthetic vegetation (PV), non-photosynthetic vegetation (NPV) and bare soil (BS) (Guerschman et al. 2015). Consistent and continuous observation of such features not only allows to track directional change but also deepen the knowledge on temporal dynamics in dryland systems (Francis et al. 2023; Shumack et al. 2021).

The combination of remote sensing products and field observations of ecosystem condition is a fundamental step towards robust monitoring schemes that facilitate adaptive land management (Lawley et al. 2016). Several attempts of modelling vegetation/rangeland condition from remote sensing have been made with varying degrees of field data integration (Lawley et al. 2016; Retallack et al. 2023). In Australia, VFC time series data are increasingly being employed to this end (Department of Environment and Science 2021; Love et al. 2020; Williams et al. 2021). However, only the 'Spatial Biocondition' classification model was trained and evaluated employing over 9,000 field observations within the state of Queensland (Department of Environment and Science 2021). Moreover, links between VFC statistics and the variables that determine condition (e.g., vegetation structure, phenology and ground cover dynamics) have not been thoroughly explored.

Here we employed open-source field observations to explore relationships between time series statistics of remotely sensed VFC and dryland ecosystem condition. Our analyses aimed to answer two main questions:

1. How well do VFC time series statistics predict semi-arid woodland ecosystem condition? Which variables are more important?
2. How well do VFC time series statistics characterise vegetation structural complexity across multiple vegetation types and climatic regimes?

Methods

We obtained ecosystem condition indicators depicting woodland soil health and vegetation structure complexity of 450 'NSW grazing study' sites (State Government of NSW and NSW Department of Climate Change 2023). Soil health indicators were related to soil surface characteristics (i.e., landscape function analysis – nutrient cycling index (Tongway and Hindley 2000)) and topsoil physicochemical properties (i.e., total C, total N, total P and bulk density (Eldridge et al. 2016)). Structural complexity was obtained as an index following Val et al. (2018).

Further characterisation of vegetation structural complexity was undertaken based on TERN Ausplots surveys from dryland (i.e., areas with a rainfall to potential evapotranspiration ratio lower than 0.65) rangelands across the Australian continent (Munroe et al. 2021; TERN 2024). Point-intercept data of 740 plots were processed into woody and herbaceous fractional cover, and five metrics of structural complexity: height coefficient of variation (heightcv), growth form Shannon diversity (GFdiversity), height class Shannon diversity (HCdiversity), plot scale vegetation volume (vegvol, obtained as the product of average height and total cover), and volume coefficient of variation (volcv). Sites were classified according to combined major vegetation groups (NVIS Technical Working Group 2017) and agroclimatic zone (Hutchinson et al. 2005).

Time series of Landsat fractional cover (Joint Remote Sensing Research Program 2021) spanning 5, 10 and 30 years before field sampling were extracted for all overlapping pixels of each 'NSW grazing study' site. Time series statistics (seven for each cover fraction) were then calculated. Apart from typically used central tendency metrics (mean and median) we explored measurements of stability (standard deviation), persistence (intra and inter-annual minima), and dominance (intra and inter-annual maxima). Preliminary analysis showed little difference in model performance among time series extents; the process above was repeated for AusPlot sites using 10-year time series.

Models of woodland ecosystem condition indicators and vegetation structure were fitted through elastic net regression, a method for fitting multiple regression in cases where predictors are highly correlated employing coefficient shrinkage (Zou and Hastie 2005). Optimum parameters (α and λ) values were obtained (from a list of 275 possible combinations) through 250-fold cross validation. Model performance was assessed on the entire dataset through the root mean square error (RMSE) for accuracy assessment and the normalised RMSE (NRMSE = RMSE/standard deviation of observed values) for predictive power comparison across different variables. Models with NRMSE values close to 1 have null predictive power. Coefficient values and selection frequency of predictors across the candidate models were used to assess their importance.

Results

Woodland ecosystem condition

VFC time series yielded good models of woodland ecosystem condition (Figure 1). Although NRMSE was often well below 1, models of soil chemistry were the most accurate. Time series statistics of all cover fractions were found to be important predictors in elastic net models of ecosystem quality variables. Soil C and N were highly correlated with each other, thus shared the same main predictors (i.e., PVmedian, PVmean). Soil P was also related to C and N, however it was more strongly predicted by the annual maximum of green vegetation and negatively influenced by the annual persistence of the dead fraction. The average interannual minimum photosynthetic vegetation fraction was the most important remote sensing predictor of vegetation structure complexity and nutrient cycling index, as it was the most frequently included variable and displayed the highest relative importance in the tested models. Even though vegetation structural complexity displayed a moderately high NRMSE (>0.65), elastic net models were capable of distinguishing between low, medium, and high levels (Figure 1). This result encouraged more detailed analysis of vegetation structural components and continuous measurements of its complexity.

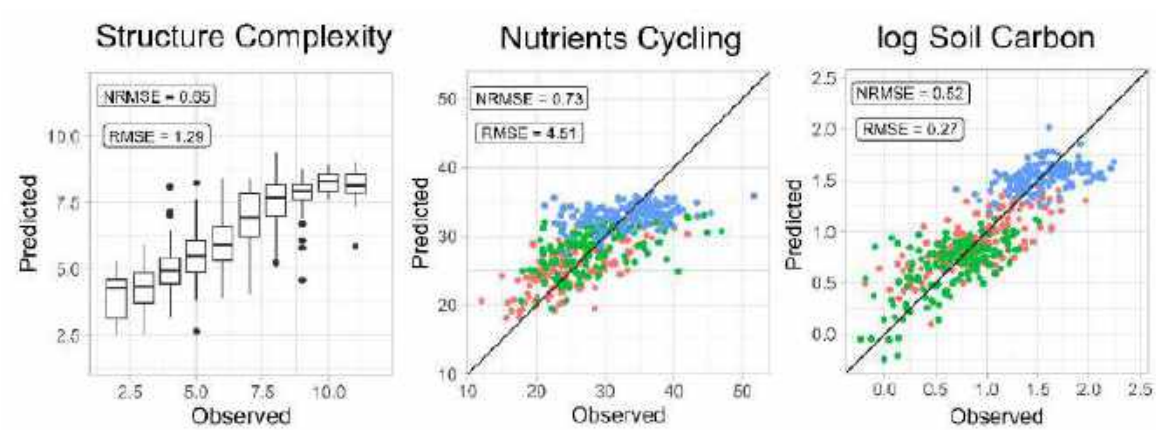

Figure 1. Box and scatter plots of modelled against observed values of the vegetation structural complexity index (dimensionless, left), the nutrients cycling index (dimensionless, centre) and the natural logarithm of soil carbon content (%, right). Root mean square error (RMSE) and its normalization by the standard deviation of observed values (NRMSE) are shown for all 3 models. Different colours indicate different woodland communities (i.e., blue = river red gum, red = black box, and green = white cypress pine).

Vegetation structure and structural complexity

Elastic net modelling based on Landsat fractional cover produced low-bias models of vegetation type cover across dryland ecosystems (Figure 2). Woody cover was more accurately modelled than herbaceous cover. Different fractional cover statistics were important for the prediction of vegetation cover type. In woody cover models, time series statistics related to both inter-annual and intra-annual variability were important. Variables related to the persistence of the green fraction were the most frequently included and most important positive predictors, whereas statistics related to the occurrence of high levels of bare soil were also important but negatively related to woody cover. Herbaceous cover was positively related to statistics describing the variability of both dry and photosynthetic vegetation.

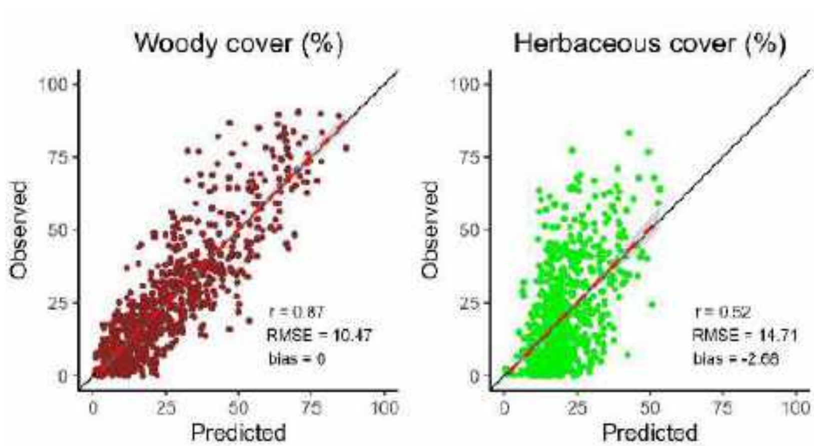

Figure 2. Scatterplots showing the observed and estimated woody component (left) and herbaceous component (right) of 740 AusPlot sites across the Australian drylands. The black line corresponds to the 1:1 agreement, the red dashed line represents the best linear fit between predicted and observed values. Pearson's correlation coefficient (r), root mean square error (RMSE), and bias (calculated as the mean difference between observed and predicted) are displayed.

VFC time series statistics produced structure complexity models of varied performance at the continental drylands scale (Figure 3). Elastic net models of vegetation volume and height class diversity performed the best, other models had an error close to the sample variability (i.e., NRMSE > 0.85). Models calibrated within specific vegetation - climatic groups were able to satisfactorily predict these metrics (NRMSE < 0.72). The most important predictors of HCdiversity were related to the occurrence and persistence of green cover and had positive coefficient values, while the temporal stability of the non-photosynthetic fraction was positively related to HC diversity. Vegetation volume was strongly related to the persistence of the remotely sensed green vegetation fraction. Predictor importance across specific vegetation-climate group models was variable.

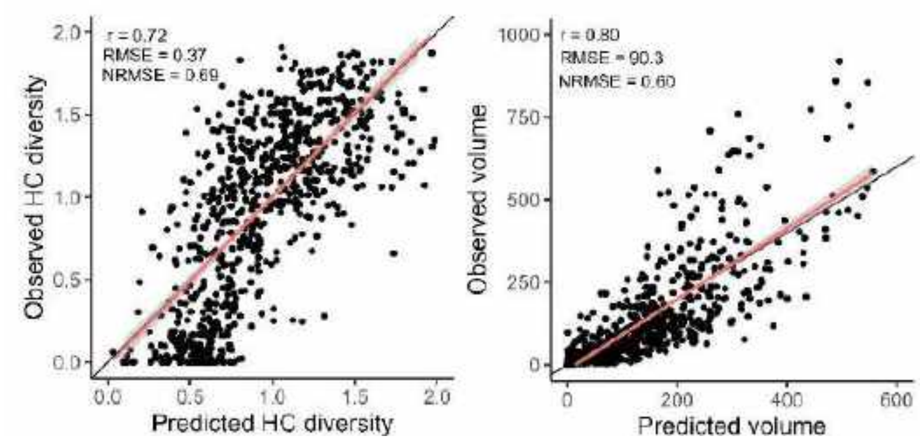

Figure 3. Scatter plots of observed versus modelled structure complexity indicators of all plots (n=740). Vegetation volume is expressed as the product of cover (%) and height (m). The black line corresponds to the 1:1 agreement, the red line represents the best linear fit between predicted and observed values.

Discussion and Conclusions

Variable importance for ecosystem condition indicator models in this study accord with assumptions and findings of previous research, but also revealed new insights. Metrics related to the dominance and stability of remotely-sensed green vegetation were important predictors of structure complexity, the nutrient-cycling index, soil carbon and soil nitrogen in woodlands. This aligns with the criteria employed by expert knowledge-based habitat condition models (Harwood et al. 2016; Love et al. 2020; Williams et al. 2021) and the evaluation of more complex data-driven models of 'BioCondition' (Department of Environment and Science 2021). Accordingly, long term seasonal averages of PV have been identified as important predictors of top-soil organic carbon, surpassing descriptors of climate, lithology and relief (Wang et al. 2018). Moreover, these metrics were also important for woody cover models at the continental scale and agrees with previous methods for modelling tree cover (Gill et al. 2017). Conversely, time series metrics of BS and NPV were often negatively related to woodland condition. This followed expectations, as the dominance and variability of BS in semi-arid woodlands are often respectively related to areas of consistently low and frequent heavily grazed vegetation cover, both cases resulting in poor vegetation structure and degraded soils (Eldridge et al. 2017; Val et al. 2018). Bare soil metrics were also previously identified as important predictors of biological condition class (Department of Environment and Science 2021) and top-soil organic carbon (Wang et al. 2018). The temporal variability of PV and NPV were positive predictors of herbaceous cover at the continental drylands scale, reflecting the seasonal behavior of C4 dominated grasslands (Munroe et al. 2022). This was evident in models of heightCV in savannah woodlands where the stability of BS and persistence of PV were important predictors negatively related to this indicator of structural complexity reflecting that the herbaceous stratum is either absent or overshadowed (in terms of relative cover) by the woody component.

Our research demonstrated the relevance of Landsat VFC as a strategic tool to monitor dryland ecosystems. We found significant and ecologically interpretable relationships between time series statistics of satellite observations of PV, NPV and BS and field observations of vegetation structure and structure complexity, and soil health. Our results set a robust basis for the identification of metrics to monitor the state of different dryland systems, and support informed selection of variables for data-driven modelling techniques.

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What standard error metrics don't tell us about model performance – a fractional cover use case

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Key words: spatial prediction models; remote sensing; fractional cover

Abstract

Environmental monitoring by land managers and land administrators using remote sensing has entered the era of big data, machine learning and open data. Remotely sensed data are commonly used in models as predictors for machine learning algorithms trained on field observations, to develop new products and applications as more data and greater computing power become available.

Despite the wealth of remote sensing data, it is often difficult to obtain representative reference data for these applications, and complete coverage of the predictor space is rare. Users are left to assume that the model outputs will apply to regions where reference data are unavailable. This can result in situations where stated accuracy and error metrics show good model performance, however at a local and possibly regional scales, the map products may not be representative of the true state and therefore not serve its intended purpose. Users of new remote sensing products and applications need to be aware of the uncertainty inherent in the products they use.

In this paper, we present an approach to communicate uncertainty by adding a spatial component to performance metrics by applying the 'Area of Applicability' (AOA) of spatial prediction models, to the Joint Remote Sensing Research Program's Fractional Cover 3 (FC3) product.

The FC3 product is widely used in research and applied settings to monitor vegetation cover and bare ground and inform other models such as pasture biomass or land condition across Australia's rangelands. It is imperative that we continue to improve our understanding of fractional cover models, and their strengths and limitations, to provide appropriate advice and direction to users who are reliant on these data. It can also help to inform future investments in field data collection or other methods of training data collection.

Introduction

The geographic coverage and repeatability of remotely sensed monitoring approaches are useful characteristics to overcome the challenge of monitoring Australia's rangelands, which cover more than 80% of the continent (ACRIS, 2008). The Joint Remote Sensing Research Program Fractional Cover 3 (FC3) product is one such approach which models the percentage of bare ground, photosynthetic vegetation and non-photosynthetic vegetation for each pixel. The model is built upon a collaboratively sourced database of field observations gathered by stakeholders across Australia, mostly within the rangelands.

As for many spatial prediction models, these training data may not meet the ideal standard of representativeness, due to practical constraints over its collection. This results in increased uncertainty in environments that are unsampled or under sampled, which is difficult to communicate to users of the product. The Area of Applicability (AOA) approach of Meyer and Pebesma (2021) is a useful tool that can enable us to better understand the limitations of the FC3 product, providing a method to assess the area to which the model can be reliably applied, and conversely providing insight into those locations which are not well represented. This also extends our ability to communicate uncertainty by adding a spatial component to performance metrics.

Methods

For this example, the methodology of Meyer and Pebesma (2021) was applied, with minor variations. Rather than assessing the AOA in-situ during model fitting we have performed a post-hoc assessment of an existing model by replicating as closely as possible the original model fitting procedure.

Two datasets are used in this example. The first is the training data for the FC3 model, consisting of approximately 4000 field observations of fractional cover collected across Australia between 1997 to 2018 following the method described in Muir et al. (2011). These have been matched to the nearest date, clear Landsat 5 TM,7 ETM+ or 8 OLI overpass, and the surface reflectance values calculated using the procedures described in Flood et. al. (2013), for a 3x3 pixel window. The second is the remotely sensed imagery for which fractional cover predictions can be made, which were Landsat seasonal composite reflectance mosaics for Australia, produced using the methods described in Flood et al. (2013), and Flood (2013), between winter 2014 and winter 2024 (DES, 2021-2024).

The AOA concept attempts to define the area in predictive space for which the model's performance is relevant. That is, the published model performance metrics are only appropriate when a location's characteristics are similar to the locations used to train the model. For each new location the Euclidean distance in predictor space to each of the training data points is calculated. Further, the distances are weighted by the model variable importance scores, under the assumption that locations further away in an important variable should be considered more serious than locations further away in a less important variable. Here, weights were based on SHAP (SHapley Additive exPlanations) scores (Lundberg & Lee 2017). The dissimilarity index (DI) is defined as the minimum of these distances. Those locations in which the DI is greater than a threshold are defined to be beyond the AOA. The threshold is determined by examining the distribution of the DI calculated in the training data under cross-validation. We follow Meyer and Pebesma's (2021) suggestion of a threshold set at the 75-percentile plus 1.5 times the interquartile range (IQR) of the DI values of the cross-validated training data.

Since the distribution of DI are based on cross-validation, the method is sensitive to the type of cross-validation used. There is some evidence that, when training points are spatially correlated, the common *k*-fold cross-validation leads to overly optimistic results. Conversely, spatial cross-validation, such as block cross-validation, has been found to be overly pessimistic. To account for the spatial structure in the sampling data but avoid under-estimating performance, we chose to use *k*-fold nearest-neighbour distance matching cross-validation (*kNNDM)* (Linnenbrink et al 2023).

A sequence of seasonal (four per year) surface reflectance composites between 2014 and 2024 were used as a proxy for representative conditions for which we would likely require predictions. A corresponding DI and AOA map was derived from each one and the full set of 40 seasonal AOA maps then summarised as a frequency map representing the proportion of seasons that a location was outside the AOA.

Results

The results of the kNNDM cross validation are shown in Table 1, for the three cover fractions which the FC3 model predicts. The DI threshold to define AOA was calculated using the same cross-validation folds and found to be 0.128. This threshold was applied to the DI images computed from seasonal composites between winter 2014 and winter 2024, and the AOA summary map shown in Figure 1 produced.

Table 1: kNNDM Cross-validation results.

	Bare (% Cover)	Photosynthetic Vegetation (% Cover)	Non-photosynthetic Vegetation (% Cover)
Root Mean Square Error (RMSE)	13.1	10.0	15.4
Mean Absolute Error (MAE)	9.6	7	11.6

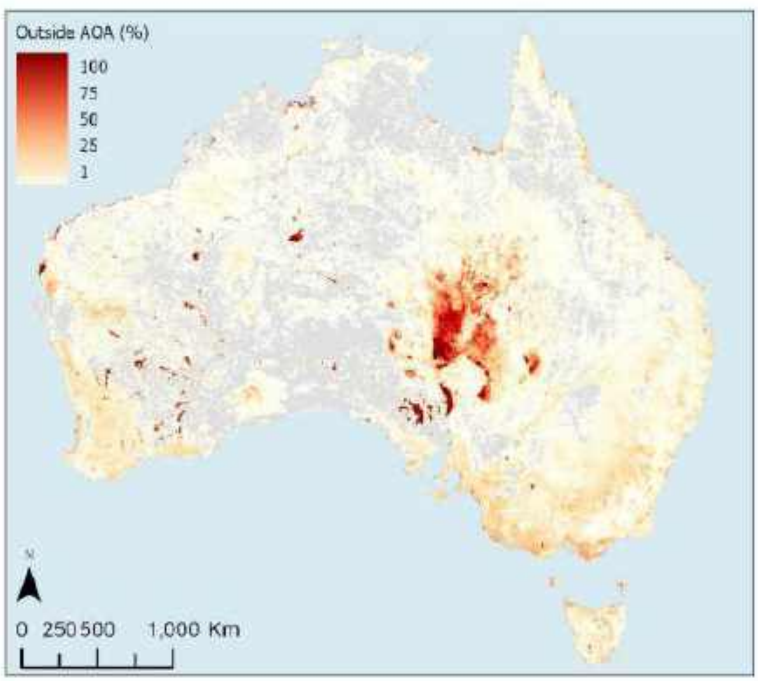

Figure 1 Percentage of seasons in which the surface reflectance was found to be outside the AOA of the FC3 model, 2014 to 2024. Locations that are always within the AOA are grey.

On average less than 10% of Australia is outside the AOA, and less than 5% is frequently outside the AOA (i.e. >50% of the time). Based on visual inspection of the summary map, the areas frequently outside the AOA often appear to be locations where either bare ground or high green vegetation cover dominate, or where cover is highly dynamic, such as the central deserts and salt lake regions, coastal areas and cropping or modified pastures across south-eastern Australia and south-western Western Australia. The bare ground category represents a variety of features including beaches, mudflats, claypans, saltpans, rocky areas and soil of diverse geologies, presumably spectrally distinct from other 'bare ground' locations sampled within the model training data. The high green vegetation cover category is unsurprising, as field site selection has mostly targeted rangeland environments dominated by open native vegetation as per the original intended use of this product. While Australian rangelands can have brief periods of high green cover, these are poorly sampled due to access constraints.

Additionally, all the major cropping regions of Australia show a moderate percentage of seasons outside AOA. This is also unsurprising given that cropping areas may cycle through bare and high green cover states, and in some locations soil moisture from irrigation may also modify the spectral response. Additionally, calibration sites within cropped locations represent a small component of the training data. Further investigation could explore any relationship between specific stages of the crop cycle and DI.

Figure 2 shows exemplar locations outside the AOA. The upper images a) and c) show the DI images for a cropped field and an area of bare soil respectively. The corresponding plots b) and d) below illustrate the spectral space covered by the training data (shown in pink) and the exemplar yellow polygons (shown in blue), as pairwise relationships between each band used for model fitting. A density distribution plot for each band is also shown. The limited overlap between the two sets of points in each example shows that the training data lacks coverage for these features, and that the AOA approach has yielded sensible and interpretable results.

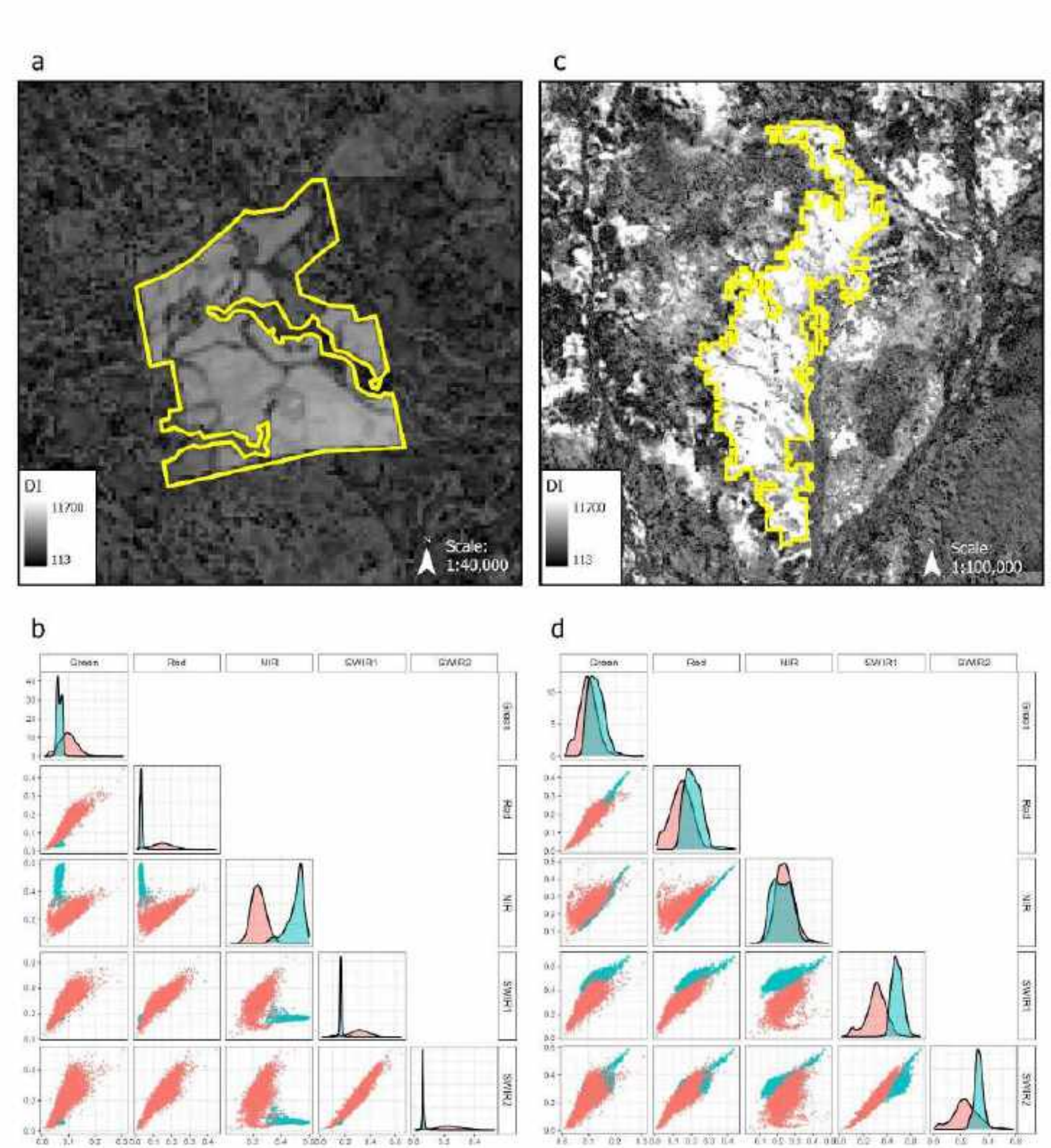

Figure 2 Examples of locations frequently (> 80%) outside AOA (yellow polygon), and comparison of their reflectance with the model training data: (a) DI image for a cropped field in north Queensland; (b) pairs plot of reflectance values for training data (pink shade) and pixels within the yellow polygon in (a) (blue shade); (c) DI image for bare soil in the Channel Country of far western Queensland; and (d) pairs plot of reflectance values for training data (pink shade) and pixels within the yellow polygon in (c) (blue shade).

Discussion

The AOA frequency product presented, provides an aid to users to assess the suitability of the FC3 product for their purposes. Areas which are frequently outside the AOA should be treated cautiously, as the error metrics provided for the product are not applicable here. It should be noted that this does not mean that the model is wrong in these locations, rather that we are unable to say anything about the likely performance in these areas.

The application of the AOA methodology to the FC3 model has proven to be a useful tool for understanding the representativeness of the underlying training data and the corresponding limitations imposed on model performance. It extends the information derived from typical performance or error metrics by giving a spatially explicit extent to which those metrics apply and identifying locations that are not represented by the training data and for which model performance is therefore unknown.

In this case we have shown that while the training data are relatively sparse for a model applied across such a broad geographic area, most of Australia is within the AOA. It is hoped that by making the AOA summary layer publicly available, the diverse users of the FC3 products can better understand how the limitations of the model may impact their intended uses of the product.

Given the FC3 model is applied in an ongoing operational context, an additional insight gained through this work is knowledge about where new calibration field data could be collected, to expand the AOA for future model iterations.

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Technological innovation and access: novel opportunities for rangeland communities

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Better Connected: building connectivity skills towards technology adoption to support rural, regional, and remote business and community.

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Key words: agricultural technology; connectivity literacy; internet; rural, regional, remote; internet-based tools; communications.

Abstract

Connectivity Literacy encompasses all the knowledge needed by a consumer to understand how to get connected and stay connected to equitable, affordable and reliable voice and broadband internet services that meet their needs and budget. It is a precursor to Digital Literacy and incorporates the knowledge needed to navigate through choice of telecommunications providers and technologies, and to understand terminologies, plans and equipment. Connectivity Literacy is challenging in rural, regional, and remote (RRR) Australia and does not have any demographic barriers such as age, gender, location, or education level.

A mixed methods approach using thematic and secondary data analysis was conducted using ten years of data collected to understand the use and understanding of internet services by women, farmers and small to medium enterprises in rural, regional and remote regions across Australia. Surveys, reports and submissions provided quantitative and qualitative data. Thematic analysis was performed on open-ended questions within the data sets, written text and through documented case studies. The findings were overlayed with the Diffusion of Innovation model and considered the extended theory of the Crossing the Chasm to help identify barriers to the adoption of internet-based tools.

The analysis has identified the difficulty that consumers and businesses are having navigating rural, regional and remote internet connectivity. It has established a baseline understanding of a new phenomenon identified as 'Connectivity Literacy' (understanding how to get and stay connected), which is a pre-cursor to Digital Literacy (understanding how to use different devices, software, and operating systems).

Understanding and applying the concept of Connectivity Literacy provides the opportunity to build critical mass around internet connectivity knowledge and understanding that can advance adoption and innovation in rural, regional and remote areas.

Introduction

Access to internet connectivity in RRR areas of Australia has improved in the past four years (Australian Government, 2020, 2021, 2022, 2023). However, for many people and businesses living in RRR areas, the ability to get connected, stay connected and use that connection remains difficult. Previously, a lack of connectivity in RRR areas has been attributed to a lack of access, expense, education level, available infrastructure and policy and operations (Curtin, 2001; Freeman & Park, 2015; Park et al., 2019; Salemink et al., 2017). However, as newer technologies and a greater choice in RRR connectivity emerges, a lack of connectivity success can also be attributed to an individual's level of connectivity ability (Deursen & van Dijk, 2010; Park et al., 2019). Whilst connectivity literacy plays a large role in the success of getting connected and staying connected, other barriers to connectivity such as adequacy, affordability, consumer guarantees, redundancy and reliability also factor into connectivity problems in regional telecommunications, all of which underpin the need for sound connectivity literacy.

Connectivity Literacy (understanding how to get and stay connected) focuses on the knowledge needed to access telecommunications services, particularly broadband and voice, which includes understanding available technologies, navigating provider options, selecting appropriate plans, and managing equipment. It addresses the practical aspects of getting connected and staying connected, including the factors that affect connectivity quality and availability. Digital Literacy (Gilster, 1997; Heitin, 2016) (understanding different types of hardware, software, and operating systems) assumes a person already has access to reliable internet and emphasises their skills to effectively use digital tools and platforms. It involves the ability to operate devices, navigate software, and engage with digital content, fostering safe and productive digital interactions. It is measured by frameworks like the Australian Digital Inclusion Index (ADII, 2021), which evaluates digital inclusion through access, affordability, and digital ability. As shown in Figure 1, Connectivity Literacy is a precursor to Digital Literacy and a barrier to digital participation.

Figure 1: Connectivity Literacy is a precursor to Digital Literacy

Due to the complexity of using digital connectivity technologies in RRR areas, residents are having to develop new types of knowledge and skills that those in major cities do not have to acquire (Park et al., 2019). This includes knowledge of the numerous technologies available, including infrastructure and devices such as cellular booster, antennas, towers, and repeaters, as well as service plans (Park et al., 2019). However, it is often more difficult for regional Australians to obtain this knowledge (Szeles, 2018), as there is a limited amount of 'on the ground' understanding and independent advice about telecommunications infrastructure that can be used in RRR properties and communities.

Methods

Secondary data research (Manu et al., 2021) allowed the researchers to leverage pre-existing data that was originally collected to examine telecommunications delivery and how the internet was used and understood by women, farmers and small to medium enterprises in rural, regional and remote regions across Australia. Secondary data selected was appropriate because it was relevant to both the population and the phenomenon under study (Silver & Wrenn, 2013), allowing the researchers to derive conclusions about Connectivity Literacy. Thematic analysis (Lyons & Coyle, 2021) was used to identify, analyse and interpret people's views, opinions, knowledge, experiences, or values to derive patterns of meaning (Belotto, 2018) within the qualitative data that supported conclusions aligned to connectivity literacy.

Secondary data sets from three academic mixed methods (Creamer, 2017) research projects provided quantitative and qualitative data (online surveys N=625; focus groups N=27) for analysis (Harrington, 2024; Hay, 2018b; Wilson, 2022). Secondary data from three large consumer surveys (N=4180) (Hay, 2016, 2017, 2018a) were also analysed. In addition, submissions from the past 10 years to government enquiries into regional telecommunications containing lived experience case studies were also included in the analysis (Australian Government, 2008, 2012, 2015, 2018; Glasson et al., 2008; Hartsuyker et al., 2021; McKenzie, 2018, 2021; Shiff et al., 2015; Sinclair et al., 2012; Single et al., 2024; Sparrow, 2015, 2018; Stretton et al., 2021). The final data set was drawn from posts on the Better Internet for Rural Regional and Remote Australia Facebook page, which started in 2014 with approx. 500 members and in 2024 has almost 16,000 members (BIRRR., 2014).

Findings were overlayed with the Diffusion of Innovation Model (Rogers, 2003) and Moore's Chasm (2014), as shown in Figure 2. Rogers (2003) describes how practices spread over time ultimately lead to adoption and Moore (2014) identified a gap between early adopters and the early majority that contain critical barriers to adoption. The findings demonstrate how poor Connectivity Literacy is a barrier to the adoption of internet-based tools.

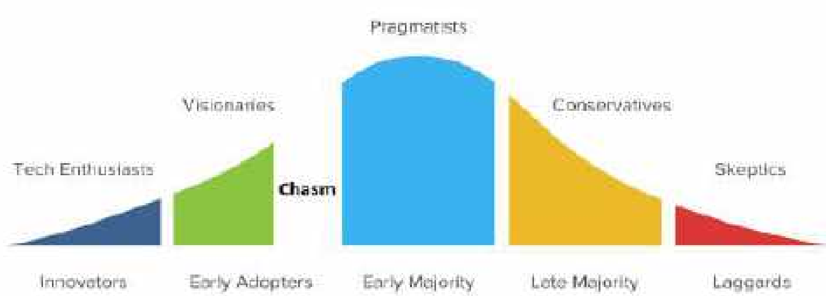

Figure 2: Moore's Revised Diffusion of Innovation Model (2014)

Results

Connectivity Literacy

The data demonstrated that Connectivity Literacy affects all types of consumers and is not limited by education, culture or age, Table 1.

Table 1: Connectivity Literacy Indicators

Topic		The Chasm	Diffusion/Dis-Adoption		
Innovators	Early Adopters	Critical Barriers to Adoption	Early Majority	Late Majority	Laggards
Connectivity Literacy – All the things a consumer needs to know to get connected and stay connected to the internet		How to choose a technology, provider, plan, choosing & installing equipment, troubleshooting a connection, staying connected in an emergency and where to go to get help.	• Mums / Dads / Children / Young Adults • Workers / Volunteers / Business Owners • First Nations / Different Cultural Backgrounds • Government (local, state, federal) • Researchers /All Education Levels • Young / Old		

Functional Literacy

Literacy is traditionally defined as the ability to read, write, and perform basic arithmetic. However, functional literacy extends beyond these basic skills to include the practical application of reading, writing, and math in real-life situations (Nutbeam, 2008). Functional literacy encompasses the ability to understand and use information effectively for daily tasks, such as interpreting graphs, managing finances, and making informed decisions. This broader definition highlights the importance of skills like media literacy, financial literacy, and health literacy, which are essential for navigating today's complex, high-tech society. While basic literacy is foundational, functional literacy ensures individuals can actively participate and thrive in their communities. In 2001, the Australian Council for Adult Literacy (2001) identified that one in five adults do not have the functional literacy skills to effectively participate in everyday life. In addition, the Australian Bureau of Statistics (2011-2012) identified that only 3% of Australians have the ability to use digital technology, communication tools and networks beyond basic applications such as email and web browsing. The data highlighted functional literacy as a foundation for digital inclusion and its impact on connectivity adoption outcomes, see Table 2.

Table 2: Functional Literacy Indicators

Topic		The Chasm	Diffusion/Dis-Adoption		
Innovators	Early Adopters	Critical Barriers to Adoption	Early Majority	Late Majority	Laggards
Functional Literacy - encompasses the ability to understand and use information effectively for daily tasks, such as interpreting graphs, managing finances, and making informed decisions (Nutbeam, 2008)		• Lack of practical skill set needed to get connected and stay connected to equitable, affordable and reliable voice and broadband services • Inability to function effectively online • Insufficient functional literacy, which is a core foundation to digital inclusion	• 44% stay with provider that does not meet their needs • 63% prevention from adopting new technology • 70% negative impact on business operations • 57% negative impact on productivity • 37% negative impact on customer service "makes me look unreliable" • 48% have not changed their provider in the past 3 years • High transactional costs: administrative time, time to learn new technology, troubleshoot issues		

Digital Apathy and Misinformation

The data shows that consumers are experiencing digital apathy caused by various factors including fear of the unknown, a lack of exposure or experience with technology, lack of time or a reluctance to change or try new things. A state of digital apathy can also be caused by people trying their best to solve their connectivity problems and 'giving up' as it becomes too difficult and takes too much time. Adding to digital apathy, widespread misinformation is often confusing, disruptive and causes consumer fatigue and frustration. Digital apathy makes it incredibly difficult to engage consumers including RRR users, industry, government, media, and researchers in understanding how to get connected and stay connected. The data highlights digital apathy and misinformation as significant barriers to connectivity adoption, as summarised in Table 3.

Table 3: Digital Apathy and Misinformation Indicators

Topic		The Chasm	Diffusion/Dis-Adoption		
Innovators	Early Adopters	Critical Barriers to Adoption	Early Majority	Late Majority	Laggards
Digital Apathy - an indifference or a deliberate lack of enthusiasm or interest towards digital technologies such as the internet, smart phones, computers, and other digital devices, that results in a genuine fatigue towards technology		• Lack of experience and exposure • Fear of the unknown • Negative messages from the bush grapevine, social media, the media • Negative past experience • Consumer fatigue/Cognitive overload • Inertia (tendency to do nothing) and status quo bias • Historical RSP practices	• "BUT there is only one provider, nothing else to choose from" • "Current plan restricted by sky muster" • "Don't think there are any other options" • "I don't know if I am locked in" • "I think we have just changed by default" • "There's no choice in what I can compare to as I really have one plan to choose from" • "We were waiting for Starlink to arrive, no other alternatives" • "I can't get NBN, I live remotely"		
Misinformation - false, inaccurate or misleading information; and **Disinformation** - information that is covertly spread deliberately to deceive or influence (O'Connor & Weatherall, 2019)		• Lack of dedicated rural regional and remote tech support • Lack of independent advice • Myths and furphies • Industry is profit driven not results driven • Industry undermined by scammers and misleading and deceptive practices, creating distrust	• Consumer confusion/mental burden • Consumer fatigue and frustration • Geographical narcissism "People in cities think what we do is less valid" • Lack of understanding from urban stakeholders – "if you're not happy why don't you move [to town]" • Constant change is disruptive and creates further barriers		

Discussion

Telecommunications have become an essential service, yet unlike other utilities (e.g., water, power) RRR consumers are expected to be intricately involved in the complexity of installation, delivery, and success of that service. Consumers lack personal resources and understanding to compare and match available technologies to their broadband and voice needs resulting in Connectivity Literacy issues. Poor connectivity literacy creates barriers for RRR consumers to get connected and stay connected resulting in negative experiences with technology that are difficult to overcome resulting in digital apathy causing people to give up, and ultimately to put up with substandard connections and ongoing issues. This is not only a significant safety concern but also creates lost productivity, affects education and mental health, and exacerbates social isolation for remote consumers.

A vast amount of industry and academic adoption literature fails to recognise functional connectivity literacy (getting connected and staying connected) as a precursor to digital literacy (using your connectivity) as a barrier to adoption. While connectivity infrastructure has considerably improved access over the past four years, it has resulted in a confusing landscape of connectivity options. There are also misconceptions about the availability of national broadband (nbn) services and alternative suppliers. To increase adoption of internet-based tools, health and education resources and land/animal business management tools, consumers need support to navigate and utilise the connectivity landscape that provisions internet access

(Get Connected) to troubleshoot their connectivity (Stay Connected) and to support adoption of internet-based tools (Use Connectivity).

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Factors influencing adoption and sustained use of agricultural technology in grazing systems of Central Queensland

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Key words: AgTech, Adoption, Grazing, Producer, Perceptions

Abstract

Agricultural technology (AgTech) offers significant opportunities for enhancing productivity and sustainability in rangeland grazing systems; however, its adoption to date has been limited. This study examines factors influencing the adoption and sustained use AgTech among Central Queensland beef producers. Through semi-structured interviews with 15 beef graziers, we explore how producers' motivations, experiences, and perceptions affect their engagement with AgTech. Thematic analysis illustrates that adoption and continued use of AgTech are more likely when it enhances a producer's feelings of competence, is positively regarded by peers, and is considered a viable financial investment. Conversely, challenges in these areas often lead to low implementation or discontinuation. These insights can inform strategies to improve AgTech development and integration, ultimately enhancing the resilience and sustainability of extensive grazing systems.

Introduction

The agricultural sector is undergoing a transformative shift with the integration of advanced technologies, collectively known as agricultural technology (AgTech). These innovations aim to improve productivity, efficiency, and sustainability in farming practices (Rose & Chilvers, 2018). In beef grazing systems, AgTech offers tools for enhanced herd management, pasture monitoring, and resource optimisation. Technologies such as remote sensing, GPS tracking, and automated feeding systems have the potential to revolutionise traditional operations (Bailey et al., 2021). Although these represent advanced applications of AgTech, integration into beef businesses can be through much more conventional forms, such as the addition of weigh scale, or farm management software.

Despite the potential benefits, the adoption and sustained use of AgTech among beef producers varies widely. Some producers successfully integrate these technologies into their long-term operations, while others discontinue use after initial adoption (Fielke et al., 2020). Understanding factors influencing uptake and continued use is crucial for developing strategies to enhance sustained technology use if we are to increase productivity and resilience in the agricultural industry. Previous research has identified barriers such as high initial costs, lack of technical support, and integration difficulties with existing systems (Pierpaoli et al., 2013).

Incorporating agricultural extension methods tailored to diverse adoption pathways is essential for addressing these challenges. Recent research by Nettle et al. (2024) emphasises that effective extension requires addressing social, technical, and institutional barriers. Their findings highlight that a combination of peer learning, co-innovation, and tailored advice is critical for supporting producers through the adoption and continued use of technologies. This aligns with the focus of this study on understanding the roles of competence, community and financial risk perception in AgTech adoption, particularly as they influence producers' decisions to sustain or discontinue the use of these tools.

Methods

A qualitative research design was employed to explore the motivations, experiences, and perceptions of beef graziers regarding AgTech adoption and continued use (approval number: 24-883). A phenomenological approach facilitated an in-depth understanding of the lived experiences of producers and their involvement with AgTech (Creswell & Poth, 2018). Participants were selected using random purposeful sampling, targeting Central Queensland beef graziers. Inclusion criteria required active involvement in beef grazing operations, and willingness to discuss their experiences with Agtech. Recruitment occurred through industry networks and producer associations. A total of 15 beef graziers participated, representing diverse enterprise sizes, and levels of AgTech engagement. Semi-structured interviews were conducted either face-to-face, or via telephone. An interview guide was developed, covering topics such as business background, motivations for AgTech adoption, experiences with implementation, perceptions of usability and usefulness, and factors influencing continued use or discontinuation. With consent, interviews were audio-recorded and transcribed verbatim. Thematic analysis was conducted following the guidelines outlined by Braun and Clarke (2006). NVivo 12 software facilitated the coding and identification of patterns in the data. Initial codes were generated inductively. Themes were iteratively refined to improve accuracy and distinctness.

Results

A total of 15 interviews were conducted with six males, six females and three couples. All participants held an active role in decision making on property either through management roles or ownership. The length of interviews ranged from 15 to 120 minutes, resulting in approximately 24 hours of recorded conversations. Ten participant's businesses were primarily involved in cattle breeding and growing. Three participants had mixed farming operations with beef cattle alongside cropping enterprises. One participant had a sole focus on backgrounding and trading cattle, and one business operated as a stud. The number of cattle in each business ranged from 120 to 6,500 head.

Three primary themes emerged from the analysis that influence adoption and continued or discontinued use of AgTech: Competence, Community, and Perceived financial risk.

Competence

The theme of competence explores how the Agtech tool contributes to producer's feeling capable within their business. This emerged as a critical factor influencing both adoption and sustained use of technology.

<u>Usefulness with regard to business priorities:</u> Beef cattle businesses vary in their structure, focus and measures of success. A producer's perspective of a tool being useful varies depending on their priorities. In this study, usefulness was commonly identified through operational benefits such as labour saving, increased confidence in decision making and improved communication. Discontinuation was prevalent where the tool was not seen to add value to a producers existing skillset or where it imposed on a higher

priority value, for example doing things quickly. One producer had AgTech installed (EID's in every animal, an EID scanner and a set of scales) however indicated:

"I just don't use it because it's quicker without it. It stays slow with it. Like lots of places and that – you go through, and you watch them and they're stuffing around. And they're read this one, this one doesn't read so they've got to run it back and pull the tag out. Where I can pump them straight through in an hour."

Usability and adaptation to local conditions: The usability of AgTech tools and their adaptability to individual contexts significantly impacted producers' sense of competence. Tools that were intuitive, required minimal training and offered practical ways to maintain the system, enhanced confidence and encouraged continued use. Whereas technologies that were perceived as complicated or not suited to the producers' operating environment diminished competence, often resulting in discontinuation.

"It won't actually sync in the paddock without losing data. So then, well then you lose your confidence in the program, right? Then you've got to come back to the office and it's another job you've got to sit down and do. Whereas if you're in the paddock and you're moving them that was one of the prime draw cards to using it."

Access to training and support: Adequate training and technical support contributed to producers feeling competent and more capable in using the Agtech tools to benefit their business. Initially being connected to a person directly for follow up support was highly regarded. Often, once producers had confidence that they were supported, they were more inclined to troubleshoot on their own and successfully navigate implementation phases. An absence of support from some AgTech providers was linked to frustrations, reduced confidence and discontinuation.

Community

The theme of community encompasses the social and relational factors influencing AgTech adoption and sustained use. Producers valued acceptance within their community and were cautious about deviating from accepted norms.

Peer influence and social proof: Producers were curious about, and strongly influenced by, the experiences and opinions of their peers. Observing successful use of AgTech by peers increased confidence and motivation to explore using technology. They often sought reassurance from trusted community members before fully committing to AgTech use.

"Your next door neighbour or your cousin's uncle who has been using it for two years, or you know whatever they've all got experience. So, um, to me I would go to someone who I know has used it."

Collaborative learning and support networks: Community networks provided opportunities for shared learning and support. Often key producers were referred to as they had a reputation for being a trusted source for ground-truthed Agtech experience. Engagement with peers facilitated knowledge exchange, problem-solving, and mutual support. Producers without access to supportive networks were more comfortable with 'business as usual' which hindered exploration and sustained use of AgTech.

"Person 1 is trying to make you use that other shit. Yeah, but I don't want to use it. What happens if your phone goes flat or something? … I don't think many people do use the electric one."

Perceived financial risk
Producers highlighted several dimensions of financial risk associated with AgriTech adoption, reflecting concerns about return on investment, reliability, and economic justification.

Uncertainty around lifespan and reliability: AgTech tools were often perceived as high-risk investments due to uncertainties around their lifespan and reliability. Producers expressed frustration when tools failed to operate consistently. Others relayed experiences with discontinued technology and tools that didn't meet the expectations set. Malfunctions disrupted operations, incurred added labour and maintenance expense and eroded confidence in the technology's value.

"It's just that it's got a few hiccups that can be a pain in the butt sometimes, and I'll go down there, and I'll start a new session and it'll just throw me a curveball. And I've got to work it out, and, you know what it's like. You've got people waiting around."

Challenges in evaluating return on investment and cash flow constraints: Many producers struggled to assess the financial value proposition of AgTech tools. The economic benefits often required long-term use to materialise, while the upfront costs presented immediate challenges.

"The problem is, the case has to be so compelling because if it's not you constantly think, 'What else could I buy for that?' And we just get away with doing it."

Prioritisation of tangible benefits**:** Technologies with clear and direct economic benefits, such as preventing theft, were prioritised over other AgTech tools. Producers felt more confident investing in tools with demonstrable short-term outcomes, which contrasted with the abstract or delayed benefits of many AgTech solutions.

"Technology's not, it's important but it's not of great importance to us I guess you'd say. You know, our security cameras and stuff like that yeah that's important because we need to be able to monitor that no one's driving in and stealing all of our diesel"

Discussion and Conclusion
This study highlights the complex factors influencing the adoption and sustained use of AgTech among beef producers in Central Queensland, emphasising the importance of tailoring solutions to individual business priorities. Adoption is driven not only by technological capabilities but also by human behaviour, social dynamics, and the specific contexts of each enterprise. Technologies that enhance producers' feelings of competence, align with their priorities, and address their needs for usability and reliability are more likely to be adopted and used long-term.

Competence emerged as a critical theme, with producers favouring tools that are intuitive, adaptable to local conditions, and supported by training. This aligns with findings by Sewell et al. (2017), who highlight that competence-building through training and tailored advice is essential for successful technology adoption. Conversely, technologies perceived as unreliable or difficult to use often led to frustration and discontinuation. Community influence also plays a vital role, as producers rely on peers and trusted individuals to validate their decisions. As suggested by Prager and Creaney (2017), peer-to-peer networks and social learning environments can build confidence in adopting new technologies. Stories and experiences shared by relatable figures can build confidence and foster adoption, while negative perceptions can hinder uptake.

Perceived financial risk remains a significant barrier, with producers expressing difficulty in assessing the return on investment for many AgTech tools. Immediate and tangible benefits, such as those provided by security systems, were prioritised over tools with long-term or less visible payoffs. Clear communication about economic benefits, supported by cost-benefit analyses and evidence of success in local contexts, can help address these concerns.

The adoption of AgTech requires a process of change that often involves vulnerability and habit shifts. Extension strategies should acknowledge this, providing time, support, and accountability mechanisms to facilitate the transition. Timing is also crucial, with producers more likely to adopt new tools when triggered by specific events or compelling evidence of benefit from trusted sources.

Although the sample size of this study is small, the diversity of experiences underscores the need for a tailored approach to AgTech adoption. Strategies should prioritise building competence, leveraging community networks, addressing financial concerns, and supporting producers throughout the adoption process. By focusing on shared lived experiences and aligning with producers' values and goals, AgTech adoption can be enhanced, contributing to more resilient and sustainable grazing systems.

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Long-term chemical management of undesirable brush on southwestern U.S. rangelands

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Key words: rangeland restoration; woody plant control; aminocyclopyrachlor; *Prosopis glandulosa*; *Acacia schaffneri*

Abstract

Woody plant encroachment on rangeland used for beef cattle production and/or wildlife use in the southwestern United States has been a major problem of ranchers for many decades. Aminocyclopyrachlor premixed with triclopyr-amine was first marketed for use on grazing lands in Texas, Oklahoma, New Mexico, and Arizona in 2020. This herbicide was marketed for control of honey mesquite (*Prosopis glandulosa*) (NRCS 2025), huisache (*Vachellia farnesiana* a.k.a. *Acacia farnesiana*), and associated brush species and broadleaf forbs on grazing lands. Long-term (i.e. four to ten years post-application) honey mesquite canopy evaluations in aerial and ground broadcast-applied trials revealed more than twice the treatment life (i.e. the time from treatment until brush canopy returns to an economic threshold) with aminocyclopyrachlor+triclopyr-amine (ACP+T) treated plots versus plots treated with past industry standards (Medlin et al. 2019). Similar results were obtained for huisache treated plots evaluated four to six years post-application. Recent research has evaluated picloram and/or chlorsulfuron+metsulfuron-methyl combinations applied with ACP+T to widen the spectrum of activity and address additional undesirable species on rangelands while evaluating impacts on desirable plant species. When evaluated 40 months after application, ACP+T (140+280 g ae ha^{-1}) applied alone was highly efficacious (100% mortality) on honey mesquite, moderately efficacious (66% mortality) on guajillo (*Acacia berlandieri*), and slightly efficacious (less than 25% mortality) on all other woody plant species present. When ACP+T was applied in combination with picloram (560 g ae ha^{-1}) or picloram and chlorsulfuron+metsulfuron-methyl (10.5+33.5 g ai ha^{-1}) mortality of twisted acacia (*Vachellia schaffneri* a.k.a. *Acacia schaffneri*) increased to 25% and 50%, respectively. A tank mix of ACP+T (210+420 g ha^{-1}) with chlorsulfuron+metsulfuron-methyl resulted in 100% mortality of honey mesquite, twisted acacia, and whitebrush (*Aloysia gratissima*), less than 25% mortality of spiny hackberry (*Celtis ehrenbergiana*), and 0% mortality of ephedra (*Ephedra antisyphilitica*), guayacan (*Guaiacum angustifolium*), and lotebush (*Ziziphus obtusifolia*).

Introduction
Woody plant encroachment across southwestern United States' rangeland has reduced soil and surface water availability, forage production, diversity of desirable native forbs, livestock carrying capacity, livestock management efficiency, and wildlife habitat, while it has increased degradation of infrastructure (e.g. fences) and rangeland management costs (Allred 1949; Boggie et al. 2017; Dahl et al. 1978; Fisher 1950; Laxson et al. 1997; Smith and Rechenthin 1964; Teague et al. 1997, 2008; Thurow et al. 2000; Timmer et al. 2014). Although chemical and mechanical management options have been implemented for over five decades, woody plant encroachment on rangelands has continued to escalate. For example, the USDA Soil Conservation Service (USDA-SCS) estimated in 1963, 35.8 million hectares of Texas rangeland had been invaded by woody plants (USDA-SCS 1963). The infestation increased to 37.2 million hectares by 1973 (USDA-SCS 1973) and to 42.7 million hectares by 1985 (USDA-SCS 1985), while over 12 million hectares received treatment during that time span.

Some of the major species comprising this undesirable woody plant invasion include honey mesquite, huisache, whitebrush, tarbrush (*Flourensia cernua*), and catclaw acacia (*Senegalia greggii* a.k.a. *Acacia greggii*), however, not all woody plants on southwestern U.S. rangelands are undesirable. To complicate matters, the undesirable woody plants are typically found growing in association with desirable woody species such as hackberry (*Celtis laevigata var. reticulata*), lotebush, guayacan, etc. The close association of desirable and undesirable plants on rangeland make selective application to undesirable plants impossible with broadcast applications.

Medlin et al. (2019) reported broadcast-applied aminocyclopyrachlor+triclopyr-amine (ACP+T) more effectively killed honey mesquite and huisache, reduced the plant canopies of these species, and extended the treatment life compared to previous industry standard treatments. The research focused on long-term control of honey mesquite and huisache only, did not address other undesirable woody species, and did not include impacts on associated desirable species. Therefore, the objective of this research was to evaluate ACP+T applied alone or with chlorsulfuron+metsulfuron-methyl, and/or picloram for management of honey mesquite, whitebrush, twisted acacia, and other undesirable woody plants as well as the impacts of these treatments on desirable woody plant species.

Methods
A trial was established on a privately-owned ranch in Duval County, Texas. Individual plot dimensions were 180 m by 1300 m. Treatments were applied June 18, 2021, with fixed-wing aerial application equipment to mixed woody plant stands of actively growing brush canopies with healthy vegetation. Treatments consisted of ACP+T (140+280 g ae ha^{-1}) applied alone, with picloram (560 g ae ha^{-1}), with picloram (560 g ha^{-1}) and chlorsulfuron+metsulfuron-methyl (10.5+33.5 g ai ha^{-1}), and ACP+T (210+420 g ha^{-1}) with chlorsulfuron+metsulfuron-methyl (10.5+33.5 g ha^{-1}). All treatments were applied in 45 l ha^{-1} water carrier with 365 ml ha^{-1} methylated seed oil / organosilicone adjuvant.

Mortality assessments by species were collected 16 and 40 months after treatment. Plants were considered dead if no green vegetation was present in the leaves or stems.

Results
All treatments killed honey mesquite 100% when evaluated 40 months after application (Table 1). ACP+T applied at 140+280 g ha^{-1} killed less than 25% of the twisted acacia population and 0% of the whitebrush plants present. When this treatment was tank mixed with picloram, twisted acacia mortality increased to 50% but there was no change in the whitebrush mortality. ACP+T at 210+420 g ha^{-1} and applied with

chlorsulfuron+metsulfuron-methyl resulted in 100% mortality of honey mesquite, twisted acacia and whitebrush.

ACP+T applied at 140+280 g ha^{-1} killed 66% of the guajillo population present and 93% when applied with 560 g ha^{-1} picloram. All other traditionally accepted wildlife beneficial woody plants present suffered less than 25% mortality when ACP+T was applied alone or in a tank mix with picloram or chlorsulfuron+metsulfuron-methyl. However, when ACP+T was applied with picloram and chlorsulfuron+metsulfuron-methyl guajillo and spiny hackberry resulted in 57% and 71% plant death. The other desirable woody plants present (i.e. ephedra, guayacan, and lotebush) did not suffer significant plant losses regardless of herbicide treatment or rate.

Table 1. Three years after treatment mortality ratings (%) of woody plant species resulting from ACP+T applied alone or with picloram and/or chlorsulfuron+metsulfuron-methyl tank mix partners sprayed June 18, 2021, on a ranch in Duval County Texas.

		Aminocyclopyrachlor + Triclopyr-amine (g ae + g ae ha^{-1})[1]			
		(140 + 280)			(210 + 420)
		Tank Mix Partner (g ae or g ai ha^{-1})[1]			
		None	Picloram (560)	Picloram + Chlorsulfuron + Metsulfuron (560 + 10.5 + 33.5)	Chlorsulfuron + Metsulfuron (10.5 + 33.5)
Common name	**Latin name**	Mortality (%)			
Traditionally Undesirable Plants					
Honey mesquite	*Prosopis glandulosa*	100	100	100	100
Twisted acacia	*Acacia schaffneri*	21	50	25	100
Whitebrush	*Aloysia gratissima*	0	0	--[2]	100
Traditionally Wildlife Desirable Plants					
Ephedra	*Ephedra sp.*	0	0	0	0
Guajillo	*Acacia berlandieri*	66	93	57	--[2]
Guayacan	*Guaiacum angustifolium*	0	0	0	0
Lotebush	*Ziziphus obtusifolia*	17	0	0	0
Spiny hackberry	*Celtis ehrenbergiana*	0	3	71	23

[1] For rate calculations, g ae (acid equivalent) was used for aminocyclopyrachlor, triclopyr-amine, and picloram and g ai (active ingredient) was used for chlorsulfuron and metsulfuron.

[2] Population was insufficient for assessment.

Discussion

Late spring through summer is the recommended application time for ACP+T when targeting mesquite species (*Prosopis* spp.) across Texas while fall applications of ACP+T are most suited for huisache. Species' efficacies with ACP+T are best when applications are made during the corresponding season. This trial was sprayed mid-summer of 2021 during the recommended mesquite application window. This may explain the resulting high mortality of ACP+T applied alone on honey mesquite and its limited impact on twisted acacia, a closely related species to huisache.

ACP+T is highly effective for control of several problematic leguminous species including, honey mesquite, huisache, honey locust (*Gleditsia triacanthos*), *Lespedeza* spp., etc., but has limited impact on other non-leguminous species such as hackberry, lotebush, oaks (*Quercus spp.*) and other desirable species. This is advantageous for land managers whose goals include more diverse plant communities, e.g. wildlife habitat management. For these land management models ACP+T applied alone has a good fit for its limited impact on many desirable wildlife browse and wildlife-positive habitat species such as lotebush, ephedra, spiny hackberry, and guayacan. However, when land managers' goals are more grazing land focused for domestic livestock, ACP+T alone may leave too many woody plant species to compete with desirable grasses and forbs. In these instances, tank mixtures with other herbicides such as picloram, chlorsulfuron+metsulfuron-methyl, etc. can expand the spectrum of activity and help to transform the land to closer meet the landowner's goals.

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Greenhouse gas mitigation strategies in East African pastoral systems: beyond technical solutions

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Key words: pastoralism; methane; climate

Abstract

Prioritizing the support of pastoralists in Kenya through a bottom-up approach, this study focuses on identifying strategies to enhance their livelihoods, with subsequent evaluation of the impact on greenhouse gas emissions. Using the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model and Tier 2 emissions factors, we develop a region-specific emissions inventory and evaluate how supporting pastoralist livelihoods intersect with emissions mitigation. Pastoralism, vital for local economies and ecosystems, has often been misrepresented in climate policy due to the application of industrial-focused emission reduction strategies that do not fit these extensive systems. Our research identifies effective interventions, both institutional and technical, to support pastoralist livelihoods while addressing climate change. Institutional strategies include enhancing public health and education, improving early warning systems, leveraging social capital, and promoting mobility, each of which contributes to resilience and adaptation but requires further exploration of their emissions impacts. Technical measures, such as fodder harvest and storage and disease prevention through vaccination, are shown to reduce enteric fermentation emissions by 22% within pastoral systems. The study emphasizes the need for tailored climate policies that incorporate traditional practices and support pastoral systems effectively, advocating for a holistic approach to emissions reduction that respects and enhances local knowledge and practices.

Introduction

Pastoralism, in particular, has been a silenced perspective in the policy debate (Houzer & Scoones, 2021). Pastoralists are livestock keepers managing cattle, goats, sheep, camels, llamas, yaks, reindeer and other animals on extensive rangelands covering over half of the world's land surface and supports millions of people's livelihoods (ILRI et al., 2021). These extensive livestock systems occur where alternative forms of agriculture do not exist and play a crucial role in providing nutrition to often poor and marginalised populations (Iannotti et al., 2021; Scoones, 2021). Traditional indigenous knowledge is used amongst communities to provide ecosystem services while adapting to variable climates (FAO, 2024). Despite the opportunities offered by pastoralism, their needs in climate change mitigation and adaptation policy have often been neglected (Adesogan et al., 2020; Harrison et al., 2021). A more nuanced, balanced discussion of livestock sustainability is needed to address this inequality and can only be achieved with more specific research focusing on these regions (Hallström et al., 2015; Johnsen et al., 2019; Nordhagen et al., 2020; Paul et al., 2021).

Previous research has demonstrated that technical emissions abatement solutions typically used in industralised systems, such as breed and feed optimisation, are not applicable to pastoralists in Africa due to differing priorities (Cheng et al., 2022; Höglund-Isaksson et al., 2020; Houzer & Scoones, 2021). Rather than productivity as a core focus, indigenous breeds and management systems are crucial in supporting cultural practices, nutritional security and risk management as well as providing low emissions per head. Instead, emissions are more closely linked to underpinning institutional factors (Reid et al., 2004). As of current, limited research exists that uses a transdisciplinary approach to identify strategies that support pastoralists in Africa from the bottom-up in climate adaptation while also examining the associated emissions.

Supporting pastoralism in the context of drylands in East Africa while considering emissions is a '*wicked problem*' that requires a transdisciplinary approach introducing complexity (Lawrence et al., 2022). Leveraging the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model from International Institute for Applied Systems Analysis (IIASA), this research aims to provide nuanced insights into region-specific strategies that align with the diverse pastoralist systems, cultural practices, and dietary patterns of East Africa. Drawing on local knowledge from bottom-up social science research (Ash et al., 2024) focused on climate adaptation amongst pastoralists in East Africa, strategies that support livelihoods in climate adaptation are identified.

Methods

Emissions Estimation

The GAINS model estimates emissions bottom-up, i.e., quantifications of human activities contributing to emissions are multiplied by an emission factor representing the average emissions per unit of activity. This research builds upon existing Tier 1 national inventories of methane (CH_4) emissions from enteric fermentation in livestock systems in Kenya (Höglund-Isaksson et al., 2020) by using country-specific information to allow for deriving country- and sector/technology- specific emission factors at a Tier 2 level. CH_4 emissions are estimated for enteric fermentation emissions in livestock systems in Kenya spanning a timeframe from 1990 to 2050 in five-year intervals.

Following the general GAINS methodology (Amann et al., 2011), emissions from source *s* in region *i* and year *t* are calculated as the activity data A_{its} times an emission factor ef_{ism}. If emissions are controlled through implementation of technology *m*, the fraction of the activity controlled is specified by $Appl_{itsm}$, i.e.,

$$E_{its}=\sum m[A_{its}*ef_{ism}*Appl_{itsm}],$$

where

$$\sum mAppl_{its}=1,$$

and where A_{its} is the activity (number of animals)

ef_{ism} is the emission factor for the fraction of the activity subject to control by technology *m*,

$Appl_{itsm}$ is the application rate of technology *m* to activity *s*.

Hence, for each emission source sector, country-and year- specific sets of application rates for all the possible technologies (including no control) are defined such that application rates always sum to unity.

Systems Boundary
This study focuses on estimating CH_4 emissions from enteric fermentation of livestock, specifically cattle, sheep, goats, and camels in Kenya (Figure 1). The system boundary is defined to include only methane emissions arising from enteric fermentation processes in these animals. Other potential sources of emissions, such as:

- Methane and nitrous oxide emissions from manure management,
- Carbon sequestration from soils, trees, and plants, and
- Other greenhouse gas emissions from the agricultural sector,

are excluded from this analysis.

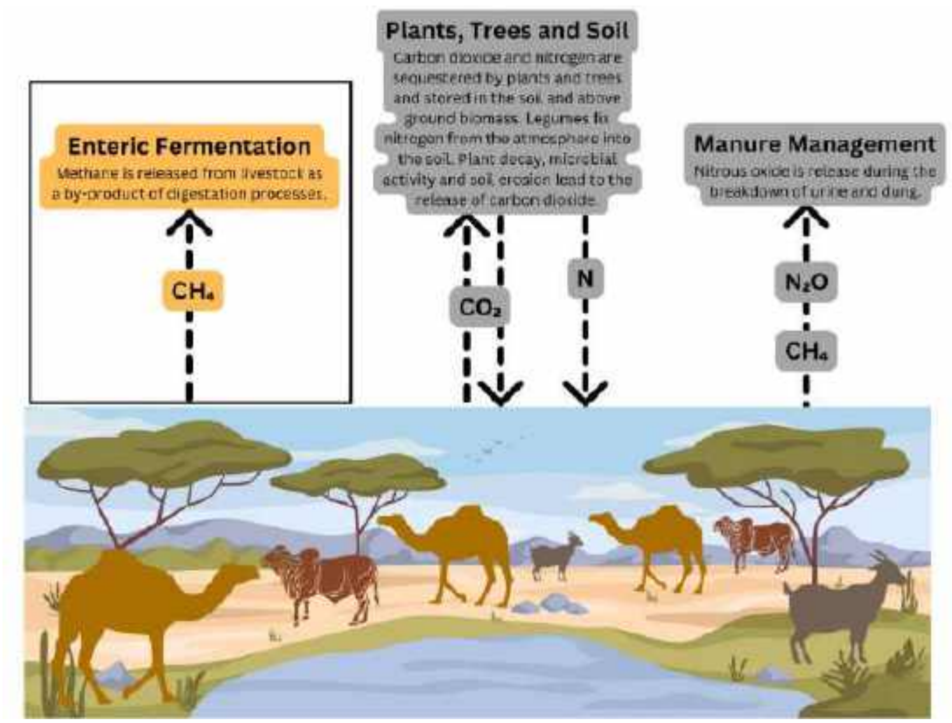

Figure 1: Emission sources and sinks in pastoral livestock systems including cattle, camel, sheep and goats. Enteric fermentation is highlighted as the focus of this study.

Emission Factors
Emission factors and calculation method (Tier 1 vs. Tier 2) for each sector used in the GAINS modelling are represented in Table 1.

Table 1: Description, emission factor and associated method and source of the sectors used in the GAINS methodology.

Animal Categories	Emission Factor Selection	Emission Factor	Method	Source
Pastoral camels	Tier II data unavailable for camels.	46	IPCC Tier I	IPCC (2006)
Pastoral sheep and goats	Aligned smallholder systems in Kenya.	4	Diet-based IPCC Tier II	Goopy et al. (2021)
Pastoral dairy cows	Smallholder dairy farm in central Kenya using local breeds and aligned milk production levels.	76.4	Diet-based IPCC Tier II	Wilkes et al. (2020)
Pastoral beef	Local breeds in smallholder systems in Kenya.	23.3	Diet-based IPCC Tier II	Goopy et al. (2018)
Agropastoral beef	Mixed grazing systems in Kenya using local breeds.	36.01	Diet-based IPCC Tier II	Ndung'u et al. (2019)
Ranch beef	Local breeds mimicking ranch conditions in Kenya.	62	Direct respiration chamber	Korir et al. (2022)
Feedlot beef	South African systems as Kenya data unavailable. Similar liveweight and species characteristics to feedlot systems in Kenya.	25	Diet-based IPCC Tier II	Tongwane and Moeletsi (2020)
Large scale intensive dairy cows	Zero grazing conditions mimicking intensive dairy production.	78	Diet-based IPCC Tier II	Wilkes et al. (2020)
Small scale intensive dairy cows	Zero grazing conditions mimicking intensive dairy production.	78	Diet-based IPCC Tier II	Wilkes et al. (2020)
Agropastoral dairy cows	Semi-zero grazing conditions mimicking agropastoral dairy production.	74	Diet-based IPCC Tier II	Wilkes et al. (2020)

Interventions

A number of institutional and technical interventions were assessed including: public health and education, anticipatory action, social capital, mobility, security, pasture enclosures, fodder harvest and storage, species diversification and disease prevention through vaccination. These interventions—whether institutional or technical—have varying impacts on pastoral livelihoods, climate resilience, human health, and food security. Each approach carries both benefits and challenges, which must be carefully balanced to ensure that pastoral systems can adapt effectively to climate change while preserving their cultural and economic importance.

On the basis of literature availability, two strategies were selected for further quantifications of impacts on methane emissions: fodder harvest and storage, and disease prevention (Table 2). While examining the impact of all interventions identified as a welfare package would be of great interest, the literature is not currently advanced enough to make these linkages. In addition, the inherent nature of pastoralism not being constant or linear, but rather adapting to variability, makes the prediction of stock flux variation due to intervention a challenge. However, both fodder harvest and storage as well as disease prevention pathways have a direct impact on methane emissions at the animal level and can therefore be modelled using the GAINS methodology.

Table 2: Interventions and their associated methane reduction mechanisms, removal efficiency (%) and sources.

Intervention	CH_4 Reduction Mechanism	Removal Efficiency (%)	Source
Fodder Harvest and Storage	Increased digestibility and reduced methanogen activity	5-20	(Adesogan et al., 2020; Beauchemin et al., 2011; Hristov et al., 2013)
Disease Prevention	Reduced mortality and replacement rates, improved feed conversion efficiency, reduced methane yield through gastrointestinal interactions	33	(Ezenwa et al., 2020; Fox et al., 2018)
Combination		45	As above.

Results and Discussion

Figure 2 represents that with implementation of disease control and improved fodder quality at a feasible adoption rate in pastoral systems, annual enteric fermentation CH_4 emissions in 2050 would be 22% less in pastoral systems and 11% less across all livestock systems compared to the BAU approach. This means Kenyan pastoralist systems would emit 3,406kt CH4 less between 2030 and 2050, nearly double the country's total annual CH_4 emissions in 2020 based on the recent GAINS modelling (Höglund-Isaksson et al., 2020).

Human population growth and increased demand for red meat and milk protein per capita to meet nutritional targets in Kenya underscore the unavoidable increase in emissions even with mitigation strategies. Despite the increase in absolute emissions, milk and red meat protein demand per capita in Africa will still remain 51% and 78% smaller, respectively, when compared to Europe in 2030 (Arndt et al., 2022). On the other hand, enteric CH_4 emissions per capita will be significantly higher than in Europe in 2030 due to the significantly higher emissions intensity of the systems in Africa. This disparity emphasizes the need for tailored approaches: reducing consumption in Europe may be effective for limiting emissions due to low emissions intensity but high demand in consumption, while in Africa, supporting livestock systems to meet nutritional needs while managing emissions is crucial. Understanding the drivers that create change are crucial for this process. The current literature tends to examine animal efficiency and productivity in isolation when discussing how to support pastoralists and climate (Henry et al., 2018; Krätli et al., 2013). However, previous research (Young, 2020) in the pastoral context has shown, for example, that there is no clear correlation between the immediate drivers of acute malnutrition, diet and disease, but rather, systemic and institutional factors such as livelihood systems, environmental aspects and gender relations. This research offers a region-specific perspective on integrating local context into strategies that balance livestock sustainability and climate goals.

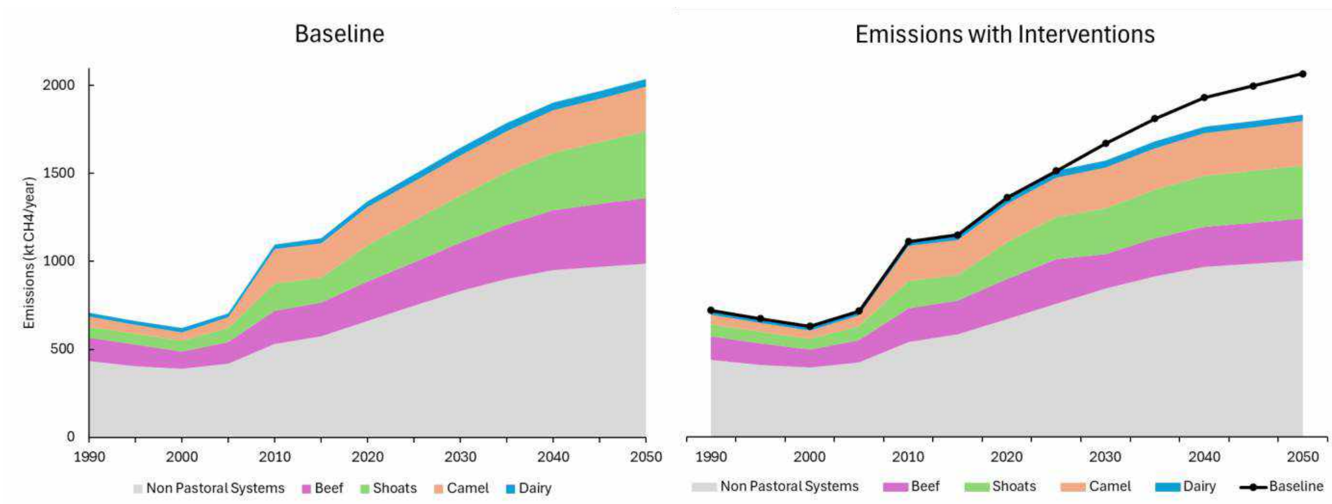

Figure 2: Enteric fermentation CH_4 emissions 1990–2050 in Kenya in the baseline scenario (left panel) and a feasible intervention scenario (right panel) with the enteric fermentation from non-pastoral systems represented in grey.

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Information technologies to empower and support land managers to participate in carbon farming projects: a case study from Australia's rangelands

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Key words: rangeland management; collaboration; farm data platforms; engagement.

Abstract
Information technologies can empower and promote active participation from land managers in carbon farming projects. As a carbon service provider, we have leveraged the capabilities of the information technology Fulcrum® to develop customised applications to support land managers undertaking Human Induced Regeneration (HIR) projects in remote rangeland environments. Through a shared platform, Fulcrum allows land managers and carbon service providers to record and share information on management interventions which promote carbon sequestration, vegetation growth and project progress. This approach can also enhance the integrity of HIR projects by using technological solutions to provide evidence of project activities and progress. In this study we look at the use of Fulcrum for the portfolio of HIR projects that we service in the southern rangelands of Western Australia (WA). We assess Key Performance Indicators (KPIs) for the database of the 'Management Activities Application' (MAA) which is the customised application that we created in Fulcrum to support these land managers. The results demonstrate the successful adoption and sustained use of Fulcrum by land managers in these locations with ongoing engagement and collaboration key contributors to this. The adoption and establishment of these ways of working provides opportunities to support land management in these areas more broadly.

Introduction
Carbon farming has become a prominent new land use in Australia's southern rangelands (Baumber et al. 2020). It presents a unique opportunity to support land managers in these areas to viably implement sustainable land management practices over the long term. Here we explore the role that information technology is playing in supporting land managers to participate in carbon farming opportunities through a case study of the portfolio of HIR projects that we service in the southern rangeland of WA. We also consider the broader opportunities to support land managers that this adoption and collaboration via information technologies presents.

A key component to the success of HIR projects, and the carbon farming industry more broadly, is capturing and sharing land management activities being undertaken as a part of a project. Land managers need to be able to demonstrate to regulatory bodies and the broader market the work that they are doing, and the causal relationship with storing carbon in the landscape. They also need a means to record and store this information over time. This can be a challenge due to the remoteness and scale of rangeland properties, and the ways of working that the people living in these areas may be accustomed to. But it is particularly critical to methods like HIR that rely predominantly on models and remote sensing to determine changes in stored carbon over time, which needs to be supported by this information. Our case study focuses on our use of Fulcrum® to address these challenges.

Fulcrum is an information technology that enables the user to capture and store different types of information with spatial and temporal attributes. We have leveraged the Fulcrum platform to create customised applications tailored to supporting land managers to collect and record the information they need to support HIR projects. Sharing of information is streamlined through automated uploads to a shared platform, facilitating collaboration as things happen. The entries then act as a database for the project, which enables information on historic land management to be easily accessed, providing further opportunities to support management learnings over the long term. In addition, the adoption and use of an information technology like Fulcrum opens opportunities to different ways of working with and supporting land managers. Fulcrum allows the user to visualise themselves and the activities they undertake in the context of other relevant spatial and temporal information such as infrastructure, livestock, vegetation and land types, and carbon estimation areas. On a smart device, this can be done while on the ground and travelling around a property, which provides great potential to support monitoring and decision making in these areas more broadly (Robertson et al. 2019).

This case study explores the adoption of Fulcrum across the portfolio of HIR projects that we service in the southern rangelands of WA. It is intended to demonstrate the potential for the adoption of new ways of working through information technologies to support and empower land managers in Australia's rangelands to take part in carbon farming opportunities and enhance land management more broadly.

Methods

Study region

The southern rangelands of WA include the Gascoyne, Murchison, and the Goldfields-Nullarbor regions – a total area of approximately 503,120 square kilometres (DPIRD 2022). These areas border the south-west agricultural region and are characterised by semi-arid to arid climates with variable and inconsistent rainfall. They are dominated by natives shrublands which support pastoralism through the grazing of livestock, which is the dominant land use of the area. There are 284 pastoral stations across the southern rangelands with an average size of around 185,000 hectares, which are typically run by families or individual land managers. As a result, these areas have limited connectivity and are some of the most remote and sparsely populated regions in Australia. This influences ways of working for people in these locations and makes communication and collaboration challenging.

Study context

We created a Fulcrum account for 32 HIR projects that we service in the southern rangelands of WA. The land managers were given the option of using the created Fulcrum account to record and share activities associated with their HIR projects in the 'Management Activities Application' ('MAA'), which is the custom application we created for this purpose. We supported land managers with the initial installation of Fulcrum on their smart devices and the use of the MAA. The projects commenced between 2018 and 2022, but the majority commenced in 2018 (22 of the 32). Associated Fulcrum accounts were typically activated shortly after this, generally within the first 12-months of commencing the project. Therefore, land managers in this study had access to a Fulcrum account for between three and six years, but most were in their sixth year. A second version of the MAA was developed and commissioned in 2021 to simplify the application in response to feedback. Land manager accounts were then transitioned to the new version of the MAA.

Method overview

We analysed KPIs for the database of the MAA to understand land managers' use of Fulcrum over the study period. The KPIs were assessed across the study period as a whole and on a 12-monthly basis commencing from the initial activation of each individual account. Most of the HIR projects report on an annual basis and so assessing on this timeframe generally captures the breadth of activities associated with a land manager's management system and provides the opportunity to better understand the utilisation of Fulcrum over time.

User adoption

User adoption was calculated based on whether or not a land manager commenced using the MAA to record project information. This was determined for the study period as a whole and across 12-month periods following activation of their Fulcrum account. Adoption was calculated as a binary yes/no for each land manager, with any level of use during the relevant period equating to a 'yes' outcome.

Drop-off rates

Drop-off rates were calculated based on whether land managers continued to use the MAA after initial adoption. This was calculated by determining whether land managers were actively recording activities in each subsequent 12-month period following the initial 12-month period in which they first starting using their account. Drop-off was determined as a binary yes/no for each land manager, with no use by the land manager during a 12-month period equating to a 'yes' outcome. Consecutive years of drop-off with no subsequent activity in the study period were deemed as complete drop-off.

Relative utilisation

Relative use was calculated for each 12-month period to provide greater insight into the effectiveness of Fulcrum in supporting land managers in the way it was designed to. This was calculated as the percentage of the total MAA entries that were created by land managers for each period. Where entries are not created by land managers, we as the service provider create these entries for the land managers by obtaining the information directly from them or during site visits.

Results

User adoption

Land managers for all except one of the 32 Fulcrum accounts that were activated went on to use the MAA at some stage, giving an adoption rate of 97 percent over the study period. Of these, 87 percent commenced using the MAA within the first 12-months following the activation of their account.

Drop-off rates

Of the 31 land managers that adopted the use of Fulcrum at any stage, four have dropped-off completely, giving a drop-off rate of 13 percent over the study period. Of the 27 land manager accounts that have remained active, 41 percent had a partial drop-off period of at least 12-months, and 22 percent for over 12-months. This was most consistently in the year immediately after they commenced using the MAA, with 82 percent of partial drop-offs commencing in the second year. A return to active use of the MAA occurred for 73 percent of land managers that dropped off, and this generally coincided with the transition of land managers to the updated version of the MAA.

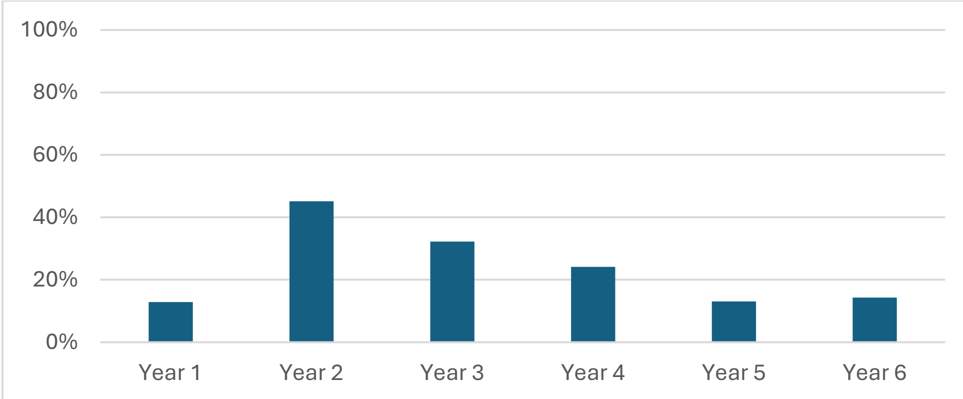

Fig.1: Percentage of land managers that dropped off for each 12-month period following account activation.

Relative utilisation
The average land manager share of MAA entries was 87 percent in the first year. It then reduced to almost half during years 2 and 3. This coincided with the peak in drop-off rates, during which we as the service provider created more entries on behalf of land managers. Between years four and six the average land manager share of entries was between 72 and 80 percent.

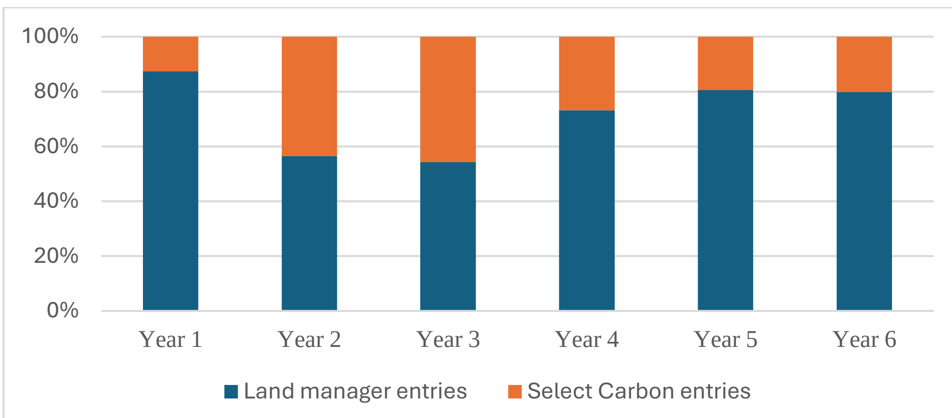

Fig.2: Average percentage MAA entries created by land managers relative to those created by us as the service provider for each 12-month period following account activation.

Discussion
The high adoption rates for Fulcrum show that land managers were receptive to trialling a new information technology to facilitate participation in a HIR project despite most not having used similar technologies in the past and having different existing processes in place to support land management. Our engagement approach was designed to streamline land managers' access to using the MAA by supporting the initial set-up and use of Fulcrum on their smart devices. The majority of land managers then commenced using the MAA within the first year of their account being activated and with high autonomy. That most have since been retained as active users suggests the engagement process was effective in supporting land managers adopt new ways of working to support their participation in a HIR project. The continued use of the MAA also indicates that Fulcrum was a functional solution that has addressed a key challenge faced by land

managers in these locations by supporting them to record and share information required for HIR projects in more effective ways than existing approaches.

The recovery in use of the MAA by land managers aligns with the transition of the majority of land managers to a simplified version of the MAA. Simplification of the MAA was undertaken in response to feedback and to improve workability. The number of options and fields for data entry were reduced and the structure was made more consistent. The subsequent improvement in both active accounts and relative utilisation by land managers demonstrates the effective ongoing engagement and collaboration facilitated by the platform, and the importance of this in effectively establishing and maintaining new ways of working that support ongoing participation in new industries such as carbon farming.

These results demonstrate the successful adoption and ongoing use of Fulcrum by land managers in remote rangeland locations to support their active participation in carbon farming opportunities. This is a significant outcome considering the lack of prior use of similar information technologies for most of these land managers. The benefits associated with the HIR opportunity would have played a role in initial willingness to adopt the use of Fulcrum (Baumber et al. 2022), but the ongoing engagement and collaboration has been key to the sustained success of this collaborative approach. The establishment of these ways of working over the Fulcrum platform presents broader opportunities to support land management in these remote rangeland environments. Farm data platforms widely used in other sectors are largely absent from the pastoral study area. There is further scope for Fulcrum to provide wider property record keeping solutions and to act as a decision support tool through its ability in collecting and visualising data on the ground. It also opens the door for increased collaboration between land managers and a range of governmental and other private services. Further engagement and research using methods such as surveys would be beneficial in understanding how land managers in these areas can best realise these opportunities.

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Remote sensing for rangeland management

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Leveraging Earth Observation services for enhanced livestock farming productivity

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Key words: Livestock farming, productivity, precision pasture, dry matter biomass, satellites

Abstract

Under the European Space Agency's Global Development Assistance (GDA) programme, GMV leads a pilot project in Paraguay with the World Bank and FECOPROD to enhance livestock farming using Earth Observation (EO) services. By integrating EO-derived data into FECOPROD's digital systems, the project optimizes grazing, monitors water availability, and prevents overgrazing, improving resource management and reducing environmental impact. Dry matter biomass is estimated using the Carnegie-Ames-Stanford Approach (CASA) model, which leverages Sentinel and Landsat data, meteorological inputs, and environmental stress factors. These insights predict pastureland condition and yield, aligning feed production with seasonal cycles for efficient, cost-effective operations.

The EO-based approach provides farmers with detailed land condition data, enabling informed decisions on breeding, health, and farm management. This scalable solution fosters sustainability in livestock farming, reducing environmental pressures while boosting productivity and resilience for Paraguay's agricultural sector and beyond.

Introduction

Two principal methodologies exist for estimating dry matter biomass (DMB): direct modelling using vegetation indices and productivity models (Wenquan et al., 2024). Productivity models, particularly net primary productivity (NPP)-based approaches, are divided into three categories: climate-based models, physiological/ecological models, and light use efficiency (LUE) models (Pei et al., 2024). The widely used CASA model exemplifies LUE models, leveraging remote sensing data for broad applicability (Wang et al., 2022).

This study emphasizes the use of multispectral imagery, with the Moderate-Resolution Imaging Spectroradiometer (MODIS) onboard Terra and Aqua satellites being historically dominant. Since the Sentinel-2 (S2) missions began in 2017, the CASA model has been employed to generate NPP maps at higher spatial resolution (Fang et al., 2021). In addition to EO data, the CASA model requires climate inputs, such as the ERA5-Land dataset, which provides global climate reanalysis data with high spatial and temporal resolution.

The NPP calculation using CASA involves several key steps, notably the estimation of the fraction of Absorbed Photosynthetically Active Radiation (fAPAR). Traditional fAPAR derivation relies on long-term Normalized Difference Vegetation Index (NDVI) data. However, red-edge bands in S2 data improve on NDVI by addressing saturation issues in crop biomass estimations (Fang et al., 2021). While previous studies focus on seasonal or annual NPP calculations, this study targets 10-day intervals. Shorter intervals increase gaps caused by cloud cover, necessitating gap-filling techniques to preserve phenological trends in fAPAR time series. Such approaches also enhance cumulative DMB estimates (Chen et al., 2004).

To mitigate NDVI saturation, this study applies the Beer-Lambert law to fAPAR calculation, linking it to Leaf Area Index (LAI). The Simple Sentinel-2 LAI Index (SeLI), derived from near-infrared and red-edge bands, is used for LAI estimation (Pasqualotto et al., 2019). Reflectance composites over 10-day periods, integrating bands from blue to shortwave infrared (SWIR), are generated by selecting the day with maximum NDVI, ensuring consistent data quality.

Like fAPAR, albedo is integral to CASA's NPP computation, particularly in Photosynthetically Active Radiation (PAR) estimation (Wang et al., 2022). Using S2 reflectance composites and methods from Landsat-8/9 OLI data processing, S2 albedo is calculated (He et al., 2018). As OLI and Sentinel-2 MSI sensors provide comparable imagery, harmonization between the missions is feasible.

The LUE parameter, crucial in NPP estimation, reflects the relationship between biomass accumulation and solar radiation use efficiency. It is influenced by multiple factors and can be derived empirically from photosynthetic responses or simulated using ground-based or global datasets (Propastin et al., 2012).

Converting cumulative NPP into DMB requires field data specific to vegetation types, such as carbon allocation capacity ($C_{allocation}$) and root-to-shoot biomass ratios (Fu et al., 2023). In the absence of local data, global or regional studies may be used (Bolinder et al., 2006).

This study aims to produce 10-day DMB estimates, resulting in 36 maps annually. Such time-series data provide sufficient temporal resolution for phenometric analysis, offering an alternative to spectral indices commonly used in phenology studies. The detailed 10-day DMB profiles facilitate identification of critical phenological events and their corresponding biomass values.

Methods

The study area covers 1,260 km² in Paraguay's Central Chaco region, spanning longitudes 59° 58' 12" to 59° 37' 4.8" west and latitudes 22° 35' 38" to 22° 16' 44" south. It includes parts of the municipalities of Loma Plata, Filadelfia, Tte 1º Manuel Fernández, and Mariscal José Félix Estigarribia (Figure 1). This predominantly pasture area hosts trial plots managed by FECOPROD and two dairy farms.

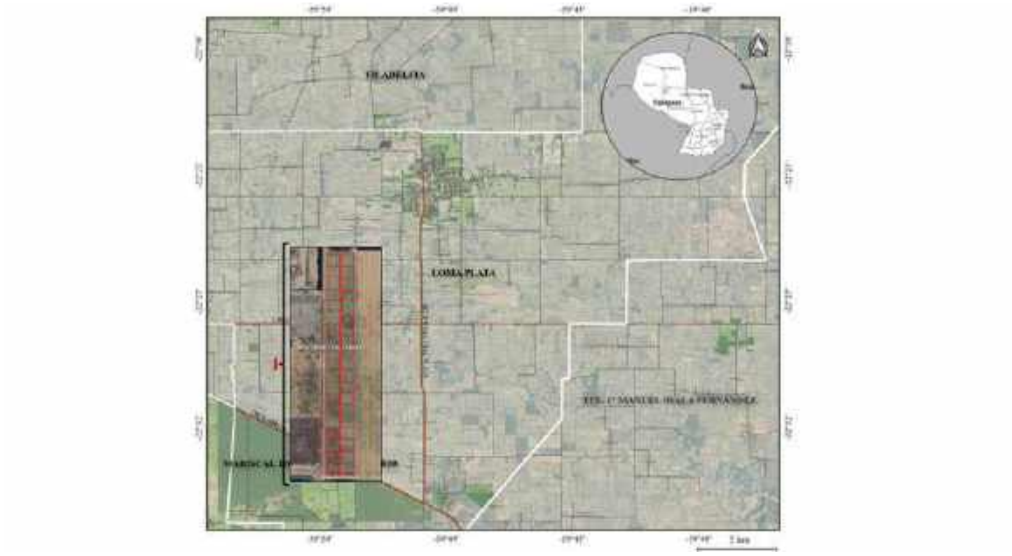

Figure 1 Study area.

The methodology includes four main stages: data collection, time-series preparation, NPP calculation, and DMB calculation with phenometric analysis (PA). The workflow is illustrated in Figure 2 and detailed below.

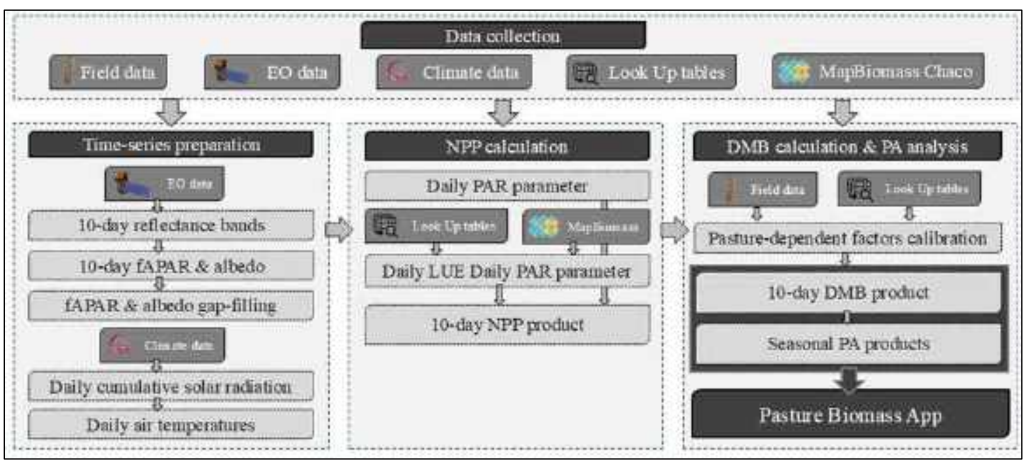

Figure 2 Workflow employed in this study.

Data collection

Data collection involved field data, EO data, climate data, and look-up tables. Field data from FECOPROD included 38 trial plots with forage species' sowing and mowing dates for the 2022 season and average bale weights per species. S2 Level 2A data (2016 onward) provided the EO dataset, while climate data came from the ERA5-Land dataset via Copernicus Climate Data Store (CDS). Look-up tables included global sources like the Biome-Property-Look-Up-Table for MODIS GPP/NPP (Zhao et al., 2005) and $C_{allocation}$ parameters from Bolinder et al. (2006). Pasture maps were sourced from MapBiomas Chaco.

Time series preparation

Daily S2 scenes were used to calculate the NDVImax-day product, which identifies the optimal day within each 10-day period based on maximum NDVI. Using the NDVImax-day, 10-day composites were created for blue to SWIR narrow-bands by assigning reflectance values directly from the sensor rather than averaging. These composites formed the basis for calculating 10-day fAPAR and albedo using equations (1) and (2):

$$fAPAR = 1 - \exp(-k\,(5.405 \cdot (SeLI - 0.114)) \quad (1)$$

$$albedo = 0.0134 + 0.246\,blue + 0.146\,green + 0.191\,red + 0.304\,nir + 0.105\,swir1 + 0.008\,swir2 \quad (2)$$

Here, SeLI (Pasqualotto et al., 2019) was used to estimate fAPAR, and the albedo equation for OLI sensors (He et al., 2018) was adapted for S2. Time-series gaps in fAPAR and albedo were addressed through outlier removal, a combination of interpolation and forward-fill methods, and Savitsky-Golay smoothing (Chen et al., 2004). Climate data, including solar radiation (SSRD) and minimum air temperature (TMIN), were generated daily from CDS.

NPP calculation

The CASA model calculated NPP using equations (3) to (6):

$$PAR\,[MJ/m^2/day] = SSRD\ (1 - albedo) \quad (3)$$

$$tmin_{LUE}\,[^{o}C] = (TMIN - tmin_{min})\,((1 / (tmin_{max} - tmin_{min}))) \quad (4)$$

$$LUE\,[gC/MJ/day] = LUE_{max}\ tmin_{LUE} \quad (5)$$

$$NPP\,[gC/m^2] = fAPAR\ LUE\ PAR \quad (6)$$

Parameters $tmin_{min}$, $tmin_{max}$, and LUE_{max} were derived from the Biome-Property-Look-Up-Table (Zhao et al., 2005).

DMB calculation

DMB was calculated using equation (7):

$$DMB = \sum NPP\ (root\text{-}shoot\ ratio / C_{allocation}) \quad (7)$$

Field trials were conducted to calibrate the root-to-shoot ratio parameter. NPP time-series data were accumulated throughout the 2022 season, and by grouping field trials with the same forage species, average total NPP values were compared to ground-truth bale weights. At this stage, the $C_{allocation}$ value was adopted from Bolinder et al. (2006), and the root-to-shoot ratio was calibrated for each forage species.

Since no forage species map was available outside the field trials, the root-to-shoot ratio used to infer DMB in the Chaco region was approximated as the average value of all calibrated forage species. This average ratio (0.4136) aligns with previous findings for the Chaco region (Baldassini et al., 2020).

The following table compares ground-truth bale weights (kg/ha) with DMB estimates from the CASA model (LUE approach) for each forage species in the 2022 field trials, applying the average root-to-shoot ratio instead of the species-specific calibrated values. During model calibration, the accuracy achieved was a coefficient of determination (R^2) of 0.87 and a root mean square error of 29.03%.

Table 1 Ground-truth bale weights (kg/ha) vs. CASA model DMB estimates using the average root-to-shoot ratio in 2022 field trials

Forage species	DMB - Bale weights [kg/ha]	DMB - LUE approach [kg/ha]
Callide	4,735	4,712
Cayman	2,438	2,605
Dicantio	2,705	2,968
Gatton panic	2,475	2,484
Lucero	3,370	3,127
Paiaguas	3,800	3,306
Quenia	2,525	3,017
Ruziziensis	3,860	3,555
Tamani	2,103	2,254

Using the calibrated root-to-shoot ratio, 10-day DMB products were generated for the entire study area, enabling phenometric analysis with high temporal resolution. This approach allows tracking of phenological events and biomass trends in pastures at 10-day intervals. While ground-truth data from FECOPROD field trials ensured proper model calibration, additional in-situ DMB data from other locations within the inference region were unavailable. As a result, DMB estimates could not be validated outside the Chaco region, except for the comparison shown in the previous table.

Results

The catalogue of products from this study is available through the Pasture Biomass Production App (last accessed November 2024). The products, at a 10-meter resolution, include:

- 10-day DMB
- Total DMB annually
- PA products such as start, peak, and end of season (times and DMB values)
- Daily DMB increase or decrease rates from start to peak times or from peak to end times

These products can be compared using the 'Split Map' mode. Additionally, by activating the contextual layer for Pastures experimental plots and selecting 'Display timeseries for selected product,' time-series statistics at the trial plot level are shown when clicking on each plot. Figure 3 illustrates the 10-day DMB product. The DMB products start on fixed days (1, 11, and 21), so the length of the last 10-day interval varies depending on the month.

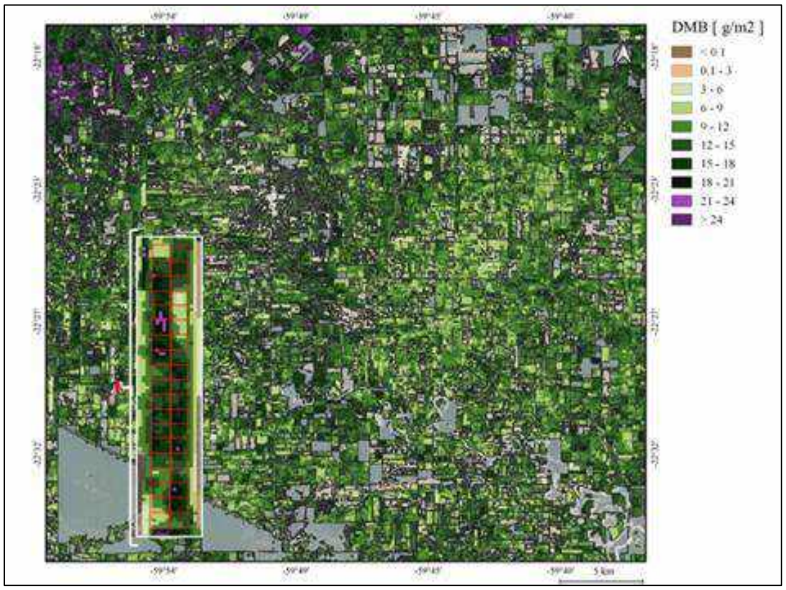

Figure 3 10-day DMB product. DMB generated in the interval 11th-20th, January 2022.

Discussion and conclusions

This study primarily uses datasets from the Copernicus services, but the processors are adaptable to other sources. The time series preparation strategy enables 10-day interval pasture monitoring. Unlike most studies that use a fixed albedo value, this study employs a detailed, updated albedo product from EO data.

The pasture map can be replaced with other maps, such as farm cartography or species-specific maps, as the root-shoot ratio parameter was calibrated for various forage species. The $C_{allocation}$ parameter and environmental stress factors in the LUE calculation were fixed based on local information, but alternative approaches can be considered.

FECOPROD, while technically advanced in data acquisition, lacked the ability to add value to the recorded information. It needed to analyse available data with EO data to generate value-added information like dry matter biomass and its variability over different time spans. The study's initial objectives were achieved, providing a scalable solution that addresses environmental concerns, promotes resource management, and enhances the sustainability of the livestock industry in Paraguay and beyond. This contributes to a more efficient, productive, and environmentally conscious agricultural sector.

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Integrating drone technology into rangeland management: plants, livestock, and wildlife

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Key words: 3D models; adaptative grazing; spatial heterogeneity; multi use rangelands.

Abstract

The use of drones in studies of rangeland ecology and management has increased significantly in the last 10-15 years. Drone imagery has been used to measure woody cover, forage biomass, spatiotemporal changes in vegetation cover, rangeland condition, and to monitor wildlife habitat in rangeland systems. The development of 3D models derived from drone imagery has facilitated new opportunities to quantify the spatial structure of land cover. For example, fine-scale structural changes influenced by grazing can be quantified using drones and subsequently translated to potential impacts on wildlife habitat. Technological developments like terrestrial LiDAR systems and higher resolution imagery allows for the improvement on the understanding of very-fine scale ecological processes in these dynamic systems. These terrestrial sensors can add valuable information to the current airborne data collection systems.

However, there is still a need to evaluate the relationship between different drone-based sensors and how the information collected and analysed can be integrated into traditional rangeland metrics. More importantly, we seek to better understand how to translate these analyses and metrics into practical management information that is critical for these socio-ecological systems. Here we demonstrate (1) the use of multispectral imagery to quantify the configuration of brush cover in semiarid landscapes, (2) the use of 3D drone data to assess the fine-scale impact of grazing on upland game birds (*Galliformes*), and (3) the integration of LiDAR, multispectral, and natural color cameras to generate data to inform livestock and wildlife habitat management. Finally, we provide insights on how drone technology could be potentially used in the future to assist in rangeland management to forecast forage growth and multi-species use for wildlife objectives.

Introduction

The use of remote sensing in rangelands has been critical to understand landscape level processes (Allred et al. 2021, Rhodes et al. 2022.) In the last 50 years, a variety of satellite platforms have been used to estimate forage production (Rhodes et al. 2022, Bestelmeyer et al. 2024) and vegetation spatial configuration to integrate this information with livestock production and wildlife habitat management. In the last 15 years, the development of drone technology has emerged as a new opportunity to collect data at very-high spatial and temporal resolutions and provides a bridge between satellite imagery and field-based data collection (Rango et al. 2006, Jackson et al. 2020, Perez-Luque et al. 2022, Avila-Sanchez et al. 2024). Derived products in 2D and 3D formats from drone data acquisitions have been used to quantify woody vegetation height (Page et al. 2022), estimate forage biomass (DiMaggio et al 2020, Perotto-Baldivieso et al. 2021), determine spatiotemporal changes in vegetation cover (Perez-Luque 2022), determine rangeland condition (Amputu et al. 2023) and monitor wildlife habitat in rangelands (Friesenhahn et al. 2023, Zabel et al. 2023). Drones offer flexibility in the variety of sensors that can be utilized to collect data. Some of the most popular sensors include natural color (with pixel resolutions from 20 to 129 megapixels), multispectral, hyperspectral, thermal-infrared and LiDAR. However, there is still a need to evaluate the relationship between the different drone-based sensors and how this information collected and analysed can be integrated into rangeland metrics. More importantly, we seek to better understand how to translate these analyses and metrics into practical management information using consumer grade drones. We demonstrate (1) the use of multispectral imagery to quantify the configuration of brush cover in semiarid landscapes, (2) the use of 3D drone sensors acquired data to assess the fine-scale impact of grazing on upland game birds (*Galliformes*), and (3) the integration of LiDAR, multispectral, and RGB cameras to generate information for livestock and wildlife habitat management. Finally, we will provide future directions on how drone technology could be potentially used to assist in rangeland management to forecast forage growth and multi-species use for wildlife objectives.

Multispectral imagery for estimating woody cover configuration

The increasing spatial and spectral resolution of multispectral cameras to acquire rangeland imagery generates new opportunities to assess woody vegetation cover, composition, and spatial configuration, particularly in semiarid and arid landscapes. For instance, the Tamaulipan thornscrub (hereafter "thornscrub") ecosystem is characterized by dense, diverse shrub, arid-adapted shrub communities and provides critical habitat for endemic and endangered species (Jahrsdoerfer and Leslie 1988, Creacy 2012, Mohsin et al. 2021). This ecosystem, located within northeastern Mexico and South Texas, USA, has been reduced to <2% of its historic distribution due to novel pressures related to urbanization, woody plant removal for livestock forage production, and land use change (Jurado et al. 1998, Ricketts et al. 1999, Lombardi et al. 2020). Little information exists on its current distribution, but it is estimated that there is >75% native mixed brush cover in these communities (Flores 2019). Our objective was to evaluate the feasibility of identifying brush species composition within this complex community using very-high resolution multispectral imagery. We used a MicaSense Altum Multispectral camera that collects imagery in six spectral bands: blue, (443 – 507 nm), green (533 – 587 nm), red (654 – 682 nm), red edge (705 – 729 nm), near-infrared (785 – 899 nm), and long wavelength infrared (8000-14000 nm; MicaSense 2019). Images were collected in five plots (0.4 ha per plot) in Webb County, Texas, USA. Each flight was conducted at an altitude of 21 m aboveground level with an 80% image overlap in September 2022. Once images were acquired, they were processed in Pix4D mapper (Pix4D Inc., San Francisco, CA, USA) to create orthoimagery, a digital terrain model and a digital surface model. We then used the orthoimagery to classify vegetation cover. We subtracted the digital terrain model from the digital surface model to estimate a canopy height model to remove the herbaceous layer and focused on the shrub components. We conducted an accuracy assessment (i.e. confusion matrix) with 643 points collected within the plots. Our image classifications yielded overall accuracies of 78%. We were able to correctly classify 19 out of the 24 species present in our study area: guajillo (*Acacia berlandieri*), blackbrush (*Acacia rigidula*), shrubby blue sage (*Salvia ballotiflora*), cenizo (*Leucophyllum frutescens*), chomonque (*Nahuatlea hypoleuca*), coyotillo (*Karwinskia humboltiana*), desert yaupon (*Schaefferia cuneifolia*), lime prickly ash (*Zanthoxylum fagara*), honey mesquite (*Neltuma glandulosa*), huisache (*Acacia farnesiana*), Texas persimmon (*Diospyros texana*), prickly pear (*Opuntia engelmannii*), Spanish dagger (*Yucca treculeana*), Texas kidneywood (*Eysenhardtia texana*), whitebrush (*Aloysia gratissima*), oreja de raton (*Bernardia myricifolia*), la coma (*Sideroxylon celastrinum*), allthorn (*Koeberlinia spinosa*), and granjeno (*Celtis pallida*). These techniques have proved promising towards obtaining scalable estimates of woody plant composition and configuration within this imperilled ecosystem characterized by high woody plant species richness and complexity.

Fine-scale assessment of herbaceous cover during cattle (*Bos taurus*) grazing

The development of 3D models derived from drone imagery has opened new opportunities to integrate 3D model classifications to evaluate the spatial heterogeneity of vegetation cover in rangelands (Avila-Sanchez et al. 2024). To illustrate this concept, we conducted a study in a pasture grazed by cattle with adaptive management (Derner et al. 2022, Avila-Sanchez et al. 2024) in Duval County, Texas, USA. The principle behind adaptive management is to use grazing as a tool to change herbaceous vertical structure (stubble height) to create or enhance wildlife habitat, in this case, for northern bobwhite (*Colinus virginianus*). Once average herbaceous stubble height of 30 cm was obtained, cattle were moved to a different pasture. We flew seven sites (27 ha each) at an altitude of 50 m above ground level (DiMaggio et al. 2020) with a 70° camera angle, 80% overlap, and a 20 megapixel natural color camera. We acquired natural color imagery that was processed in Pix4D (Pix4D Inc., San Francisco, CA, USA) to generate an orthoimage, a digital surface model, and a digital terrain model. We subtracted the digital surface model from the digital terrain model to obtain a canopy height model. We classified the canopy height model pixel values into five different height classes (Avila-Sanchez et al. 2024): bare ground (0 to < 5 cm), low herbaceous vegetation (5 to < 30 cm), grazing target height herbaceous vegetation (30 to < 40 cm), tall herbaceous vegetation (40 to < 120 cm), and brush/shrubs (> 120 cm; Fig. 1). The classified raster image was used to assess the amount and spatial configuration of the different vegetation classes using landscape metrics at the class level: percent class cover, patch density (PD; patches/ha), and mean patch area (MPA; m²) (Fragstats 4.2; McGarigal et al. 2023). We found that this grazing system provided 51.9% ± 5.80% low herbaceous vegetation cover and 9.55 ± 6.15% grazing target height herbaceous vegetation cover within managed pastures. The configuration of this cover resulted in a large number of small patches in the low herbaceous vegetation (PD=49,222 patches/ha [SE= 6,821 patches/ha]) and MPA= 12.14 m² [SE=2.08 m²] and the grazing target height herbaceous vegetation (PD=111,036 patches/ha [SE= 28,525 patches/ha]) and MPA= 1.14 m² [SE=0.14 m²]) covers. Moreover, the spatial configuration of stubble height in these grazed pastures were within the required vegetation cover configuration requirements suggested for northern bobwhite habitat (Hernández and Guthery 2012).

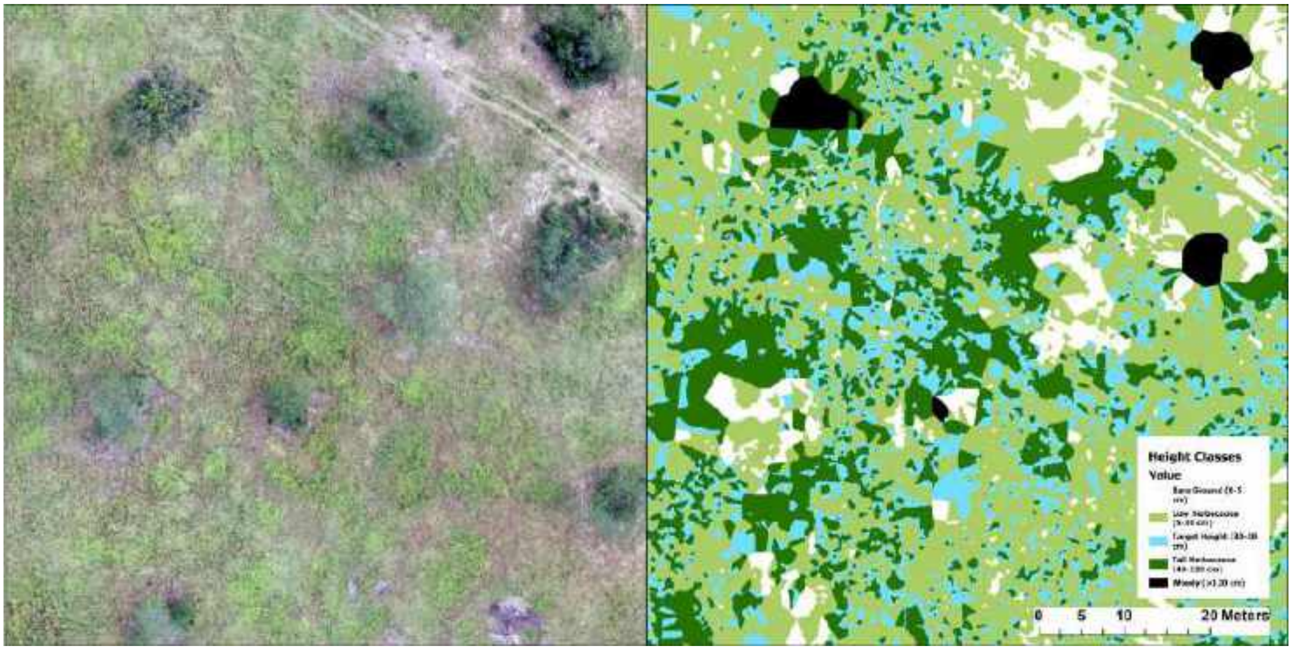

Figure 1: Example of classified vegetation height maps from drone-based imagery. white represents bare ground (<5cm), light green represents low herbaceous (5-30cm), cyan represents target grazing height (30-40cm), dark green represents tall herbaceous vegetation (10-120cm), and black represents woody vegetation (>120cm).

Integrating LiDAR, multispectral, and natural color data in rangelands to derive rangeland metrics
While consumer-drone data can provide substantial information towards managing rangelands, there is still a need to evaluate the relationship between the different drone-based sensors and how the information collected and analysed can be integrated into rangeland metrics. More importantly, we seek to understand how we can translate these analyses and metrics for outreach and management purposes. Therefore, our goal is to develop methodologies and approaches that can identify proxies that can be used by ranchers and managers to assess rangeland health and condition at the pasture scale for livestock and wildlife operations. We plan to achieve this objective by collecting data in a 1200 ha research facility in South Texas, USA. Data collection is being conducted during the growing season (March-April) and at the beginning of the dormant season (September-October). We have selected a variety of land cover types (e.g. open grass, interspersed savannah, and closed canopy brush) to collect vegetation cover information. Within these land cover types, we are marking 80-100 locations using Planet imagery (daily 3-m resolution satellite imagery) based on current land management practices. We are acquiring drone-based data within two weeks of field data collection: natural color, multispectral, hyperspectral, LiDAR, and thermal data. We will select 5-10 locations and collect vegetation data using line transects similar to DiMaggio et al. (2020). Once the information is collected in the field, we will complement it with a terrestrial mobile station to collect 3D vegetation structure. Data collected with different sensors and field data will be analyzed to evaluate the relationship between data collected in the field and sensor data following similar approaches used by DiMaggio et al. (2020), Page et al. (2023), and Massey (2023). With these data, we will build a model that links multiple sensor information to natural color data to significantly improve our ability to derive information from less expensive drones with more efficient approaches. This will increase the opportunity to adopt natural color technology by ranchers to assess a variety of metrics in rangelands.

Conclusions

The case studies highlighted in this manuscript provide a good example of the opportunities that drone technology can provide for management of multiple species in rangelands. We used technology to evaluate the use of multispectral data to assess woody cover composition in rangelands and the assessment of herbaceous vegetation cover spatial heterogeneity managed by grazing to provide a potential proxy for vegetation composition complexity. Finally, we are integrating information from multiple drone sensors to develop proxies into a meaningful and user-friendly landowner tool and resource that will be key to maintaining producer efficiency and stewardship without compromising rangeland integrity.

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Fusion of pixel & object-based image analysis to improve stratification of soil carbon projects in the semi-arid rangelands, Australia

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Key words: soil carbon; soil sampling design, stratification, image analysis

Abstract

Soils in the semi-arid rangelands of southeastern Australia are inherently low in organic carbon (SOC) content due to a combination of climatic and historic land degradation factors. Small increases in SOC attributable to improved management in such expansive landscapes offers an opportunity to restore rangeland function and play an important role in mitigating climate change.

Soil Organic Carbon stocks and fluxes are influenced by complex interactions between plant growth, climate, soil type, topography and land management resulting in high spatial and temporal variability. Variability creates a challenge for designing soil sampling strategies to detect small, incremental changes in SOC. In the rangelands, this challenge is accentuated by low SOC stocks, low SOC sequestration rates, presence of soil inorganic carbon and cost of labour-intensive soil sampling programs across large pastoral properties. Optimal stratification by clustering homogenous areas within a paddock, combined with adequate sampling density can reduce variance and improve SOC stock estimations.

Remotely sensed earth observation data can be used to determine stratification in soil carbon projects. This paper presents a basic stratification framework that integrates multiple sources of high-resolution landscape data. The study area is a dryland crop and grazing property located in the semi-arid rangelands of New South Wales (NSW). The method fuses a temporal ground cover raster classified by pixel-based analysis, with a segmented image processed by object-based image analysis. The success of the stratification can be judged by a moderately small variance in mean SOC within each carbon estimation area (CEA) and for the total project area. A validation baseline survey is planned for February 2025.

Introduction

Rangelands play an essential role in sequestering carbon to offset greenhouse gas emissions in Australia. Semi-arid soils contain naturally low levels of soil organic carbon (SOC) (Orgill et al. 2017). Small increases in SOC which may occur over time with improved management of rangeland systems offer the opportunity to sequester a significant amount of carbon over an extensive area (Orgill et al. 2017). However, detecting the differences due to management are problematic to measure and rely on high quality soil sampling stratification (Beverly et al. 2024). Soil sampling stratification can improve SOC estimation efficiency and accuracy to detect and monitor temporal changes (Potash et al, 2023). Current attention is focused on understanding and measuring influences of management practices and climate fluctuations on SOC (Bastin et al.2024, Orgill et al. 2017). Effective stratification is vital to capture small changes in SOC over large project areas, allowing the opportunity for carbon sequestration in rangelands to be quantified. A strategic low-cost baseline stratification of rangeland soils will be a critical first step towards accurate SOC reporting and monitoring change over time.

This paper focuses on the application of remotely sensed high-resolution temporal ground cover and soil colour imagery to enhance stratification design in soil carbon projects. Soil colour is a potentially useful attribute to stratify for SOC because the soil organic matter of which the carbon is part is a primary determinant of soil colour (ref: Leeper & Uren, 1993?). The approach fuses a temporal ground cover raster classified by pixel-based analysis (unsupervised classification), with a segmented image processed by object-based image analysis (OBIA) using dry soil colour reflectance.

Pixel-based analysis is processed on a per pixel level, using only the spectral information available for that individual pixel, values of neighboring pixels are ignored. A common example of pixel-based analysis is unsupervised classification which groups pixels based on statistical similar class means without training data. This unbiased technique can reveal hidden patterns in the landscape not clearly visible in the imagery. By comparison, OBIA groups pixels together based on how similar they are in colour and shape to adjacent pixels using both spectral and spatial information for classification. Image segmentation tends to generate objects that resemble real-world landscape features. The aim of this paper is to combine the benefits of pixel-based classified ground cover with object-based segmented soil colour in comparing landscape features to enhance the stratification process.

Methods

Temporal Ground Cover

The study area is a dryland crop and grazing property located in the semi-arid rangelands, NSW. Seasonal fractional cover Sentinel-2 (10 m resolution) created by the Joint Remote Sensing Research Program & Department of Environment and Science, was sourced to provide insight into ground cover spatial variability over time. The product is based on the JRSRP Fractional cover V3.0 algorithm applied to Sentinel-2 Level 1C data from the ESA (Joint Remote Sensing Research Program, 2023). A multilayer perceptron model was used to estimate percentage of cover in three fractions, bare ground, photosynthetic vegetation, and non-photosynthetic vegetation from surface reflectance (Joint Remote Sensing Research Program, 2023).

The bare fraction from the Seasonal fractional cover product (capture date: December 2018 to February 2019) was classified for each carbon estimation area (CEA) using the ISODATA unsupervised classification task in ENVI. Results were cleaned for isolated pixels. Zonal statistics were generated for each class within each CEA. Classes were then merged if means had less than 5% separation. Polygons <2ha in size were aggregated into larger adjacent polygons of a similar soil colour and ground cover type.

Dry soil colour segmentation

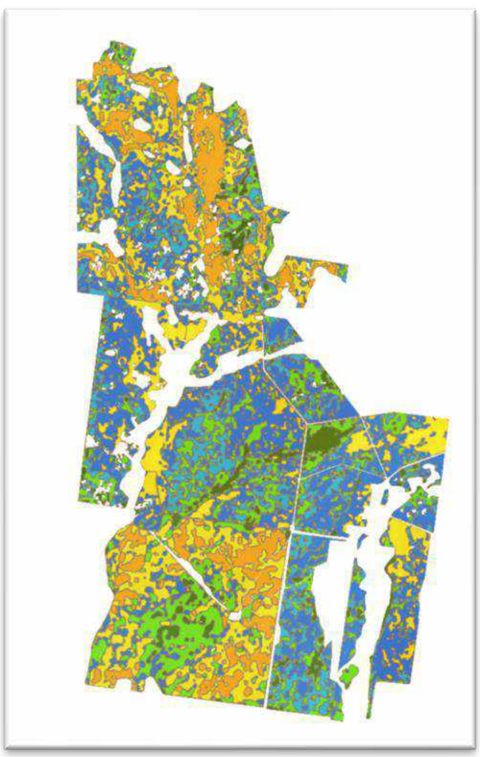
A Sentinel-2 (10 m resolution) true colour image (RGB) captured during a low rainfall period (capture date: 22nd December 2018) was segmented in ArcGIS Pro, using visible bands only (bands 2, 3 and 4). Spectral detail function (The level of importance given to the spectral differences of features in the imagery) was set high on 20 units, spatial detail (The level of importance given to the proximity between features in the imagery) was set at 6 units (minimum segment size in pixels 50). Providing a high-level representative segmentation of soil colour across the study area (Figure 1). The segmented raster output is converted to a vector format, then cleaned and simplified by merging small polygons, then clipped to the study area. Classes were labelled based on soil colour and CEA.

Fusion

The goal is to combine two significant variables that can assistance with visualising SOC spatial variability. Soil colour is the base of the stratification for each CEA. Ground cover polygons will be nested within the soil colour polygons. A union between the two layers was completed for each CEA in ArcGIS Pro. The vector outputs are cleaned by aggregating small, fragmented polygons (<0.5 ha) and slivers. The area of strata within each CEA is reviewed. Small strata will be merged into adjacent larger strata of similar soil colour and ground cover (based on strata means of bare% ground cover).

Results

Stratification based on temporal ground cover resulted 4-5 classes per CEA (Figure 1). Dry soil colour segmentation generated a 4-5 classes per CEA (Figure 2). Combining the two stratification data sets generated 8-10 strata per CEA (Figure 3).



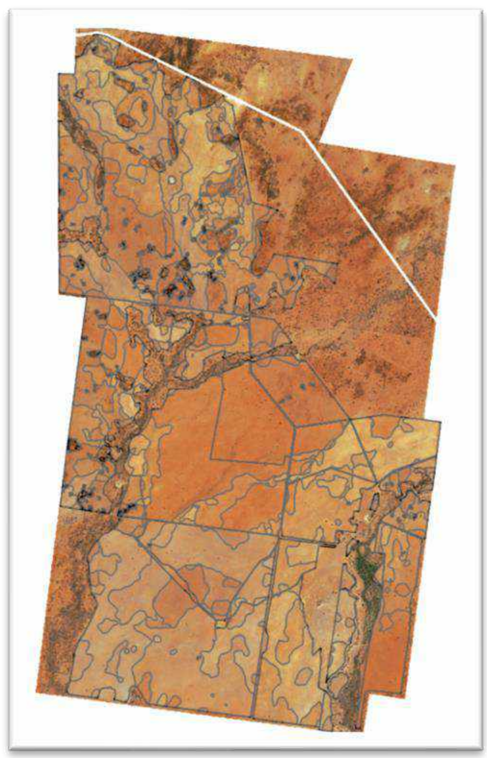


Figure 1. Temporal ground cover classification. Figure 2: Dry soil colour segmentation results.

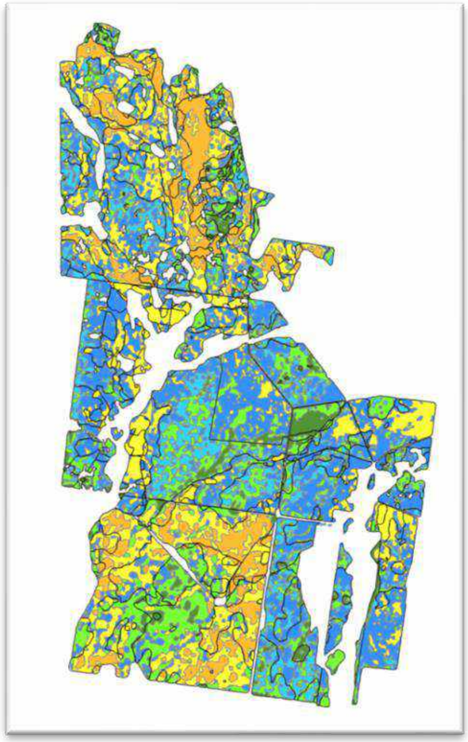


Figure 3. Stratification of ground cover and soil colour.

Discussion

The quantity of SOC in soils is influenced by a combination of factors, predominantly climate, soil type and recent vegetation cover management, plus other factors including topographic position (Grey 2021). The amount of ground cover can also be influenced by soil characteristics (informed by soil colour), management, and differences in topographic position/aspect. Merging ground cover with soil colour increased the number of strata in each CEA.

The patterns of temporal ground cover classification align with the soil colour segmentation outlines (Figures 1 2, & 3). There are similar patterns of stratification when comparing the two layers side-by-side and when both are overlayed (Figure 3). For example, note the center of the bottom southwest paddock, there is a dark red island surrounded by lighter red soil, delineated in both datasets (Figure 3). Similar patterns can be expected due to the interrelationships of soil properties and groundcover. However, there are also differences between the two datasets, that could be related to management practices impacting ground cover within the composite fractional cover timeframe (capture date: December 2018 to February 2019). A validation baseline survey, planned for February 2025, will collect SOC data from each CEA. The success of the stratification will be quantified by comparing the variance in mean SOC within each CEA and for the total project area with that of each individual stratification approach.

While this desktop approach offers a relatively quick and data-driven approach to stratification, it is important to couple it with consideration of on-ground management factors that may influence the results. For example, in drier areas of cropping zones it can be common to incorporate a fallow into a cropping rotation to preserve moisture for a following crop, therefore this may reduce ground cover in those areas. Similarly, the presence of high numbers of feral herbivores (e.g. goats) may result in patch overgrazing of specific areas of the landscape resulting in periodic reduction in ground cover that may not necessarily be indicative of soil production or carbon storage potential.

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Integrating remote sensing and in pasture weighing technology to estimate dry matter intake for grazing beef cattle

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Key words: Precision livestock technology, dry matter intake, beef cattle

Abstract

Precision livestock technology (PLT) can improve sustainability of beef production on rangelands. Key to the advancement of PLT is the integration of technologies and data streams with animal nutrition models to better inform management decisions. Knowing dry matter intake (DMI) is essential for setting stocking rates and estimating forage removal by grazing beef cattle; however, estimating DMI for grazing cattle is difficult due to dynamic changes in forage quality and animal weight throughout a grazing season. A study was conducted from 2021-2023 at the South Dakota State University Cottonwood Field Station (Cottonwood, SD, USA) to estimate daily DMI for grazing steers. The objectives of our study were to 1) utilize machine learning (ML) to predict daily estimates of forage quality, 2) estimate average daily gain (ADG) using in pasture weighing systems, and 3) incorporate forage quality and ADG estimates into animal nutrition models to predict individual animal DMI. From 2021-2023, bi-weekly forage samples were collected and used to train a multivariate random forest model to predict daily acid detergent fiber (ADF) based on climate and imagery metrics derived from Google Earth Engine. Root mean square error of prediction was 2.6 with a 0.81 correlation between predicted and observed values of ADF. SmartScales™ (C-Lock Inc., Rapid City, SD, USA) were deployed in six pastures to estimate daily animal weights for grazing steers. Smoothing splines were used to estimate ADG allowing for non-linear changes in animal performance. Daily estimates of ADF and ADG were used to calculate daily DMI for individual animals using equations from the Nutrient Requirements of Beef Cattle. Overall, average DMI estimates for individuals ranged from 2-3% of body weight, which is within expectations for free ranging livestock. This paper address how big data, technology, and machine learning can be integrated to better aid grazing monitoring and forage demands for livestock.

Introduction

The promise of precision livestock technology (PLT) is to increase operation efficiency and reduce the associated environmental footprint of grazing on rangeland systems. A suite of recent novel technologies such as remote sensing products to estimate plant fractional cover and net primary production (Jones et al. 2017) and in-pasture weighing systems (Parsons et al. 2023) has enhanced our ability to measure and manage livestock production within rangeland systems. Individually, these technologies can increase the temporal and spatial resolution of data collection that can help inform management decisions at finer scales; however, integration of multiple different technology platforms with machine learning and animal nutrition models is needed to maximize the impact of PLT.

Estimating dry matter intake (DMI) is essential for beef producers to identify more efficient animals and optimize cattle performance. In addition, DMI is an essential component for calculating stocking rates and estimating forage utilization from grazing animals. Estimation of DMI for cattle grazing on extensive rangelands is difficult due to changes in environmental factors, forage quality, and animals' physiological state, which can result in large variability among animals grazing in the same pasture (Galyean and Gunter 2016). Traditionally, fixed estimates of DMI such as 3% of body weight (BW) have been used to calculate forage demands for grazing animals; however, this doesn't account for the dynamic changes in forage quality, animal BW, and DMI inherent within rangeland systems. Previous work has demonstrated the use of models to predict DMI required to achieve a specified level of performance based on animal nutrition equations to determine net energy required for a given animal BW and average daily gain (ADG) (Anele et al. 2014). The integration of in-pasture weighing systems to measure individual animal performance and BW, remote sensing to estimate daily forage quality, and animal nutrition equations may be able to estimate DMI for grazing beef cattle. The objectives of our study were to 1) utilize machine learning (ML) to predict daily estimates of forage quality, 2) estimate average daily gain (ADG) and daily BW using in pasture weighing systems, and 3) incorporate forage quality and ADG estimates into animal nutrition models to predict individual animal DMI.

Methods

Study Site

Research for this study was conducted at the South Dakota State University Cottonwood Field Station (CFS), Cottonwood, SD, USA (43.960297, -101.857913) from 2021-2023. Rangeland at the CFS is typical of a Northern Great Plains mixed-grass prairie, consisting primarily of western wheatgrass (*Pascopyrum smithii* Rydb.), green needlegrass (*Nassella viridula* Trin.), buffalograss (*Bouteloua dactyloides* Nutt.), and blue grama (*Bouteloua gracilis* Willd. Ex Kunth.). This study was overlaid on a long-term experimental grazing study setup as a randomized complete block with three levels of stocking rate replicated in two pastures each (heavy (1.78 AUM/ha), moderate (0.99 AUM/ha), and light (0.79 AUM/ha)) for a total of six pastures. In each of three years, yearling steers (n = 116, 131, 127 in 2021, 2022, 2023, respectively) were stratified by BW into one of six pastures. Steers in 2021 grazed from June 10 to August 17, steers in 2022 grazed from June 8 to August 21, and steers in 2023 grazed from June 6 to August 30.

Remote Sensing

Forage quality was estimated by clipping five bi-weekly georeferenced forage samples from May to October in 2021-2022 across each of the six experimental pastures. Forage samples were dried for 72 hrs in an oven at 60˚C and weighed for biomass. After weighing, samples were ground in a Wiley mill (Thomas Scientific, Swedesboro, NJ, USA) with a 1 mm sieve. Forage digestibility was analysed for neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) using a fiber analyzer (ANKOM 200 Fiber Analyzer, ANKOM Inc., Macedon, NY, USA). To develop a predictive model, dependent variables were extracted from Google Earth Engine (GEE) for each sample location using an Application Programming Interface (API) developed in Python. Climate predictor variables were derived from the GRIDMET dataset and included daily cumulative and percent of 40-year normal precipitation and growing degree days (Abatzoglou 2012). Season long normalized difference vegetation index (NDVI) values were extracted for each clip plot pixel from the Sentinel-2 satellite imagery dataset. For each pixel, a cubic spline was fit and used to estimate daily NDVI values and the estimated NDVI for the day the plot was clipped was used as a predictor variable in the model. A multivariate random forest model was trained with ADF as the dependent variable and climate and satellite imagery metrics as the predictor variables. This model was then used to predict daily ADF values for each pasture.

Animal performance
Daily animal BW were measured using SmartScales™ technology (C-Lock Inc., Rapid City, SD, USA). Briefly, SmartScale™ is an in-pasture weighing technology that is placed in front of existing water tanks that measure animal BW while drinking by recording RFID tag data and front-end weight, which is converted to full BW through a linear transformation (Brennan et al. 2023). Spurious weights were removed from the dataset using robust regression technique (Parsons et al. 2023). For each individual animal, smoothing splines were fit with BW as the dependent variable and date as the independent variable. Smoothing splines models were then used to predict daily BW for each steer allowing for non-linear dynamics of animal growth. Daily ADG was estimated as the difference between modelled BW on consecutive days.

Dry Matter Intake Calculations
Individual steer growth performance and daily forage ADF determinations to were used to estimate the daily DMI required for gain. Briefly, a DMI function (DMI_{func}) was developed in program R. The DMI_{func} takes the inputs of ADF to estimate ME, initial BW (BW_t), final BW (BW_{t+1}), and days on feed to determine daily gain. Daily ADF values for each pasture were derived using the random forest model described above; BW_t and BW_{t+1} were derived from the smoothing spline model described above for each steer, with days on feed set to one in the function. Metabolizable energy was determined based upon estimating total digestible nutrients from ADF, and mathematically converting to digestible energy, metabolized energy, and forage net energy for maintenance and growth based on equations outlined in NASEM (2016).

Results
On average, estimates of DMI as a percentage of BW ranged from 2.39% to 2.80% over the entire trial period (Table 1). The daily estimate of DMI as a percentage of BW for each individual steer ranged from 1.19% to 10.86%. Averaged over the course of the grazing season, as a percent of BW, DMI estimates are well within expected ranges for grazing cattle. Daily estimates above 4.5% DMI as a percentage of BW represent 1.8% of all observations, and of those 53% occurred during the first and last week of the trial. This indicates that higher estimates of DMI are likely the result of the smoothing splines over estimating ADG at the beginning or end of the trial period, perhaps due to daily weight data being less sparse within these time frames.

In addition, for each grazing steer, we calculated cumulative DMI over the course of each grazing season (Figure 1). Cumulative estimates of DMI at the herd level ranged from 497 kg in the heavy graze pastures in 2022 to 967 kg in the light graze pastures in 2023. Differences in cumulative intake between years is likely driven by the number of grazing days and average herd BW. Results presented in Figure 1 can be used to estimate forage removal by grazing livestock and subsequently inform rotational grazing decisions when desired utilization has been reached.

Discussion
Estimating DMI for grazing cattle is difficult. Previous methods have utilized animal nutrition equations, forage clip plots, and forage marker techniques, all of which have their challenges that balance precision of

estimates, time and effort, and costs. For example, estimating forage disappearance with utilization cages can be used to estimate DMI at the herd level but fails to capture individual animal variability. Likewise, approaches that estimate DMI using animal nutrition equations rely on ADG estimates over monthly time frames and may not consider day to day variability of environmental conditions of the grazing animals (Undi et al. 2008). To our knowledge, this is the first attempt to estimate daily DMI for grazing beef cattle by integrating PLT to more accurately account for dynamic changes in forage quality and animal weight gain over an entire grazing season.

The objective of this paper was to demonstrate how technology and animal nutrition models could be integrated to make predictions on DMI for grazing cattle. Though this model considers daily estimates of forage quality and BW, other factors such as ambient temperature and forage availability can also impact DMI. Factors such as ambient temperature or heat stress equations could be incorporated into energy maintenance estimates to help refine predictions. In addition, these results can be used to determine the impact that stocking rate, rotational grazing patterns, or heat stress have on daily DMI and subsequent ADG to help optimize livestock production.

Often in the field of rangeland management, stocking rates are set based on average forage production, average herd BW, and a constant percentage of BW for estimating DMI. Given the high variability in forage production and quality between wet and dry years, this approach will likely miss grazing management targets within a given year as stocking rates often don't account for the dynamic nature of animal BW and forage quality. The objective of PLT is to utilize technology to generate real time data collection, which can be integrated into models to inform decision making allowing land managers to better hit their production goals either at the individual animal or herd level.

Table 1: Mean estimates of daily dry matter intake (DMI kg), DMI as a percentage of body weight (% BW), average daily gain (ADG kg/head/day), and acid detergent fiber (ADF) for steers grazing native range over 3 years at the South Dakota State University Cottonwood Field Station (Cottonwood, SD). USA).

Year	Stocking Rate	Daily DMI	% BW	ADG	ADF
2021	Heavy	9.62	2.39	0.79	32.17
	Moderate	10.95	2.69	0.88	34.21
	Light	10.32	2.57	0.82	34.23
2022	Heavy	7.66	2.39	0.65	33.06
	Moderate	8.00	2.73	0.75	34.29
	Light	9.30	2.58	0.76	34.31
2023	Heavy	10.27	2.59	0.91	32.37
	Moderate	9.92	2.72	0.88	33.76
	Light	11.26	2.80	0.89	33.89

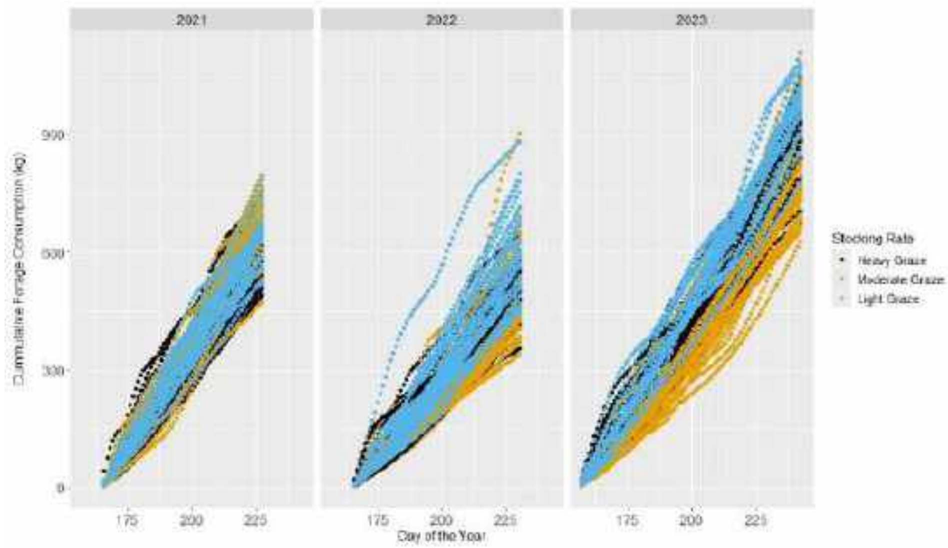

Figure 1: Cumulative estimates of forage consumption for each individual steer over three grazing seasons and three stocking rates.

Acknowledgements

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The application of state-and-transition models to remotely sensed vegetation cover datasets.

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Key words: State-and-Transition, Remote Sensing, Spatial applications

Abstract
Assessing vegetation conditions in expansive rangeland ecosystems has long posed a persistent challenge. Recent advancements in remote sensing technologies have provided new tools for improving this assessment process. In this study, conducted at two ranch sites in Nevada, we integrated existing line-point-intercept monitoring data with additional field observations to evaluate the vegetation condition or "State" at various monitoring points. We then employed machine learning techniques to classify gridded raster datasets, aligning them with existing State-and-Transition models (STMs) specific to each study area. Leveraging Landsat-derived fractional cover datasets, as well as climate and soil predictors, we aimed to predict vegetation State in specific land types. The resulting vegetation State maps were then combined to generate a cohesive representation of vegetation conditions across the study sites. Our analysis revealed that relative functional group cover emerged as a superior predictor of vegetation state and ecological processes at the site level. However, we encountered variations in state mapping accuracy ranging from approximately 14% to 44% error. These discrepancies were influenced by factors such as study location, landscape heterogeneity, availability of training data, and species-specific challenges, all of which complicate the accurate classification of remote sensing datasets.

Introduction
For over a century, understanding rangeland dynamics has guided rangeland management. Central to this understanding are state-and-transition models (STMs), which describe vegetation changes driven by ecological processes (Westoby et al., 1989; Stringham et al., 2001). However, applying these models across large landscapes remains challenging, as ecological sites—the foundational spatial units for STMs—often vary at scales too fine for practical management (Stringham et al., 2016). To address this, recent efforts have focused on aggregating ecological sites into broader units known as Disturbance Response Groups

(DRGs), enabling the application of remote sensing to ecologically similar areas (Stringham et al., 2016; Phipps & Stringham, 2024).

Advancements in remote sensing have improved the ability to quantify vegetation cover by functional group, providing a cost-effective alternative to extensive on-ground monitoring (Rigge et al., 2021; Allred et al., 2021). However, integrating remotely sensed data with STMs at landscape scales remains limited, as current datasets often fail to contextualize vegetation conditions relative to ecological site potential (Briske et al., 2006; Smith et al., 2023). Digital soil mapping offers a promising solution, correlating soil properties with ecological sites to enhance STM application (Nauman et al., 2022, Phipps and Stringham 2024).

This project aims to create spatially explicit STMs by combining remotely sensed vegetation data, soil mapping, and ground-based monitoring. The resulting framework provides land managers with a scalable, spatially informed tool for effective rangeland planning and decision-making. The workflow, illustrated in Figure 1, highlights the integration of vegetation cover, soil data, and iterative refinements to advance landscape-scale STM applications. Details of the methodology are outlined in subsequent sections.

Methods

Study Area:

This study focused on two Nevada ranches participating in the Bureau of Land Management (BLM) Outcome-Based Grazing Alternative (OBGA) pilot project, emphasizing ecological, economic, and social outcomes. The Winecup Gamble Ranch (northeast Nevada) and Smith Creek Ranch (central Nevada) were selected for their contrasting fire histories and ecological characteristics, as well as representation of major Western United Sates eco-regions. Together, the study areas spanned approximately 464,525 hectares.

Data Collection:

State-and-transition models (STMs) for land types which respond similarly to disturbance were developed using ground-based vegetation data from multiple sources, including BLM, NRCS, and University of Nevada research plots. Data were analysed using the Landscape Level Ecological Inventory and Assessment (LLEIA) database. Plots were classified into varying land types based on ecological site and DRG determinations. Wyoming Sagebrush plant community plots underwent detailed clustering and ordination using Principal Component Analysis (PCA) and Non-Metric Multidimensional Scaling (NMS) to define vegetation states, such as Shrub and Annual Herbaceous States.

Remote Sensing:

Vegetation cover data were derived from USGS RCMAP (2009–2021), incorporating variables such as shrub, tree, annual herbaceous, and perennial herbaceous cover, averaged over six years to normalize precipitation variability. Additional environmental predictors, including elevation, precipitation, soil pH, and reflectance indices, were integrated into analyses. Predictor variables were aligned to a 30m pixel size for consistency with Landsat imagery.

Data Analysis and Modelling:

Relative vegetation cover for functional groups was calculated for each plot. A Random Forest model was trained using extracted predictor variable values at plot locations to predict vegetation states across the study area. Iterative model refinement reduced error by eliminating low-importance variables. Final predictions were validated with plot photographs and mapped to represent vegetation states spatially.

Output and Applications:
The resulting vegetation state maps provide spatially explicit tools for rangeland management, highlighting ecological conditions and guiding decision-making at the landscape scale.

Results
A Random Forest model was used to classify vegetation states across study areas based on pixel-level predictions for each land type. Accuracy was assessed using withheld training data, yielding error rates from 14% to 44%, depending on the plant community. Error terms for each land type are summarized in Table 4. Key predictor variables included the relative proportion of shrub, annual herbaceous, and perennial herbaceous vegetation cover, while absolute cover metrics performed poorly. Final maps were generated by combining land type-specific classifications and incorporating pasture boundaries for enhanced visualization.

Key Findings by Land Type

- **Wyoming Sagebrush**: Largest extent and highest accuracy, with error rates of 13.8% (WGR) and 12.5% (SCR). Errors primarily occurred in rare states, such as the Current Potential State at SCR (66% error).
- **Low Sagebrush**: High error rates (44% WGR, 35% SCR) due to spectral similarity between dominant species (e.g., Sandberg's bluegrass) and cheatgrass.
- **Low Sagebrush (High Resilience)**: Predicted only at SCR with a 33% error rate, primarily in the Annual and Tree States.
- **Black Sagebrush**: Error rates of 24% (WGR) and 18% (SCR). The Annual State at SCR showed 100% error due to its rarity.
- **Mountain Sagebrush**: Errors were 21.4% (WGR) and 36.8% (SCR), influenced by terrain complexity and sparse observations of certain states.
- **Shadscale Saltbush/Bud Sagebrush**: Errors of 40% (WGR) and 28.6% (SCR). Shrub State was consistently accurate. Alternative states may not be present in the study sites.
- **Winterfat**: Sparse observations yielded error rates split across Shrub and Annual States.
- **Greasewood**: Modeled only at WGR with a 15.8% error rate, mainly between Annual and Current Potential States.

Figure 1 illustrates vegetation state maps for WGR and SCR, aiding management and monitoring. Detailed accuracy matrices for each VGG are provided in Figures 7–14.

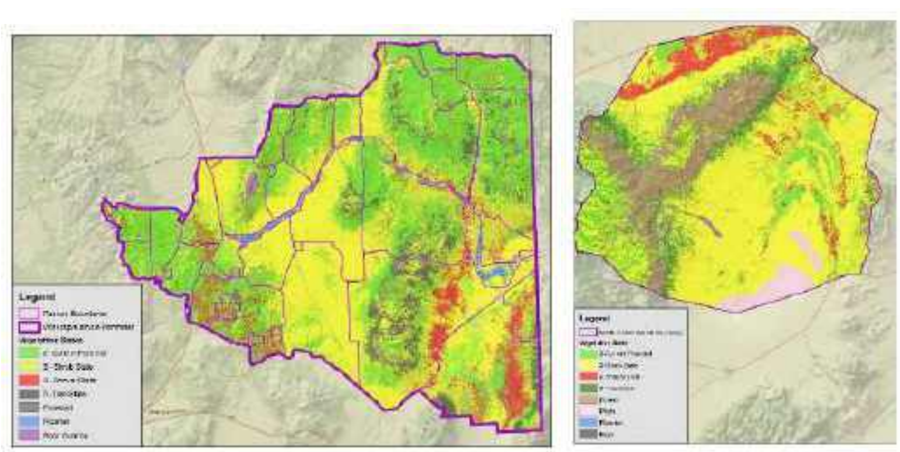

Figure 1: Vegetation state map of the Winecup-Gamble and Smith Creek Study areas. Showing states mapped across the management area, including pasture boundaries, to assist in management and monitoring decision making.

Discussion

This study highlights the effective application of fractional cover mapping technologies for spatially mapping vegetation states, adding a critical spatial dimension to State-and-Transition Models. This advancement enables practical management applications across scales, from pastures to regional planning, aiding proactive restoration and conservation efforts. It facilitates rapid assessment of areas that may have crossed ecological thresholds, requiring active restoration, or areas that could benefit from passive resilience-enhancing strategies.

While this analysis utilized vegetation monitoring data as training points, the approach can also work with visually assessed state conditions by experienced ecologists. Accurate soil and plant community mapping is essential, as plant community proportions vary significantly across these units. Relative cover emerged as a robust predictor of vegetation state, providing insights into the structural and functional dynamics of plant communities, outperforming absolute cover measurements.

The study focused on categorizing pixels into vegetation state categories to inform management priorities rather than tracking trends in vegetation cover or landscape outcomes. The RCMAP dataset effectively captured relative cover proportions, with perennial vegetation, shrub, and annual cover strongly predicting the Current Potential, Shrub, and Annual States, respectively. Climatic variables, including minimum and maximum temperatures and precipitation averages, further enhanced accuracy, particularly in the Wyoming Sagebrush land type, where they improved model performance by 7%.

Challenges remain in distinguishing areas seeded with agricultural cultivars, such as Crested Wheatgrass, from native perennial grass states. Secondary tools like the Monitoring Trends in Burn Severity dataset and the Land Treatment Digital Library can help identify seeded areas, though uncertainties persist due to historical mapping gaps. From an ecological perspective, these areas, while distinct in management context, may function similarly to native plant communities in terms of site dynamics.

Incorporating climatic variables and leveraging additional datasets can refine vegetation state mapping, providing greater precision for ecological assessments and management interventions, especially in expansive, heterogeneous landscapes like the Wyoming Sagebrush biome.

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Continental-scale modelling of pasture growth with the AussieGRASS model: Learnings from 30 years of operation

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Key words: Modelling, Pasture, AussieGRASS

Abstract

The AussieGRASS model has been run operationally for Australia since 1995, with modelling outputs of current conditions and forecasts provided each month to the Long Paddock website – and is considered an 'environmental calculator' rather than just a model of pasture growth. AussieGRASS was initially built to help quantify current conditions 'relative to history' to assist with drought and seasonal conditions assessment but has since been used for many additional purposes. There have been many challenges to building and maintaining 'the operational system' – some of these challenges are summarised in this paper with regard to: input data sets (historical and current climate, climate forecasts, tree density mapping, grazing pressure, land use etc); calibration and validation (integrating field and satellite observational data sets); computation (high performance computing and storage); extension (Long Paddock web site); and human capital (staff, collaborators, and management).

Introduction

The AussieGRASS system was developed using funding provided from the Land & Water Australia (LWA) Climate Variability Program in collaboration with other states (i.e. WA, NSW, SA and NT) to extend its application from Queensland to all of Australia. The driving forces and enabling mechanisms for its establishment were: the existence of the well-calibrated GRASP pasture growth model (Rickert et al. 2000), along with (SOI-based) climate forecast systems, and land degradation of Dalrymple shire which highlighted the need to track grazing pressure and pasture growth in 'near real time' (McKeon et al. 2004), and a review of drought and drought declaration policy in Queensland (Daly 1994). Modelled pasture growth typically provides a better indication of drought than rainfall alone, as runoff, soil evaporation and other climate elements (such as atmospheric moisture content) are accounted for in the simulations.

Initially, AussieGRASS was internally funded and run for Queensland only. Funding from competitive grants followed. The first of these grants allowed field validation activities for Queensland. Once operational, various States subscribed to the AussieGRASS system along with subscriptions to the SILO climate data system. This income sustained early development, however, downsizing of state agricultural departments and Queensland and interstate departmental reorganisations made it difficult to maintain subscriptions. In addition, a global move to offer 'open data' online, ultimately ended the subscription model. For most of the 30-year period the small AussieGRASS team has undertaken a range of short duration projects, including provision of data for three federal drought schemes, climate change impacts, net primary production comparison studies, estimates of biofuel potential of pastures, livestock methane production and rangeland monitoring (Bastin 2008). Maintaining the continuity of an operational AussieGRASS system given these challenges is discussed.

Systems development has been ongoing over three decades, with many ongoing improvements in software, data, algorithms, delivery platform and information technology. This paper describes some aspects of the 30-year AussieGRASS journey; whether programming innovations and data have stood the test of time – or in what direction, with the benefit of hindsight, the modelling might best have been progressed.

Model characteristics

The AussieGRASS model runs at a daily timestep, given most field measurements occur at this time scale (e.g. pasture biomass estimates) which allows modelled and field data to be matched in time and space. Remote sensing inputs are similar, in that most imagery can be matched with a model output on the same day. A monthly time step is considered too long, as some processes (e.g. runoff) occur at much shorter time scales and pasture growth in tropical regions can be rapid. Also, measured climate data at a sub-daily timestep are largely unavailable.

Historically a 0.05-degree grid (i.e. 5 x 5 km; 25 km^2) was considered optimal given computer capacity and spatial resolution of input data. It was important to define standards for coastline masks and rules for inclusion/exclusion of coastal pixels and to ensure precise alignment of independent input layers (climate, soils, tree density, fire, flood, grazing animal density). While input layers are used at 25 km^2, most were constructed at a finer 1 km^2 resolution to facilitate future higher resolution modelling. While the model is run daily at 25 km^2 resolution we recommend that users apply outputs such as pasture growth and other variables at about 10 to 30 times the spatial and temporal run resolution.

Development of climate data and other inputs

Climate data is perhaps the greatest challenge for modelling pasture growth, as plant growth models require a minimum set of daily input data. Ideally it is useful to be able to run the model back in time so comparisons with historical climate events (e.g. Australian 1901-1903 drought period and 1890s floods) can be made. Note, these historical events are still the most severe events experienced in some parts of Australia. It is also useful to examine the historical impacts of total grazing pressure on land degradation processes (e.g. McKeon et al. 2004). Quantitative drought evaluation to inform government policy necessitates a near real time supply of climate data for AussieGRASS model outputs. AussieGRASS evolved from ‘hand punching’ data to videotext and eventually internet File Transfer Protocol (FTP). Climate data interpolation algorithms and data quality control were implemented into the SILO system (Jeffrey et al. 2001). Gridded data sets were built and made available to the science community long before such data sets were available from the Bureau of Meteorology (BoM). The advantage of this ‘in-house’ climate data system is that it can be closely coupled to AussieGRASS in a shared computing environment where additional quality assurance analyses can occur. There is also the potential to add additional climate data to the system (especially rainfall). In recent times we have supplemented BoM rainfall data with rainfall observations from the Queensland flood warning network, as well as from our own network of about 30 grazing properties.

In addition to being able to run in ‘near real time’, the system needs to be able to re-run when additional rainfall data arrives in the system (especially from volunteers providing hard copy records). In Australia, data from only about 50% of rainfall stations are available in the first days of the new month, so the modelling system needs to be re-run and updated, typically four times a month. It is also useful to have climate forecast data at climate change and seasonal forecast time scales, as these forecasts combined with 'initial conditions' (typically soil moisture, nitrogen status and ground cover), can be used to estimate future pasture conditions.

Until recently, seasonal forecasts were generated from statistical systems that produced a set of 'analogue' years based on climate indicators such as the SOI. Analogue year systems are relatively easy to implement given access to a climate data archive. In the last decade or so gridded climate data from weather models has started to become available – and while these new data sources appear to be beneficial, they entail significant overheads as data needs to be bias-corrected and downscaled, automatically downloaded, resized to the user's grid dimensions and formatted.

Climate data quality and availability has declined since ~ 1970's due to a reduction in measurement sites. For example, both pan evaporation and cloud cover (a solar radiation proxy) have caused issues due to a lack of detection and slow switch over to satellite radiation estimates. Other important variables such as estimated total grazing pressure also present challenges as the Australian Bureau of Statistics (ABS) no longer collects annual agricultural statistics. Remote sensing is used for tree density inputs as well as fire scar data for biomass resets and the Landsat archive provides green and dry cover time series to assist model calibration.

Data formats and processing

An early decision in development of the AussieGRASS framework, derived from the group's experience in remote sensing, was to process data as raster grid cells rather than polygons. Initially we used formats from an older remote sensing package DSIMP but when this platform became obsolete, we developed our own data format designed to minimise storage and file upload time. A range of raster manipulation tools was developed inhouse for post processing (e.g. calculation of percentiles). While initially essential, this system has become limiting as NetCDF is becoming a global standard for climate and some ecological data. The SILO climate data is now produced in NetCDF format and the AussieGRASS model can input and output directly in NetCDF format, avoiding file conversion when using climate forecasts – in hindsight, a direction that could have been pursued much earlier.

The AussieGRASS model is highly optimised for a High-Performance Computing (HPC) environment and runs each pixel every day, reading and writing daily grids for the model extent rather than running each pixel for the duration of the simulation then moving to the next pixel which requires disassembly and reassembly of gridded input (especially climate data) and assembly of many small files to generate output maps. In the HPC environment efficient use of resources such as caching of input data in RAM disk rather than reading from spinning disk can reduce run times by more than 5%. There are very significant speed gains to be made in code optimisation. In particular, the layout of data in memory is critical in multi-threaded systems and memory access needs to be kept local to each thread. In addition, data arrays in memory need to be structured such that the next needed variables are close, so that caching is effective. We found that memory reorganisation could improve processing times by a factor of 8 or more.

Automation and diagnostics

Automation is essential especially when the system is run by a small team. The AussieGRASS operational system has been almost fully automated since inception. Model runs and post processing are instigated automatically. To deliver in 'policy' time often requires running on weekends and public holidays as well as having a system that copes with staff being on leave (with ability to remotely access the system). Despite automation, we believe it is important to have a minimum of 2-3 dedicated staff available to cope with any problems that emerge, monitor progress and fix issues. AussieGRASS has produced monthly outputs within a few days of the end of each month for about 30 years (with the longest outage being about 10 days due to a climate data system rebuild). Operations are designed to be largely fail-safe. For example, if the input data does not arrive there is a fall back to long-term average climate or secondary data sources.

The system produces many log files and emails signifying the success or otherwise of completed tasks. These often help to diagnose any potential problems. Furthermore, additional ancillary model outputs are generated such as plant nitrogen status for rapid diagnostic examination. Along with the biophysical model code, there is a large amount of coding that supports model calibration and validation. This calibration and validation coding and data preparation programming represents the bulk of the total coding effort in the modelling system (Table 1).

Modelling Outputs

Success in modelling relies on providing useful and accessible information. The Long Paddock website (Stone et al. 2019) has been the key delivery website and has evolved over time. We believe that it is a significant advantage to have a recognisable brand and web presence that is enduring, rather than being lost amongst ever changing general government web platforms. In addition, autonomous website control allows rapid updating and fixing of issues that would otherwise be someone else's low priority. Ability to rapidly produce test web pages within an operational environment and fully automated product uploads/reloads are essential. In the early stages of the AussieGRASS development we used a specialist extension officer to extend the AussieGRASS and the Long Paddock website across Queensland and Australia. In recent years there has been no major nation-wide extension effort, and we largely rely on users outside Queensland, finding their own way to the website. A key part of the websites success has been due to the team's efforts in marketing the Long Paddock product suite at field days and workshops.

The product package from AussieGRASS includes a range of grazing and fire related products typically made available as relatively simple to understand maps and tables. Products are made available in different formats such as PDF files, GeoTIFF, and text files and are named systematically such that automated retrievals of data from the web site are possible. Information is generated as actual amounts and percentiles (of various duration) to display current conditions relative to history. While many drought products use complicated indices, we have chosen percentiles as most likely to be understood by our general audience and we support the maps with a video explaining percentiles tailored to landholders. Perhaps the most challenging issue in regards percentiles is the most appropriate baseline period to use.

Results

As a regional to national scale product AussieGRASS remains useful after 30 years and currently contributes to the national AADI program (Hughes *et al*. 2025), revised Queensland drought analysis, daily calculation of fuel loads for fires and information for plague locust modelling. A 1 km resolution version of AussieGRASS that improves accuracy of tree-grass competition is in pre-production testing, as are climate change runs to 2100 with 3 scenarios and 15 models. Its companion product FORAGE, which is designed for paddock to property-scale application, uses the same data, pasture model, computing infrastructure and website with shared 'team effort', to generate about 50,000 property scale reports per year. The SILO climate data system continues to produce ready to use climate data for a large user community.

Discussion

There are many reasons for the success and endurance of the AussieGRASS product, however, the most important to us seem to be: (a) tight integration of the modelling system with climate and other data inputs and a web-based front end, all largely under a single supportive management structure; (b) strong focus on usable products that serve a variety of users; (c) systems designed for both broadscale and property applications; (d) concentration on gathering and using a broad range of calibration and validation data sets and (e) adequate base funding to maintain computing and data infrastructure and a small number of long serving staff who apply the skills of systems analysis to provide an operational and enduring service. Challenges remain, however, as continuing deterioration of climate monitoring and agricultural statistics, broad-scale species change (e.g. Buffel grass invasion) and lack of fire and woody density clearing maps pre-1980s all present formidable challenges.

Table 1. Characteristics of the AussieGRASS system.

Subject	Comment
Time Step	Daily to match satellite and ground measurements, aim to approach reality at monthly time scales, capture runoff and erosion events. Also, matches available climate data.
Calibration spin-up	Approximately 30 years to equilibrate pasture biomass especially for slow growing arid zone species (e.g. *Triodi*a spp).
Spin-up operational	Model is run forward from 1890; state variables are saved, then last 2-3 years are updated with each model run to ingest updated rainfall and climate data. Then forecasts are run with best estimates of initial conditions.
Calibration	PEST optimisation package and manual calibration (which may include many variables).
Output timing	Run at day 1-3 each month; update runs about every 10 days to capture updating rainfall data, daily for fuel loads.
Output variables	Most model variables can be output if desired, input variables for checking, absolute values, counts > threshold.
Output method	Data grids for daily, monthly, annual, selected date, to match observations, ascii files to match single point observation, various diagnostic tables for running in single pixel mode.
Data formats	Internal Drought Research Raster (in-house, binary run length encoded), NetCDF. Outputs GeoTIFF, PDF, ASCII tables. (maps with colour blind and other accessibility features)
Post processing	Percentiles of various durations; monthly to 30 years, maps, time series plots, probabilities, anomalies.
Automation	Linux 'cron' automation utility starts (various model runs, fuel loads, 1 km experimental, several seasonal forecasts, post processing to percentiles, map generation, archiving, placement on Long Paddock).
Time duration	1880-1890 spin-up, 1890-today, 3 months ahead, standard 18 months ahead for both weather model climate and statistical forecasts. 1975-2015 climate change baseline, current to 2100 for climate change.
Spatial resolution	Projection geographic, 5 km version (pixel size 0.05 degrees; grid extent -10^{0}S, -44^{0}S; 112^{0}W, 154^{0}W) and 1 km version (pixel size 0.01 degrees; similar grid extent).
CO_2 effects	Can be fixed concentration, historical timeseries, or represent CO_2 associated with climate change forecasts (i.e. Shared Socioeconomic Pathways).
Climate inputs	Daily rainfall, Tmax, Tmin, vapour pressure, solar radiation, potential evaporation (wind optional).
Additional inputs	Fire scars (1-3 days), total grazing pressure (annual, 6 animal types), floods from Landsat water masks, ocean mask.
Satellite calibration/validation	(Initially NOAA AVHRR NDVI) Landsat main source of calibration data (all scenes in Australia for fractional green and total cover), ancillary; GRACE soil moisture, OCO_2 chlorophyll fluorescence, CO_2, Scimachy CH_4, AMSR surface soil moisture, Sentinel 1 G0 backscatter for soil moisture., ERS2 radar altimeter backscatter.
Site based calibration /validation	TSDM > 600,000 observations, pasture N concentration, soil nitrate, soil moisture, pasture utilization, grass basal area, live weight gain, erosion, runoff, tree litter fall and mass, grass litter, grass root mass, ground cover, pasture growth.
Inputs static	Soils type and soil parameters, pasture community map, tree density map.
Coding	Main model code Fortran 90 (~ 31K lines), post processing shell scripts and plotting (R), python, (~17K lines). Data preparation e.g. total grazing pressure (shell, python, Fortran 90 (> 85K lines), calibration/ validation, etc (> 172K lines)

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Quantifying and interpreting the utility of foraging behaviour metrics derived from on-animal sensors in extensive rangelands

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Key words: Accelerometer; GPS tracking; Precision livestock management;

Abstract

The use of on-animal sensors to manage and monitor free-ranging livestock has advanced rapidly over the past decade, particularly with the emergence of virtual fencing technology to manage livestock distribution. Low-cost GPS tracking for purposes of virtual fencing creates new opportunities to monitor animal health and behaviour when combined with an accelerometer to quantify the animal's behavioural state. However, our understanding of how behaviors can be quantified via GPS plus accelerometer measurements, and how foraging behavior metrics relate to diet quality or animal growth rate remains in its infancy. Here, we provide an overview of multiple studies that use on-animal sensors to quantify daily foraging behaviour of both yearling steers and mature cows in semi-arid rangelands of central North America (Colorado and Wyoming). We examine analyses of behaviour at varying time steps (seconds to minutes) summarized over the daily cycle using both commercially available and custom-built GPS plus accelerometer combinations. Foraging behaviour could be most accurately predicted by analyzing both sensors at a time step of 90 seconds, but an accelerometer algorithm calculated at a 30-second time step could be linking to longer GPS fix intervals with nearly equivalent prediction accuracy. We then focus on the utility of three key behavioral metrics: (1) mean daily grazing bout duration (GBD), (2) mean velocity while grazing (VG), and (3) the tortuosity of grazing pathways quantified as the mean turn angle while grazing (TAG). Our analyses identify GBD and VG as key indicators of declining forage availability, which could be used to guide the timing of pasture rotations or provision of supplemental feed. Furthermore, VG and TAG are significantly affected by stock density (herd size relative to pasture size), and hence could potentially be used to identify a threshold density that inhibits selective foraging and reduces weight gain.

Introduction

On-animal sensors are increasingly used to monitor and manage livestock in intensive production systems, but have received less attention in extensive rangeland settings (Trotter et al. 2019). However, the emergence over the past decade of virtual fencing technologies that rely on GPS tracking of individual animals creates new opportunities to monitor animal health and foraging behaviour in extensive settings where managers do not have frequent visual checks of their livestock. Advancing the effective use of on-animal sensors in extensive settings will rely on understanding how GPS tracking and behavioral sensors such as accelerometers can be combined to quantify animal foraging behaviors, developing durable and cost-effective sensors and associated attachment to animals, and developing of cost-effective means to transmit sensor data to managers (Bailey et al. 2018). Here, we provide an overview of multiple studies that have used on-animal sensors to quantify daily foraging behaviour of both yearling steers and mature cows in semi-arid rangelands of central North America (Colorado and Wyoming). We examine (1) accuracy of calibrations of grazing, walking and stationary activities using varying models of devices, (2) use of resulting predictions to quantify metrics of daily foraging behaviour, and (3) how these foraging behaviour metrics vary in relation to factors such as forage allocation and quality, and paddock and herd size.

Methods

We first compare predictions of cattle (*Bos taurus*) activity states (grazing, walking, stationary) using (1) commercial GPS tracking collar with a 2-axis activity sensor (Augustine and Derner 2013), (2) commercial GPS tracking collar with a 3-axis accelerometer (Augustine et al. 2023), (3) in-house constructed collar with off-the-shelf GPS and 3-axis accelerometers (Cunningham et al. 2024), and (4) commercial GPS tracking ear tag with 3-axis accelerometer. All devices were capable of collecting GPS fixes at 5-min intervals. The in-house collar collected GPS fixes at 1-second intervals, allowing us to rarify the data to varying epoch lengths (e.g. 10 sec to 15 min), and examine the optimal length for prediction of activity states via GPS+accelerometer or accelerometer alone. The eartag device was the xTPro produced by 701x (Fargo, ND, USA; 701x.com). We fitted xTPros on 69 yearling steers (23 in each of 3 different pastures) at the Central Plains Experimental Range in northeast Colorado during May – Sept of 2024. The 3 study pastures differed in stocking rate (low, moderate and high), and in vegetation composition, where the light stocking pasture was dominated by C3 midgrasses, and the heavy stocking pasture dominated by C4 shortgrasses (Porensky et al. 2017). We conducted direct observations of behaviours of 24 different steers wearing these eartags during May – July of 2024, where activity (grazing, walking, stationary, other) was recorded at a 30-second time step as described by Cunningham et al. (2024). The eartags collected GPS fixes at 5-min intervals, and used a 3-axis accelerometer in combination with a proprietary algorithm to predict the number of seconds in each interval the animal was grazing, walking, stationary (sum of resting and ruminating), or unknown. We classified each 5-min interval based as whichever activity occurred for >=50% of that interval, based on both direct observations and eartag predictions. Intervals in which no single activity occurred for >=50% of the time were classified as mixed.

We compared metrics of foraging behaviour from three studies that deployed (1) GPS collars with a 2-axis activity sensor (Lotek 3300LR) on yearling steers grazing shortgrass rangeland (data from Augustine et al. 2023), (2) GPS collars with a 3-axis accelerometer (MOOnitor.com) on yearling steers grazing shortgrass rangeland (data from Augustine et al. 2022), and (3) GPS collars with a 3-axis accelerometer (MOOnitor.com) on 12 mature cows with calves within a herd of 120 pairs grazing mixedgrass rangeland in northeastern Wyoming. In the latter study, collars were deployed during the 2021 growing season, with GPS fixes at 5-min intervals. Collared cows and their calves were individually weighed at the beginning and end of July, when vegetation was greening up and near peak biomass, and again at the beginning and end of September, when vegetation was senescing and reduced in biomass. We used data from the collars to calculate mean daily velocity while grazing (VG, in m min^{-1}), mean daily grazing bout duration (GBD, in min) and mean daily turn angle while grazing (TAG, in degrees measured as deviation from a straight line), following the same methods as Augustine et al. (2022).

Results

Table 1. Comparison of different on-animal sensors for their efficacies to predict cattle grazing and other activities for yearling steers grazing shortgrass rangeland in northeastern Colorado. Activity categories are G = Grazing, NG = Not Grazing, W = Walking, S = Stationary, and M = Mixed. Data sources are [a]Augustine and Derner (2013); [b]Augustine et al. (2022); [c]Brennan et al. (2021), [d]this study, [e]Cunningham et al. (2024).

Sensors	Attachment	Model	Timestep	Activity categories	Misclass Rate	Source
GPS + 2 axis activity sensor	Collar	Lotek 3300 LR	5 min	G, NG	13%	a
GPS + 3 axis accelerometer	Collar	MOOnitor	5 min	G, NG	9%	b
GPS + 3 axis accelerometer	Collar	Columbus P1; Gulfcoast	1 min	G, NG	11%	c
GPS + 3 axis accelerometer	Eartag	701x	5 min	G, NG	9%	d
GPS + 2 axis activity sensor	Collar	Lotek 3300 LR	5 min	G, W, S, M	16%	a
GPS + 3 axis accelerometer	Collar	Columbus P1; Gulfcoast	5 min	G, W, S, M	18%	e
GPS + 3 axis accelerometer	Collar	Columbus P1; Gulfcoast	90 sec	G, W, S, M	10%	e
3 axis accelerometer only	Collar	Gulfcoast	90 sec	G, W, S, M	13%	e
GPS + 3 axis accelerometer	Eartag	701x	5 min	G, W, S, M	13%	d

Predictions of cattle grazing activity via different on-animal sensors

Misclassification rates for cattle activity were lower when making binary predictions of grazing vs. non-grazing activity, compared to predictions of four activity classes (grazing, walking, stationary, and mixed; Table 1). When distinguishing between all four activity classes, misclassification declined from 16-18% using GPS with an activity sensor at 5-min intervals, to 10-13% using accelerometer data at 90-sec intervals. Misclassification rates were similar for GPS plus accelerometers mounted on an eartag, compared to the same type of devices mounted on a collar.

Variation in daily foraging behavior quantified via on-animal sensors

Mean daily velocity while grazing, grazing bout duration, and turn angle while grazing all varied in relation to forage conditions, stock density, and animal type. For yearling steers, a reduction in forage quantity and quality that reduced ADG from 1.11 to 0.25 kg steer-1 day-1 (HQl, HQt vs. LQl, LQt in panels A,D,G) also reduced VG by >2 m min-1, increased GBD by >80 minutes, and reducted TAG by 8 degrees. For yearling steers, a 10-fold increase in stock density (which reduced ADG by 15%) was associated with a reduction in VG by 1.5 m min-1, an increase in GBD by 10 min, and a reduction in TAG by 6 degrees.

Discussion

Rangeland scientists have long recognized that foraging behaviours are likely to reflect variation in feed intake and the quality of herbage eaten, and hence could serve as indicators of animal growth rates (Stobbs 1973, Chacon et al. 1976, Carvalho et al. 2015). Today, the increasing deployment of GPS collars on cattle for purposes of distribution management via virtual fencing creates opportunities to additionally monitor animal foraging behaviour via the addition of other sensors such as accelerometers. A synthesis of studies calibrating these various types of GPS + accelerometer combinations to predict cattle grazing activity at time steps of 1.5 to 5 min shows that misclassification rates of less than 15% can be achieved, both with collar- and eartag-mounted devices, even when non-grazing activity is separated into stationary vs. walking vs. mixed categories.

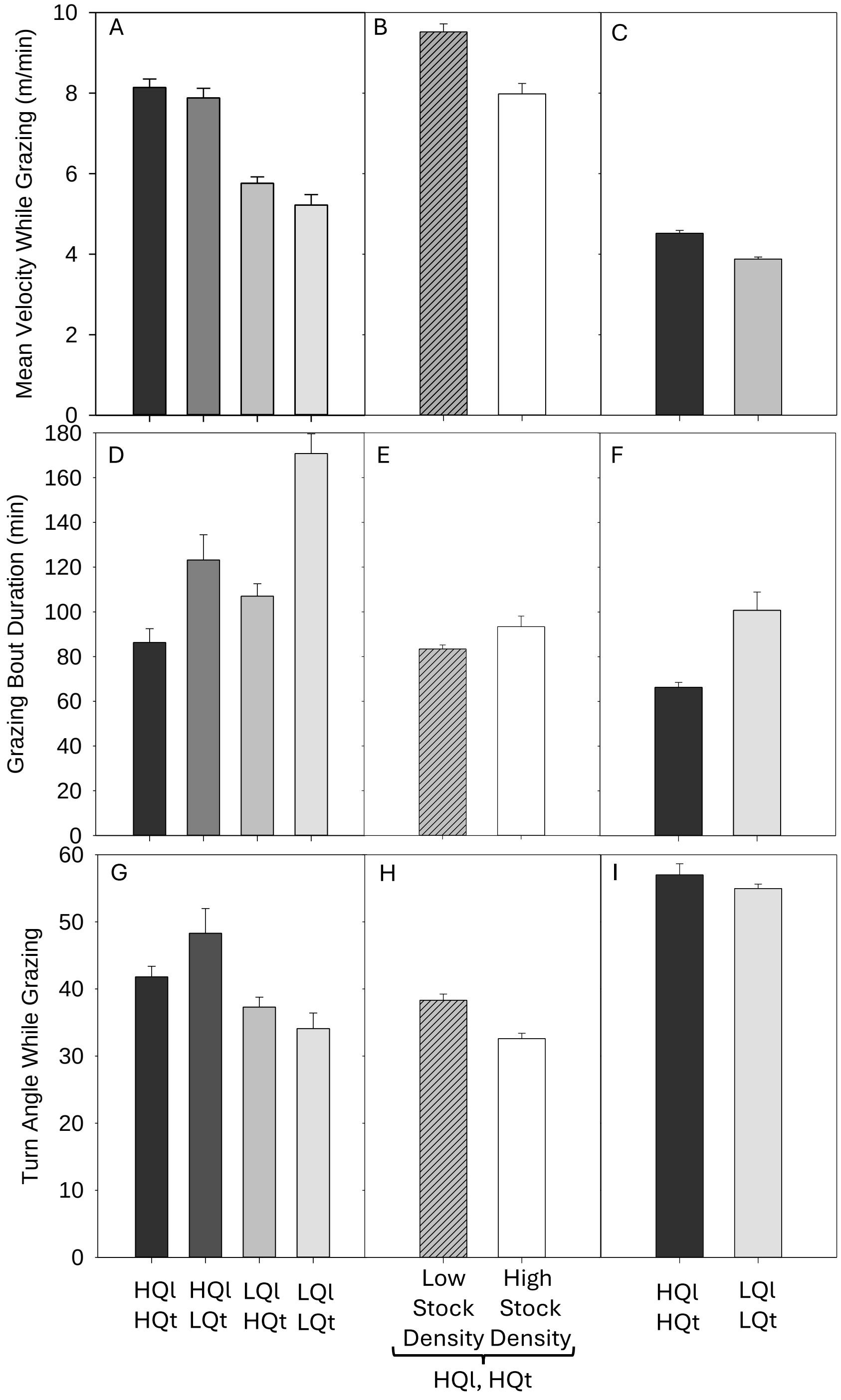

Figure 1. Comparison of three daily foraging behavior metrics quantified for free-ranging cattle in the semi-arid western Great Plains of North America using GPS collars combined with a 3-axis accelerometer. Panels A,D,G show results for yearling steers grazing shortgrass rangeland paddocks with varying forage conditions in 2020 (Augustine et al. 2022). Panels B,E,H show metrics for yearling steers grazing shortgrass rangeland with the same forage conditions early in the 2017 growing season, at high vs. low stock density (1.9 vs. 0.19 steers/ha; Augustine et al. 2023). Panels C,F,I show results for mature cows with calves grazing mixedgrass rangeland with varying forage conditions, quantified via MOOnitor

collars (GPS+3-axis accelerometer at 5-min intervals; this study). HQl = high quality forage; HQt = high quantity forage, LQl = low quality forage; LQt = low quality forage. Error bars show +1SE.

A key question is how to use these types of data to quantify foraging behaviour, and whether such behavioural metrics vary in response to foraging conditions and grazing management practices in predictable ways (Orr et al. , Carvalho et al. 2015). When we focused on 3 behavioural metrics calculated from collar data at a daily timestep (VG, GBD, and TAG), we found that VG is especially sensitive to both changes in forage conditions and management of stock density, both for yearlings and mature cows, in a way that reflects variation in cattle weight gain. Furthermore, VG was nearly equally sensitive to changes in forage conditions (both for steers and cows) as to a 10-fold increase in stock density. In contrast, TAG was more sensitive to changes in stock density, and GBD was more sensitive to changes in forage conditions. Findings also indicate that lactating cows graze at lower velocity and shorter GBD than steers for any given set of forage conditions, and cows exhibited more tortuous grazing pathways (greater TAG) compared to steers. As technologies for on-animal sensors to track foraging behaviour continue to advance and become more cost-effective, we encourage comparisons of consistent metrics such as VG, GBD, and TAG across varying rangeland conditions, animal breeds and age classes, and management regimes to develop a framework for real-time monitoring of animal condition and growth rates.

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Cattle daily movement distance & habitat selection relative to production stage, phenotype, and demographics in northern Great Plains rangelands

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Key words: cattle, phenotypic variation, movement, production stage, step-selection

Abstract
Within a group of phenotypically homogeneous cattle, there may be genotypically driven individual variation that can influence daily movement patterns of cows. This suggests that individual animal selection is a potential strategy to improve grazing distribution in complex rangelands. In North America, there have been industry trends for larger and black-hided beef cattle yet there is limited information about how sized and colour influence movement rates and habitat selection. Annual production stages may further influence cattle movement due to time-varying nutritional and physical demands on reproductive females. To better understand beef cattle movement ecology, we placed GPS collars on multiparous Angus beef cows at the Padlock Ranch in Montana and Wyoming, USA to understand how daily distance travelled and habitat selection differed among age classes, body sizes, hide colour, production stage, and temperature. Daily travel distance was shortest during the mid-gestation stage, and greatest during breeding. We found interactions between temperature and both hide colour and production stage. Red cattle moved more during colder temperatures and cows moved more during late-gestation, lactation, breeding stages as temperature increased. Larger cattle selected greater herbaceous cover and forage production in most stages and closer proximity to water during lactation. Additionally larger cattle selected steeper slopes during breeding. Younger cows selected greater heat loads during late-gestation and lesser heat loads during breeding. Older cows also selected gentler slopes during breeding and weaning. Together, our findings provide information to livestock managers regarding individual characteristics that could be advantageous to their operation and may inform adaptive grazing management practices. Black hided cattle may be better suited to northern latitudes due to higher solar radiation capture. Larger cattle consume more forage but evidence of steeper slope selection during part of the year may offer trade-offs between feeding efficiency and distribution.

Introduction

Global Position System (GPS) technology has revolutionized animal movement research with important applications for livestock research and management on extensive rangelands. Such rangelands can be characterized by topographical heterogeneity and hydrological variability and consequently may constraint livestock distribution (Holechek et al. 1989). Within a group of phenotypically homogeneous cattle, individual genotypic variation can influence daily movement patterns of cows (Bailey et al. 2004). This suggests that individual animal selection is a potential strategy to improve grazing distribution in complex rangelands.

In North America, there has been an industry trend towards larger beef cattle due to the selection for genetic growth traits (Johnson et al. 2010). Concomitantly, there has also been an increase in the proportion black-hided beef cows. Larger cattle consume more forage and hide colour can influence thermoregulation (Scasta 2021), but there is limited information about industry trends relate to interactions between the animals and their environment. Research indicates that moderately sized cows may be more efficient or profitable than larger cows (Davis et al. 1994; Scasta et al. 2015) but we lack sufficient understanding about the size influences slope use or proximity to water. Additionally, as animals deal with dramatic seasonal temperature variation and escalating extremes due to climate change, an understanding of movement ecology in the context of hide colour becomes increasingly important (Shepard and Maloney 2023).

Annual production stages, including breeding, gestation, lactation, and weaning, may further influence cattle movement. These stages correspond with different nutritional and physical demands on reproductive females (Burns et al. 2010). Importantly, late-gestation and early-lactation, sometimes referred to as the "transition" stage, have significantly higher nutritional requirements due to the rapid foetal growth followed by the demand for lactation post-parturition (Lean et al. 2014). Thus, to better understand beef cattle movement ecology, we used GPS collars data to assess how daily distance travelled and habitat selection differed among age classes, body size, hide colour, production stages and ambient temperature.

Methods

We placed 40 GPS collars (Vertex Lite-2D Iridium collars, Vectronic Aerospace; Berlin, Germany) with a 2-hr fix rate on multiparous Angus beef cows (*Bos taurus*) in late-November to early-December 2018 at the Padlock Ranch along the Wyoming-Montana border. Cattle were collared for 3 years unless individuals were selected to be removed from the herd earlier. We deployed GPS collars on cows stratified across 4 management units and selected 10 cows per unit, with 5 red and 5 black cows in each unit. We selected study individuals to obtain variation in body size (hip height) and cow age. We classified production stages as mid-gestation (6 Dec–14 Feb), late-gestation (15 Feb–15 May), lactation (15 May–19 Jul), breeding (20 Jul–30 Sep), and weaning (1 Oct–5 Dec) based on information provided by the ranch manager. We calculated daily distance travelled by calculating the distance moved between successive GPS fix and then summing the resulting distances across each day. We obtained the mean ambient temperature experienced per cow per day using the air temperature sensor readings from the GPS location fixes.

We modelled daily distances travelled with generalized linear mixed models incorporating a lognormal distribution and a log link function. In all models we included year and management unit as fixed effects and a random intercept of individual ID to account for repeated measurements. We assessed models including fixed effects of production stage, hide colour, age, and hip height, along with interactions between each pairwise combination. Additionally, we assessed models with temperature, and interactions between temperature and production stage, colour, age, and hip height.

We used an integrated step-selection analysis (iSSA) to assess cattle habitat selection as they moved across the landscape. We fit individual iSSA models (Avgar et al. 2016) to each cow by year by production stage combination. Each model included 7 environmental covariates: heat load index (HLI), slope, topographic position index (TPI), proportion of herbaceous cover, distance to water, forage production (NDVI), and forage quality (instantaneous rate of green-up [IRG]). We used inverse-variance weighted regression to summarize selection responses at the population level and to test for differences in cattle age, hide colour, and body size.

Results

Daily Distance Travelled

The mean daily distance travelled per cow was 3016.65 m (SE = 9.98). Daily distance travelled varied by production stage with the shortest average distance occurring in mid-gestation, then increasing during late-gestation and lactation, before peaking during breeding and decreasing during weaning. Post-hoc comparisons revealed significant differences between each production stage. We found no significant differences among hide colour, age, and hip height; however, we discovered interactions between production stage and both age and hip height. Distance travelled decreased with age during mid-gestation and weaning, but increased during late-gestation, lactation, and breeding seasons. Daily distance travelled decreased with greater hip height during mid-gestation, lactation, and weaning, and increased during late-gestation, but did not differ during breeding. Black cattle moved less during mid-gestation, late-gestation, and weaning. We found no significant interactions between age and colour or hip height nor colour and hip height.

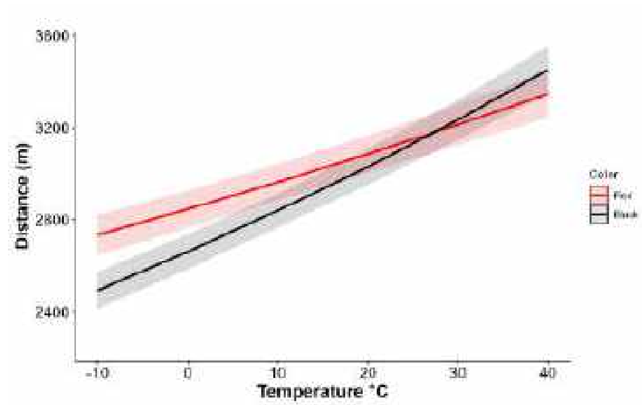

Figure 1. Average daily travel distance as a function of hide colour and ambient temperature, Padlock Ranch, Montana/Wyoming, USA, 2019–2021.

Daily distance travelled significantly increased with temperature. We found an interaction between temperature and colour with red cattle moving more during colder temperatures (Fig. 1). We also found an interaction between temperature and age with the oldest cows moving more than the youngest cows during the hottest periods. Lastly, we found an interaction between temperature and production stage with cows moving significantly more during late-gestation, lactation, breeding stages as temperature increased, but no difference during mid-gestation and weaning (Fig. 2). We found no interaction between temperature and hip height.

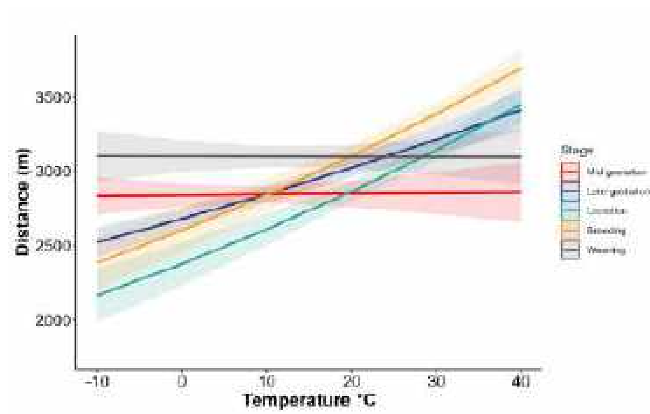

Figure 2. Average daily travel distance as a function of production stage and ambient temperature, Padlock Ranch, Montana/Wyoming, USA, 2019–2021.

Habitat Selection

Across all production stages, cattle selected greater herbaceous cover, gentler slopes, closer proximity to water, and lower topographic positions (e.g. low-lying areas). Selection for heat loads changed between the colder (mid- and late-gestation) and warmer (lactation, breeding, weaning) periods with cattle selecting greater heat loads during cold periods and lesser heat loads during warmer times. Cattle selected less vegetation production in mid-gestation and lactation but greater production during breeding. Year-round, cattle selected vegetation patches offering lower forage quality. Larger cattle selected greater herbaceous cover during mid-gestation and breeding, greater overall vegetation production during weaning, and closer proximity to water during lactation (Fig. 3). Additionally larger cattle selected steeper slopes during breeding. Younger cows selected greater heat loads during late-gestation and lesser heat loads during breeding. Older cows also selected gentler slopes during breeding and weaning (Fig. 4).

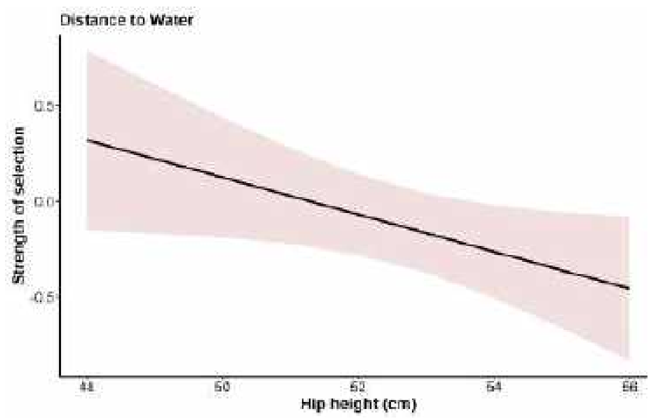

Figure 3. Strength of selection for distance to water during the lactation production stage as a function of cattle size (hip height), Padlock Ranch, Montana/Wyoming, USA 2019–2021. More negative values indicate stronger selection for closer proximity to water.

Discussion

We found that beef cow production stage, hide colour, age, and size can influence beef cattle daily travel distances or habitat selection in northern Great Plains rangelands. Production stage and temperature had the largest influences on daily distances travelled. Beef cattle managers should anticipate greater daily movements during breeding and weaning compared to mid- and late-gestational periods. Cows moved more per day with increasing temperatures during the warmest periods (late-gestation, lactation, and breeding). Longer travel distances during hot periods may be necessary to balance foraging arenas, shade, and water which can be disparately located across the landscape. Red-hided cows moved more than black cows during the coldest periods, perhaps to help with thermoregulation. We did not have data to equate

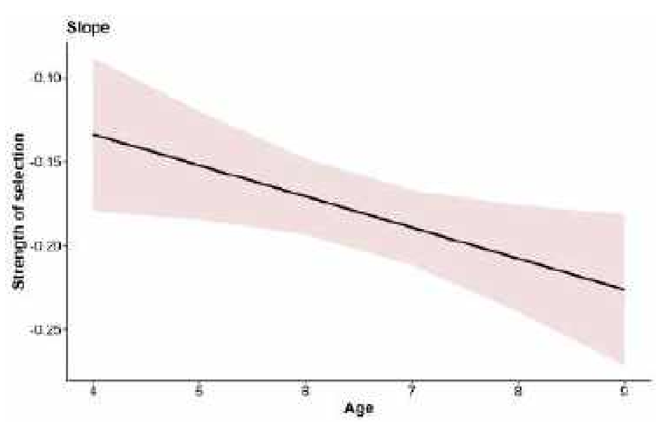

Figure 4. Strength of selection for slopes during the weaning production stage as a function of cattle age, Padlock Ranch, Montana/Wyoming, USA 2019–2021. More negative values indicate gentler slopes.

daily movement distances with energy expenditure or daily weight gains, but black cattle may be better suited to this region due to higher solar radiation capture (Scasta 2021).

We found seasonal differences in habitat selection based on cow age and body size. Younger cows selected cooler areas during the hottest time of the year (breeding) and warmer areas during the coldest period (mid-gestation), thus they may not yet be fully accustomed to this environment. Older cows more strongly avoided steeper slopes during breeding and weaning, which may be attributed to less vigour than younger animals at the end of the annual cycle. Outside of the most energetically demanding periods stages (late-gestation and lactation), larger cows likely consumed more forage evidenced by greater selection of herbaceous cover and vegetation production. Moreover, larger cattle used areas closer to water during the lactation period, perhaps to compensate for increased lactation demand relative to smaller individuals (Prichard and Marshall 1993). Together, our findings provide information to livestock managers regarding individual characteristics that could be advantageous to their operation and may inform adaptive grazing management practices. Regarding industry trends, black hided cattle may be better suited to northern latitudes with long and cold winters where heat transfer between an organism and its environment can be influenced by the difference between the surface temperature of an organism and the temperature of the surrounding environment (Scasta 2021). Conversely, lighter coloured individuals may be better situated to deal with extreme heat in more southern locales, although this has yet to be tested. Larger cattle ostensibly eat more but we also found evidence that they select steeper slopes during part of the year, thus there may be trade-offs between feeding efficiency and distribution. Lastly, younger cattle appeared to be less habituated to the thermal extremes of the environment but were more willing to use steeper slopes, again offering a trade-off for managers.

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Scaling rangeland restoration in East Africa through synergies in the biodiversity-water-climate nexus

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Key words: Restoration; soil and land health assessments; soil-plant-water nexus; knowledge exchange and co-learning; monitoring.

Abstract

Healthy land is a prerequisite for sustainable development and human well-being. With high levels of biodiversity and provision of critical ecosystem services, rangelands support 50% of the world's livestock and over 2 billion people. Rangeland degradation thus represents a major global challenge with severe negative impacts on biodiversity, climate change, and water and food security, affecting the livelihoods of millions of people. In the drylands of East Africa, these challenges are particularly acute. Halting rangeland degradation and restoring degraded land is thus essential in safeguarding ecosystem services and ensuring human well-being. Understanding the dynamics and patterns of rangeland degradation is critical for guiding restoration efforts to achieve positive and sustainable outcomes.

Here, we present results from systematic assessments of soil and land health conducted across contrasting rangeland landscapes in East Africa using the Land Degradation Surveillance Framework (LDSF). We conducted assessments of vegetation diversity, with an average of 15 perennial grass species per 100 km^2 LDSF site. The results indicate contrasting land degradation dynamics among and within the different sites. We applied Earth Observation in combination with field and lab data collected using the LDSF to produce high-accuracy predictive maps of different biophysical indicators, including soil organic carbon and soil erosion. The maps of soil and land health indicators showed clear spatial patterns across the landscapes. These results demonstrate the importance of simultaneously assessing multiple indicators of soil and land health and their interactions. We also present results from our work in four 'Livestock Cafés' in the cross-

border area between northern Kenya and Uganda. Livestock Cafés are experimental sites and knowledge-sharing hubs where we are engaging with local stakeholders to test and demonstrate innovative land restoration options for enhanced fodder production and regenerative kitchen garden development for improved food and nutrition.

Introduction

Rangelands cover an estimated 50% of the world's land area and provide a wide range of ecosystem services, including habitat provisioning, carbon sequestration, and food and water supply (Briske, 2017; UNCCD, 2024). However, interlinked land degradation, climate change, and biodiversity loss crises threaten rangeland ecosystems, jeopardizing the provision of these vital ecosystem services and the livelihoods and well-being of the people they support (IPBES, 2018; IPCC, 2019; UNCCD, 2024). In East Africa, rangelands constitute the dominant land use system, covering vast areas of land and supporting the livelihoods of millions of pastoralists (ILRI, 2021). Here, widespread rangeland degradation, climate change, and biodiversity loss constitute significant social-ecological challenges. These crises are mutually reinforcing; climate change is a principal driver of land degradation and biodiversity loss, while land degradation and biodiversity loss further accelerate climate change (IPBES, 2018; IPCC, 2019). Halting land degradation and restoring degraded rangelands is critical to reverse these negative trends (IPBES, 2018). Kenya, Uganda, and Tanzania have pledged to restore millions of hectares of degraded lands in the coming years, and many of these commitments specifically target rangelands. Understanding the dynamics and patterns of rangeland degradation and tracking the impact of restoration interventions is crucial for guiding such restoration efforts to achieve more positive and sustainable outcomes.

Here, we present some preliminary results and experiences from the research project Restore4More (2024-2027). The entry point of Restore4More is to identify the synergies in the biodiversity-water-climate nexus to accelerate the restoration of degraded rangelands for enhanced climate change adaptation and mitigation, biodiversity, and water and food security in the drylands of East Africa. We conducted systematic assessments of soil and land health across five rangeland-dominated landscapes in northern Kenya and Uganda with the aim of understanding the dynamics and patterns of land degradation across these sites to guide the planning and implementation of restoration interventions. We show key findings from these assessments, some examples of rangeland restoration interventions co-designed and implemented with local communities in knowledge-sharing hubs, and how we monitor restoration activities through an innovative approach combining field and lab data, Earth Observation and assisted citizen data collection.

Systematic assessments of land and soil health

We systematically collected data on soil and land health indicators across five rangeland-dominated sites in the cross-border area between northern Kenya and Uganda using the Land Degradation Surveillance Framework (LDSF) (Vågen & Winowiecki, 2023). *Chepareria, Lokiriama,* and *Kalama* sites were located in West Pokot, Turkana, and Samburu counties (Kenya), respectively, while *Matany* and *Rupa* sites were located in Napak and Moroto districts (Uganda).

Indicators measured included soil organic carbon (SOC), soil infiltration capacity, erosion prevalence, vegetation structure, tree density and species diversity, herbaceous cover and species diversity, soil texture, and pH. A total of 778 plots were sampled across the five LDSF sites. Plots (1000 m^2) were nested within clusters (1 km^2) and clusters within sites (100 km^2), following a hierarchical sampling design. Further details on the LDSF methodology, including the field sampling protocols and analysis of soil samples, can be found in Vågen and Winowiecki (2023).

Lokiriama and *Kalama* had the highest woody cover, with an average density of woody plants (trees and shrubs) of 275 and 243 individuals ha^{-1}, respectively, whereas in *Matany*, the average density was only 18 individuals ha^{-1}. Species richness was highest in *Chepareria* (50) and lowest in *Matany* (10). In *Lokiriama* and *Rupa*, nearly 50% of the sampled trees belonged to a single species - *Acacia reficiens* and *Acacia mellifera*, respectively. Tree species diversity was also low in *Matany*, whereas *Chepareria* had the highest diversity of trees, including several species that are important sources of fodder, food, and fuelwood. *Chepareria* was also the site with the highest richness of perennial grass species (37), whereas *Lokiriama* was the lowest (16).

Soil erosion is a major problem in the Kenyan sites (*Lokiriama, Kalama,* and *Chepareria*), where severe erosion was detected in 50-100% of the plots per cluster. In contrast, only a few plots presented severe erosion in *Matany* and *Rupa* (Uganda). Median topsoil organic carbon (SOC) content was lowest in the *Kalama* and *Lokiriama* sites (3.6 and 4.6 g kg^{-1}), whereas in *Matany* and *Rupa*, it was nearly threefold. The differences in SOC among sites were partly explained by differences in soil texture, with more fine-textured soils with higher clay content in *Rupa* and *Matany* sites compared to the rest. Saturated topsoil hydraulic conductivity, which controls the soil infiltration capacity, was relatively low in all five sites, with median values ranging between 10 mm h^{-1} in *Chepareria* and 60 mm h^{-1}in *Matany.* There was a clear negative relationship between erosion prevalence and soil infiltration capacity, especially for soils with higher clay content. This hints at a critical self-reinforcing feedback loop that amplifies land degradation: soil degradation and reduced infiltration capacity lead to more surface runoff and erosion, which in turn lead to further land and soil degradation and reduced infiltration.

Results from this assessment indicate contrasting land degradation dynamics among and within the different sites. For example, In *Lokiriama*, the encroachment of the invasive *Acacia reficiens* is a major problem and soil erosion was widespread. In contrast, Chepareria had severe erosion despite no signs of woody encroachment and higher diversity of both trees and grass species. In *Matany* nearly no signs of erosion were observed in the surveyed plots, but the diversity of perennial grasses and tree species was low compared to the other sites.

Using machine learning models trained on field and lab data collected using the LDSF and Earth Observation data (Vågen & Winowiecki, 2019; Vågen et al., 2016), we produced high-accuracy predictive maps of different biophysical indicators, including SOC and soil erosion. The maps of soil and land health indicators showed clear spatial patterns across the five rangeland landscapes.

These results demonstrate that rangeland health is multidimensional and highlight the importance of simultaneously assessing multiple indicators of soil and land health and their interactions across the plant-soil-water nexus.

Rangeland restoration in knowledge-sharing hubs

In 2021, we established four knowledge-sharing hubs, known as 'Livestock Cafés', in *Chepareria*, *Lokiriama, Matany*, and Rupa sites. Here, we engage with local communities, extension workers, NGO practitioners, and authorities to co-develop, test, and demonstrate innovative rangeland restoration and management options. We draw from the baseline assessments of soil and land health and local needs and priorities to guide and tailor restoration. Restoration interventions span a combination of agronomic, vegetative, structural, and management measures – including half-moons, retention ditches, contour bounds, manure addition, reduction of grazing intensity and 'cut-and-carry' of fodder, reseeding of indigenous rangeland grasses and forage legumes, and planting of fodder trees and shrubs. By managing the plant-soil-water-nexus, such restoration interventions contribute to halting land degradation and accelerating the recovery of degraded rangelands. Within the 'Livestock Cafés,' we have also established regenerative kitchen gardens together with local women's groups with the aim of enhancing food security and dietary diversity throughout the year and providing opportunities for income.

From the 'Livestock Cafés', the knowledge is disseminated further through a network of Community Facilitators and Lead Farmers & Pastoralists. Rangeland restoration activities across the four sites will be monitored using the newly launched Rangeland Module in The Regreening App (CIFOR-ICRAF, 2022) – a free mobile-based application for assisted citizen science data collection of restoration activities – combined with Earth Observation. These data will allow assessing the effectiveness of different restoration interventions and will provide much needed evidence regarding rangeland restoration efforts in the region. The app also provides a unique opportunity to promote wider public engagement and co-learning in rangeland restoration.

Conclusions

Restore4More will contribute to developing the capacity of restoration actors at multiple levels through context-specific co-learning and knowledge exchange. The project will provide restoration practitioners and other actors, including policymakers, local authorities, NGO's, farmers, and livestock keepers, with robust science-based evidence and tools to support and guide rangeland restoration efforts in the drylands of East Africa, improving their capacity to plan, implement, monitor, and assess restoration activities and practice adaptive management.

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Assessing drought vulnerability and water resource management in the Great Artesian Basin: insights from GRACE data and climate projections under varying emission scenarios

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Key words: Great Artesian Basin (GAB); Climate Change Projections; Total Water Storage-Drought Severity Index (TWS-DSI); Climate Scenarios; Remote Sensing.

Abstract:
This study examines the projected impacts of climate change on drought in the Great Artesian Basin (GAB), Australia, a vital groundwater resource for agriculture, industry, and ecosystems, which is increasingly vulnerable to prolonged droughts and climate variability. Using the Gravity Recovery and Climate Experiment (GRACE) satellite data and CMIP5/CMIP6 climate model simulations, the analysis, based on scenarios RCP2.6, RCP6.0, SSP126, and SSP370, reveals increasing drought severity, particularly under high-emission scenarios. The integration of GRACE-derived Total Water Storage (TWS) anomalies with climate projections enhances drought forecasting, highlighting critical drought hotspots in southern and central GAB regions. These findings underscore the importance of adaptive water management strategies, such as managed aquifer recharge, and the role of satellite-based observations in improving water resource sustainability in the face of climate change.

Introduction
Droughts are major natural hazards, especially in semi-arid and arid regions where they severely impact water resources, agriculture, and ecosystems. Understanding drought dynamics is crucial for managing groundwater systems, such as the Great Artesian Basin (GAB) in Australia, which is vulnerable to climate change and prolonged droughts (Rohde et al., 2017; Zhao et al., 2020). Effective water resource management relies on accurate drought forecasting, which is essential for addressing long-term drought risks. Recent advancements in remote sensing, notably through the Gravity Recovery and Climate Experiment (GRACE) satellite, have greatly improved monitoring of drought conditions. GRACE's ability to observe variations in Total Water Storage (TWS) is due to its high sensitivity to changes in the Earth's gravity field, which is directly influenced by changes in water mass. This enables GRACE to detect variations in water storage across both surface and groundwater reservoirs, offering unique insights into the spatial and temporal distribution of water resources during droughts, which cannot be captured through

traditional ground-based methods such as streamflow measurements or groundwater monitoring alone (Tapley et al., 2004; Scanlon et al., 2012). GRACE data, with its global coverage and high sensitivity to changes in water storage, provides a comprehensive view of drought dynamics, particularly in regions with limited ground-based observation networks. Complementing this, climate models such as CMIP5 and CMIP6 project future temperature and precipitation patterns, offering insights into drought evolution under different scenarios (IPCC, 2014; O'Neill et al., 2016). This study leverages GRACE data to calibrate TWS estimates from CMIP5 and CMIP6 models, improving drought severity projections for the GAB across mid- and late-century periods. The integration of observational data with model projections enhances drought assessments, underscoring the importance of combining satellite data and climate models for effective water resource management in climate-sensitive regions (Scanlon et al., 2012; Zhao et al., 2020).

Case Study: The Great Artesian Basin (GAB)

The Great Artesian Basin (GAB) is one of the largest underground water reserves in the world, covering much of northeastern and central Australia. It provides vital water resources for agriculture, industry, and domestic use. The basin is crucial for Australia's water system, supporting local ecosystems and communities (Geoscience Australia, 2011). Figure 1(a) shows the GAB's geographic extent, covering Queensland, New South Wales, South Australia, and the Northern Territory, and highlighting key areas like Longreach, Broken Hill, and Birdsville. Understanding water storage dynamics in the GAB is critical, especially in the face of climate change and its impact on groundwater. Climate variability, including irregular rainfall patterns and extended dry spells, combined with rising temperatures, reduces the recharge of groundwater aquifers and increases evaporation, leading to more severe water scarcity and threatening the long-term sustainability of the GAB's water resources (Zhao et al., 2020). Satellite observations like GRACE play a key role in monitoring TWS changes in the GAB (Rodell et al., 2004). By integrating GRACE data with climate model projections from CMIP5 and CMIP6, we gain valuable insights into the basin's future water availability and drought risks under various climate scenarios (Collins et al., 2013; IPCC, 2014).

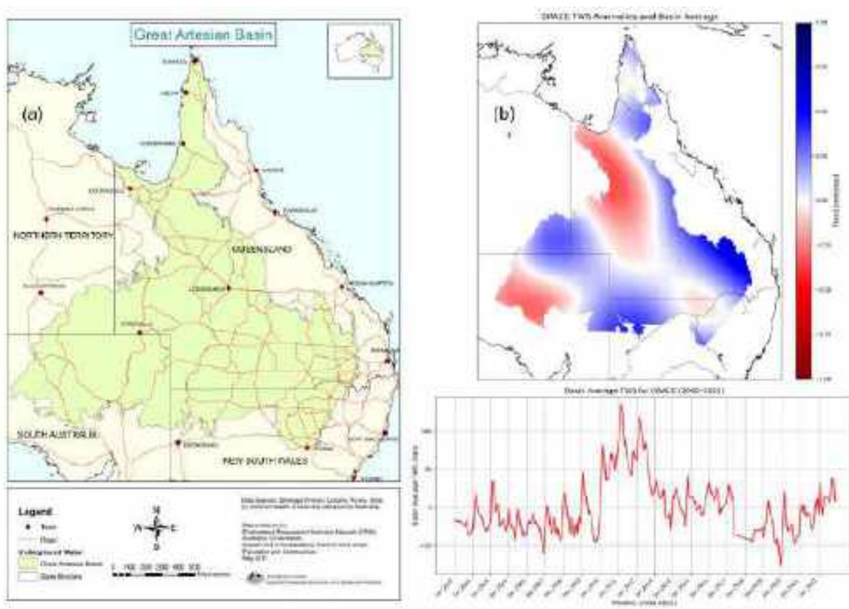

Figure 1.(a) Great Artesian Basin map, (b) Total water storage changes over GAB estimated by GRACE.

Data and Methodology

This study utilizes the Gravity Recovery and Climate Experiment (GRACE) satellite data (2002-2022) to analyse TWS anomalies in the GAB, Australia. The spatial resolution of GRACE data is approximately 250 km, providing global coverage with a focus on regional variations in water storage (Rodell et al., 2004; Tapley et al., 2004). GRACE measures changes in Earth's gravity field, providing critical insights into water storage variations over time (Rodell et al., 2004; Tapley et al., 2004). TWS anomalies are calculated by subtracting the climatological mean (2002-2022) from observed values, highlighting deviations from normal water storage conditions, which improves clarity and reduces repetition. The GRACE dataset, obtained from NASA's GRACE Data Portal, is widely used in hydrological and drought-related research. For future climate projections, we use data from CMIP5 and CMIP6 models, focusing on mid-century (2030-2059), and late-century projections (2070-2099). These models provide climate variables (e.g., precipitation and temperature) under emission scenarios: RCP2.6, RCP6.0 (CMIP5), and SSP126, SSP370 (CMIP6) (Collins et al., 2013; O'Neill et al., 2016). These scenarios were chosen because they represent a range of potential future climate outcomes, from low-emission pathways (RCP2.6, SSP126) to high-emission pathways (RCP6.0, SSP370), making them suitable for assessing the impact of various climate change scenarios on water resources and drought severity. TWS anomalies are calculated by subtracting the mean of monthly TWS values (2002-2022) from the observed values. To refine model projections, GRACE data were used to calibrate TWS seasonal cycles from CMIP5 and CMIP6 models. The calibration process involved adjusting the model outputs to better match the observed TWS anomalies from GRACE using statistical methods, such as the Root Mean Square Error (RMSE), which quantifies the difference between the model and observed values. Models with better alignment to GRACE data were weighted more heavily, based on their RMSE and structural diversity (Sanderson et al., 2017; Eyring et al., 2019). Drought severity is quantified using the Terrestrial Water Storage Drought Severity Index (TWS-DSI), which normalizes TWS anomalies by the standard deviation of monthly anomalies. The TWS-DSI indicates drought conditions based on a scale ranging from exceptionally wet to extremely dry. This method follows the World Meteorological Organization's classification guidelines, ensuring a globally consistent approach (WMO, 2012).

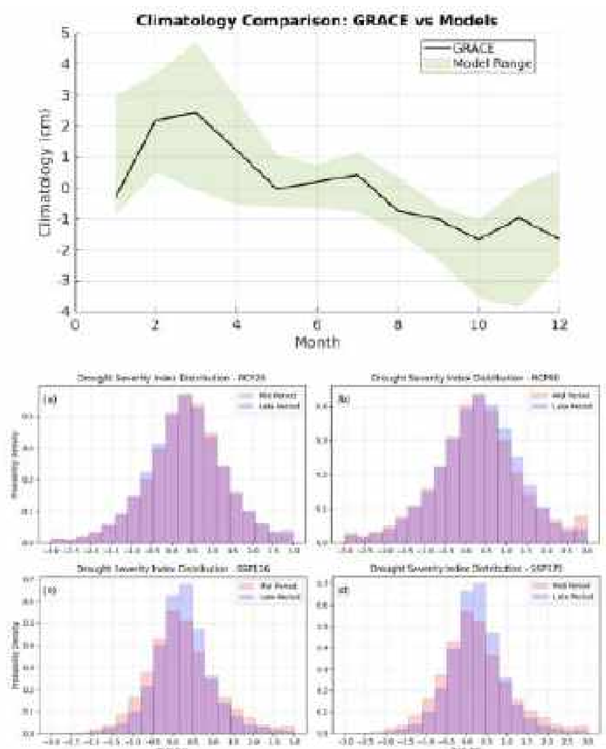

Figure 2. Top: climatology comparison between models and GRACE. Bottom: estimated drought index for mid and late century under different scenarios.

Results

GRACE TWS anomalies and basin average for the GAB (2002–2022): Figure 1(b) (top panel) shows TWS anomalies across the GAB from 2002 to 2022. Positive anomalies are observed in the northern regions, such as Weipa, while negative anomalies dominate southern areas like Coober Pedy, indicating varied water storage patterns across the basin. The lower panel of Figure 1(b) displays the basin-wide average TWS. Fluctuations include a significant positive anomaly during the La Niña event in 2010–2011 (Bureau of Meteorology, 2011), followed by a sharp decline of approximately 150% in mid-2019–2020, reflecting severe drought conditions (NSW Government Water, 2020).

Climatology comparison; GRACE vs models: The top panel of Figure 2 presents a climatological comparison between GRACE-derived TWS data and model outputs. GRACE data shows a clear seasonal cycle with higher water storage during the wet season (December to March) and lower values during the dry season (April to October). The models capture this general seasonal pattern but show discrepancies, particularly during the wet season, where some models overestimate TWS by up to 100%, likely due to overestimations in precipitation. These discrepancies highlight the need for model calibration using GRACE data to improve the accuracy of future projections.

Drought Severity Index (TWS-DSI) analysis for the GAB: The bottom panel of Figure 2 displays the probability density function (PDF) of the Drought Severity Index (TWS-DSI) for the GAB under different emission scenarios (RCP26, RCP60, SSP126, and SSP370) for both mid- and late-century periods. The PDF was derived by calculating the frequency distribution of TWS anomalies over the 2002–2022 period,

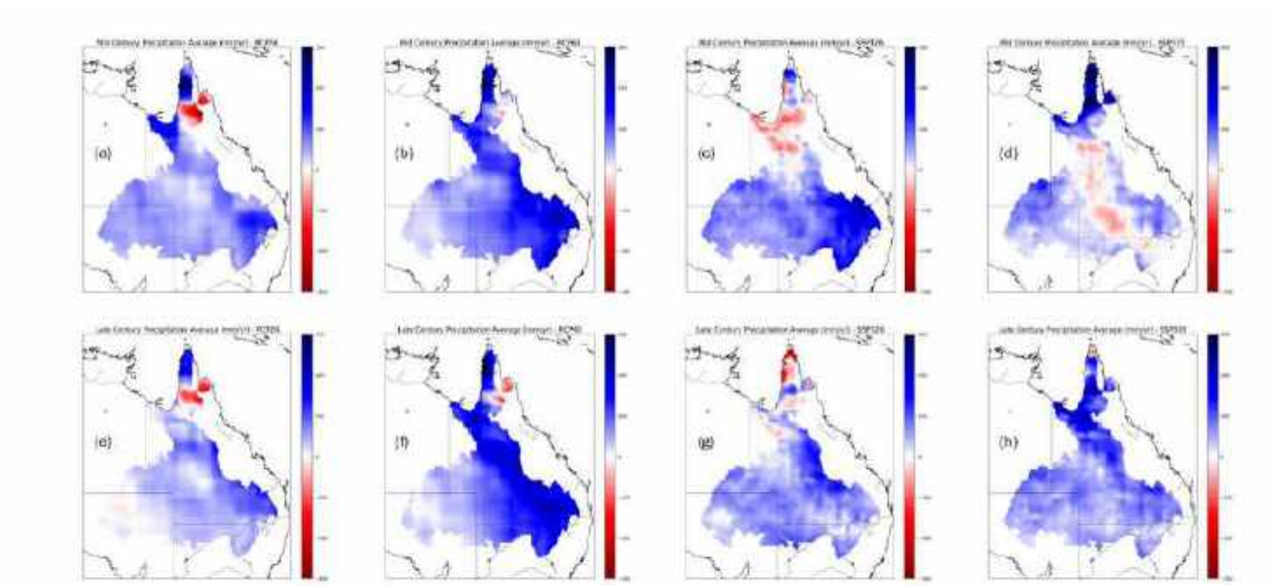

Figure 3. Precipitation projection for mid and late century under different scenarios.

categorizing the anomalies into drought severity levels ranging from -2 (extremely dry) to +2 (exceptionally wet). The histograms illustrate the distribution of drought severity under each emission scenario, with a shift toward more negative values indicating an increase in drought severity under higher emission pathways. For RCP2.6, the distribution remains relatively balanced, indicating near-normal drought conditions. However, under higher emissions scenarios like RCP6.0 and SSP370, the distribution shifts towards more negative values, signalling an increase in drought severity in the late-century period.

Climate variables and drought index correlation: Figures 3 and 4 display mid- and late-century projections of precipitation and temperature changes across the GAB, with a historical baseline (1975–2005) removed for clearer quantification of changes. Figure 3 shows a general decrease in precipitation, particularly in South Australia and Broken Hill under high-emission scenarios (SSP370), with a 20-30% reduction in some regions. These trends align with more negative DSI values observed in Figure 2. Figure 4 shows a significant temperature increase, especially in southern regions, with areas like Birdsville expected to warm by up to 4°C under SSP370, which corresponds to a 15-20% increase in temperature. This temperature increase exacerbates evapotranspiration, while precipitation deficits in southern areas further intensify drought conditions. These trends align with IPCC (2021) projections and studies by van Dijk et al. (2013) and Crosbie et al. (2010), highlighting the increased vulnerability of groundwater and ecosystems in the GAB due to climate change. The results emphasize increasing drought severity under higher emission scenarios and more moderate impacts under lower emission pathways.

Discussion and Conclusion

This study examines the projected impacts of climate change on drought conditions in the Great Artesian Basin (GAB) using GRACE satellite data and CMIP climate model simulations. The findings reveal increased drought severity across all scenarios, with the highest risks under high-emission pathways like RCP6.0 and SSP370, especially in regions like South Australia. Even low-emission scenarios (RCP2.6, SSP126) show a gradual increase in drought intensity, particularly in areas such as Broken Hill and Weipa. Temperature increases of up to 4°C, especially in southern regions like Birdsville, correspond to an approximate 15-20% increase in temperature, exacerbating evapotranspiration, which could increase by 10-15%. Precipitation deficits in southern areas, with reductions of 20-30%, further intensify drought conditions. The results emphasize that higher emission scenarios lead to more frequent and severe droughts, while lower emission pathways, such as RCP2.6 and SSP126, help mitigate extreme drought conditions. These findings are consistent with studies by Thomas et al. (2014), which suggest that higher emission scenarios are likely to result in more severe and frequent drought events. The GAB's groundwater and

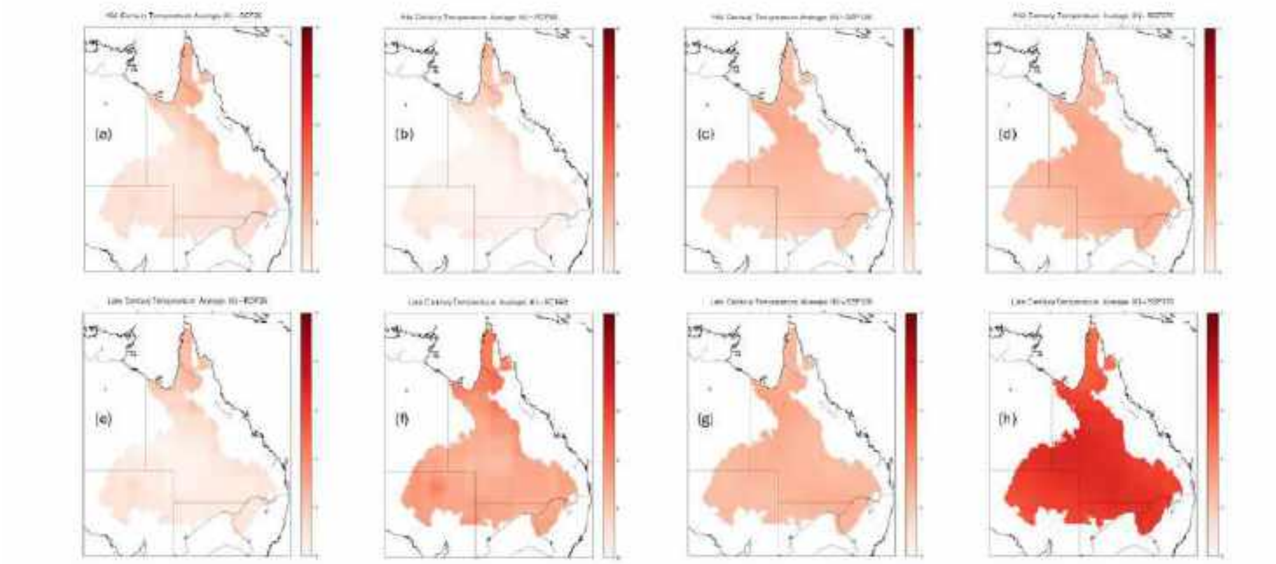

Figure 4. Temperature projection for mid and late century under different scenarios.

ecosystems are increasingly vulnerable under high-emission pathways, as confirmed by earlier studies (van Dijk et al., 2013; Crosbie et al., 2010). GRACE data has been essential for validating model projections and refining drought indices. The discrepancies between GRACE data and model outputs, such as 100% overestimation of TWS during the wet season, highlight the need for model calibration to improve accuracy in future projections. To mitigate the projected impacts, adaptive water management strategies, such as managed aquifer recharge (MAR) and improved irrigation, are crucial. Scaling up MAR in the GAB will require investments in infrastructure, alongside better real-time monitoring of groundwater levels. Transitioning to low-emission pathways (RCP2.6, SSP126) can reduce the risks of extreme droughts by approximately 10-20% and support long-term resilience in the GAB. Integrating satellite-based monitoring into decision-making will enhance drought mitigation and water resource management, ensuring sustainable water use in the region under future climate change scenarios.

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Navigating technology adoption: mapping beef producers' decision journeys

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Key words: decision-making; customer journey map; AgTech; innovation diffusion; adoption pathways

Abstract

The adoption of agricultural technology (AgTech) and innovations by graziers is crucial for enhancing productivity and sustainability in the rangelands. However, the decision-making process is often complex and fraught with risk and uncertainty. This PhD project aims to support informed adoption decisions among beef producers in Queensland, Australia.

Participatory research interviews were conducted with a diverse range of industry stakeholders. Insights from these interviews were synthesized into a co-designed Customer Journey Map (CJM), which visually maps key decision points against the Diffusion of Innovations (DOI) stages—Knowledge, Persuasion, Decision, Implementation, and Confirmation. The CJM framework effectively guided the co-design process, enabling participants to contribute their unique perspectives.

The completed CJM provides a structured visual representation of the adoption process. It served as a pivotal tool in facilitating discussions during subsequent semi-structured interviews with beef producers and AgTech companies. By framing these interviews around the dynamic adoption process, the CJM aided in recalling crucial decision points and eliciting detailed insights into decision-making processes.

Beyond this project, the CJM serves as a versatile tool applicable to research focused on adoption decisions. Future phases will explore mapped decision points, focusing on identifying heuristics and biases that influence AgTech adoption. These insights will benefit stakeholders aiming to enhance extension and adoption programs. Additionally, findings from this study are positioned to align with current trends in artificial intelligence (AI). There is potential for personalized decision support tools to leverage this knowledge to offer tailored advice, supporting adoption and reducing decision fatigue.

Introduction

AgTech adoption is inherently complex, involving multiple stages and touchpoints, as conceptualised in Rogers' Diffusion of Innovations (DOI) (Rogers 1962). Adoption decisions are shaped by various personal, social, cultural, and economic factors, along with the specific attributes of the innovation itself (Pannell et al. 2006). Producers must weigh costs and benefits while navigating practical concerns such as compatibility with existing systems and limited technical support (Kuehne et al. 2017; Montes de Oca

Munguia et al. 2021). Additionally, the overwhelming array of available technologies contributes to choice overload, creating decision fatigue and uncertainty (Iyengar and Lepper 2000). These barriers are compounded by constrained time and expertise, which restrict producers' capacity to engage with complex technologies (Reichardt et al. 2009). Such challenges can prevent producers from effectively assessing whether a new technology offers a substantial 'relative advantage'—a key determinant of adoption, defined as a perceived improvement over current practice (Pannell et al. 2006).

Understanding decision-making within adoption pathways requires a dynamic approach that accounts for systemic and individual factors. While broader systemic barriers influence outcomes, the decision to adopt ultimately rests with producers, whose motivations and attitudes are shaped by their specific contexts (Nettle et al. 2022). Decision-making is iterative, with producers often reassessing their considerations as circumstances change and new information arises (Rogers 1962; Montes de Oca Munguia et al. 2021). Capturing these dynamics can be challenging, as participants may struggle to recall or articulate past decisions, potentially limiting insights into the complexities of the adoption process (Tversky and Kahneman 1974; Nisbett et al. 1977; Reisch and Zhao 2017; Streletskaya et al. 2020).

The 'probes approach' (Gaver et al. 1999) employs design-oriented tools for gathering data and co-exploring topics. Probes are designed to encourage participants to reflect on and share their experiences, enhance dialogue between researchers and participants, and stimulate meaningful discussion and reflection (Mattelmaki 2008). This study aims to investigate the utility of a co-designed Customer Journey Map (CJM), based on the DOI model (Rogers 1962), for exploring nuanced AgTech adoption experiences. By mapping the adoption process, the study seeks to explore how such tools might enhance our understanding of critical decision points, barriers and motivations in AgTech adoption.

Methods

This study employed qualitative methods, grounded in participatory action research principles, to explore the decision-making processes of AgTech adoption among beef producers in Queensland, Australia. The study adopted a co-design approach to ensure that outcomes were directly relevant and beneficial to the target community (Trischler et al. 2019; Rundle-Thiele et al. 2021; Moretti et al. 2022). The Customer Journey Map (CJM) framework was structured with the horizontal axis representing the stages of the DOI model (Knowledge, Persuasion, Decision, Implementation, and Confirmation) (Rogers 1962), as proposed by Ong et al. (2022). The vertical axis consists of three overarching themes (Activities, Motivations, and Barriers) to provide a comprehensive lens to capture the dynamics of the adoption journey, in a similar approach to Moretti et al. (2022). Six participants, comprising a producer, consultant, economist, station manager, social scientist, and extension officer, were purposefully selected for their extensive experience with AgTech adoption decisions, to capture a broad spectrum of perspectives and enable a deeper understanding of the adoption process and its contextual factors.

Data was collected through semi-structured interviews conducted online via Microsoft Teams. Each interview lasted approximately 60 minutes and included an introduction to the study followed by an adoption journey mapping activity. A blank CJM framework was shared on-screen, and participants' insights were recorded in real time as the interviewer guided them through each segment. Opportunities were offered for refinement. The analysis synthesized interview insights into a single map. Initially compiled as a comprehensive document, themes and connections were distilled through an iterative process. The final map was refined into a concise, single-page format designed for clarity and practicality, ensuring its effectiveness as a probe for engaging beef producers in interviews. Reflexivity was incorporated to evaluate the utility of the CJM as a facilitation tool for eliciting nuanced responses, while acknowledging the researcher's influence on the process (Finlay 2002).

Results

The co-design process proved to be a highly effective approach for developing the CJM. Conducting individual online interviews facilitated a deep and nuanced exploration of the adoption process from various stakeholder perspectives, while overcoming logistical challenges posed by a workshop format such as scheduling conflicts and geographic dispersion. This approach ensured that each participant could dedicate focused time to the mapping activity, yielding rich and varied insights critical for capturing the complexities of AgTech adoption. This co-design approach laid the foundation for a robust and adaptable CJM (Fig. 1), designed as a probe for exploring the AgTech adoption process. The CJM was piloted in a follow-up study to assess its practical application and effectiveness. Semi-structured interviews were conducted with 22 producers and AgTech stakeholders in-person, during which both participants and the researcher used the printed CJM to guide discussion.

Participants actively engaged with the CJM, which facilitated rich conversations and uncovered nuanced insights into the decision-making process that might otherwise have been overlooked. Producers frequently used the map to articulate their decision pathways and reflect on their experiences. The CJM proved effective in keeping discussions focused and re-engaging participants when thought processes stalled, ensuring interviews made the best use of limited time. In the pilot interviews, AgTech providers highlighted the CJM's value in capturing the dynamic nature of adoption, reflecting their observations of how customers often move between stages and how motivations and barriers shift in response to changing circumstances and priorities. One provider noted its utility in making the adoption process more tangible, stating, "I would like a copy of this … it would help explain things to people [in the AgTech industry] so quickly and easily.

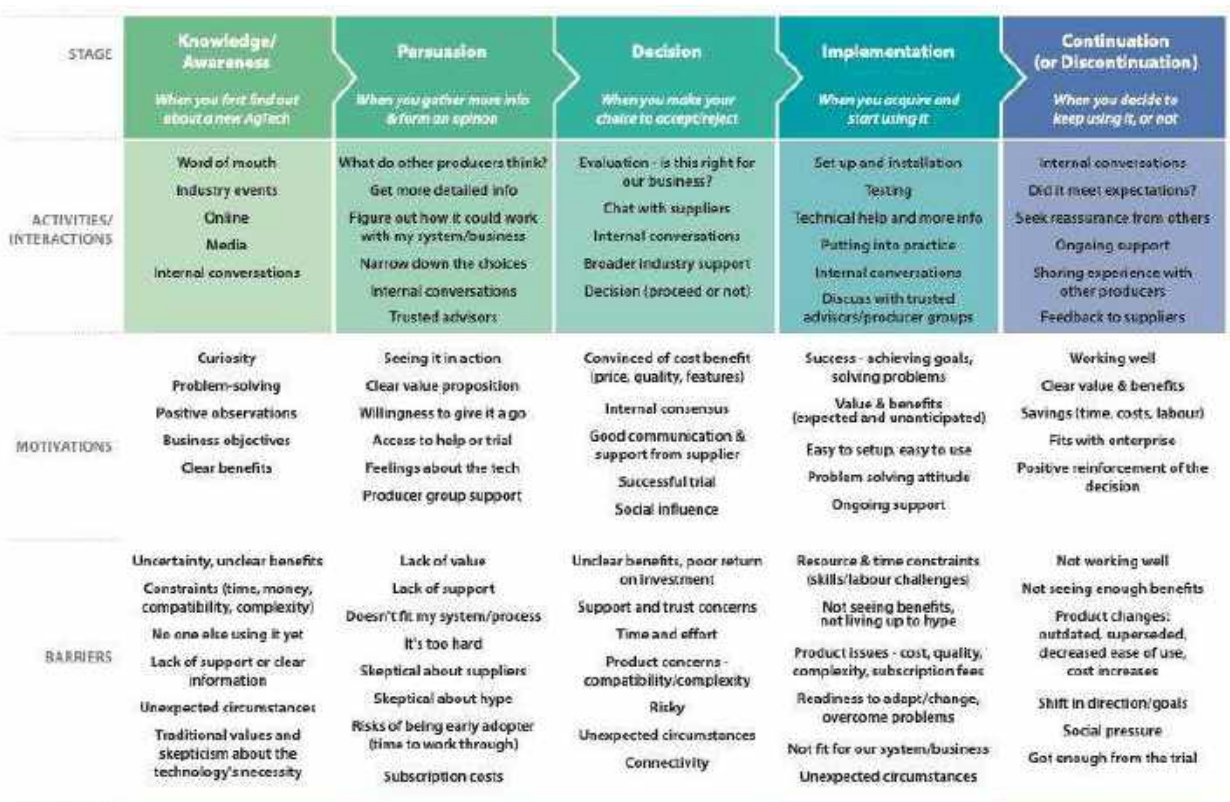

Fig. 1: Customer Journey Map (CJM) for AgTech Adoption by Beef Producers.

Discussion

Findings demonstrate the CJM as an effective probe for exploring AgTech adoption decision-making. Like other design-oriented tools described by Gaver et al. (1999) and Mattelmaki (2008), the CJM fostered participant reflection, facilitated meaningful discussions, and encouraged engagement by making abstract adoption concepts more tangible. By structuring insights across the DOI stages (Rogers 1962) and categorizing them into Activities, Motivations, and Barriers, the map aids in the examination of adoption dynamics, making it a practical tool for understanding the multifaceted challenges of adoption. Its visual and accessible format fosters participant engagement and reflection, aligning with Santos and Gonçalves (2021), who emphasize journey mapping as a method for simplifying complex processes.

Notably, the CJM serves as a valuable tool for enhancing qualitative research by structuring discussions and uncovering nuanced experiences which can be used to identify strategic leverage points for intervention. Exploring adoption pathways using the CJM aids in revealing the cascading effects of early-stage challenges. For instance, an unclear understanding of benefits during early stages often translated into a perceived lack of value and return on investment (ROI) in later stages, ultimately diminishing the perceived relative advantage.

Its adaptable design positions the CJM as a potential tool for studies across agricultural sectors and innovations (Moretti et al. 2022), holding value for stakeholders beyond academia. Developers of extension and adoption programs can harness insights to develop strategies that align with producer motivations and address barriers, enabling more targeted and effective engagement (Murray-Prior and Wright 2001; Santos and Gonçalves 2021; Nettle et al. 2022). Additionally, AgTech providers can use the CJM to better understand customer pathways and barriers and refine communication and support strategies.

The framework design and limited number of co-design contributors may have left certain aspects of adoption underexplored, such as the role of relationships and trust. However, the CJM effectively fulfilled its purpose as a facilitation tool, enabling participants in the pilot study to quickly grasp and expand upon the map, adding nuance and filling in gaps based on their own experiences. Future studies could broaden the co-design participant base, adjust the vertical axis to capture relevant factors, and experiment with more interactive probe designs to further enhance engagement and insight generation.

As a probe, the CJM provides a structured process to bridge theoretical understanding and practical application. This aligns with emerging trends in artificial intelligence, particularly the development of personalized decision-support tools. These tools could deliver tailored advice, identify leverage points, and mitigate decision fatigue to support adoption. Beyond enhancing the understanding of AgTech adoption processes, the CJM advances research methodologies and practical applications, serving as a versatile framework that can be adapted to various agricultural contexts and stakeholder needs.

Acknowledgements

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Enhancing rangeland management through technology: a case study of sheep and goat grazing in Montesinho Natural Park

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Key words: Pastoralism; GNSS Tracking; Silvopastoral Systems; Mediterranean Landscapes

Abstract

The advent of advanced technologies offers unprecedented opportunities to improve the sustainability and resilience of rangeland management. This study examines the application of Global Navigation Satellite Systems (GNSS) in monitoring and optimizing the shepherding journeys of sheep and goat pastoralists throughout the rangelands of Montesinho Natural Park, Portugal.

Two distinct flocks—sheep and goats—were each equipped with a GNSS collar to monitor their routes across seasons and landscapes from April 2022 to March 2023. The study yielded 186 grazing journeys for the sheep flock and 232 for the goats. The data collected were subsequently analyzed using Geographic Information Systems (GIS) and Principal Component Analysis (PCA). These analytical methods were employed to discern patterns and correlations between grazing journeys and environmental variables, including altitude, topographic wetness, and land use types. The land use types examined encompassed orchards, oak forests, and shrublands.

The study elucidates marked discrepancies in the shepherding landscapes of the two species under investigation. The flock of sheep exhibited a distinct preference for agroforestry zones, demonstrating heightened sensitivity to climatic fluctuations, particularly during extreme temperatures. In such conditions, the sheep sought refuge in oak woods, chestnut groves, and riparian forests. Conversely, the goats demonstrated a greater utilization of rangelands and forestlands, indicative of their superior adaptability to varying environmental conditions. Additionally, seasonal variations were pronounced, with both species modifying their grazing strategies in response to the dynamic environmental changes.

GNSS data integration with GIS facilitated the visualization and analysis of grazing dynamics, offering valuable insights for developing decision support tools for pastoralists and land managers. These tools enhance the ability to make informed decisions that promote sustainable rangeland use and contribute to achieving internationally harmonized definitions. Moreover, the research underscores the potential of technology to foster collaborative rangeland research and improve the precision of monitoring and management practices.

Introduction

Pastoral systems rely on the mobility of livestock herds and the extensive use of rangelands, often adapting to some of the planet's most challenging environments. These systems are particularly significant in arid and semi-arid regions, contributing to biodiversity preservation, carbon sequestration, and the sustainable use of natural resources. Despite their importance, silvopastoral systems face increasing threats from climate change, land-use changes, and intensifying pressures on limited resources, necessitating innovative approaches to their management and sustainability (Castro et al., 2021).

The advent of advanced monitoring technologies, such as Global Navigation Satellite Systems (GNSS) and Geographic Information Systems (GIS), has revolutionized the study and management of pastoral systems. These tools enable detailed tracking of livestock movements, analysis of grazing patterns, and insights into the interactions between herds and their environments. Such innovations are particularly valuable in regions like the Mediterranean, where the intricate interplay of seasonal dynamics, topography, and land use shapes pastoral practices.

This study examines the grazing behaviour of goats and sheep in Montesinho Natural Park, focusing on how these species adapt to diverse terrains and land-use types throughout the year. By employing GNSS tracking and advanced statistical techniques, the research explores the spatial and temporal dynamics of herd movements, offering insights into the ecological roles of these species. This research contributes to the broader understanding of pastoralism in Mediterranean ecosystems, emphasizing the potential of integrating modern technologies with traditional knowledge to support sustainable rangeland management in the face of global environmental change.

Methods

This study was conducted in Montesinho Natural Park (MNP) in Portugal. The MNP features varied topography, with significant differences in altitude and climate, which influence the pastoralists' decisions, the herding process, and the animals' behaviour.

Data collection spanned March 2022 to March 2023, using advanced technologies to monitor livestock movements and environmental interactions. GNSS collars tracked daily grazing routes, recording spatial-temporal data. Environmental variables included elevation (ALT), relative slope position (RSP), topographic wetness index (TWI), and land use/land cover (LULC) categories: orchards (ORCH), oak forests (OAKF), temporary crops (TRIC), and shrublands (SHRB). Seasonal variables captured proximity to solstices (WS, SS) and equinoxes (AE, VE). Behavioral metrics included start/end times (B-6AM, E-6PM), duration (DRT), distance (LGT), and the Shannon Diversity Index (H') for grazing environment heterogeneity.

The GNSS data were exported to Geographic Information System (GIS) software for detailed analysis. The GPS collars used in this study provide a high level of accuracy, with latitude and longitude records inherently accurate to within 2 to 3 metres. Erroneous or anomalous grazing points, such as those recorded before animals left or after they entered the corral, were identified and removed to ensure the reliability of the dataset. One GNSS collar per flock was considered sufficient for accurate tracking, given the length of the grazing routes and validation from trials in previous studies.

The collars recorded data every 5 minutes, synchronized with the communications satellite, providing consistent and detailed location information. Key characteristics of grazing trips, including trip length, duration and proximity to environmental features, were calculated to provide insight into herd behaviour. Descriptive statistics were used to summarise seasonal variations in the herding process, ensuring a comprehensive understanding of the interaction between the herds and their environment.

Principal Component Analysis (PCA) was employed to assess the impact of environmental factors on grazing patterns. Simultaneously, correlation and inferential tests were utilized to identify significant relationships between grazing metrics and environmental variables. Spatial maps were created to superimpose the grazing route locations over the terrain, incorporating various land use types. A visual representation comparing seasonal grazing behaviours was developed to highlight patterns across winter, spring, summer, and autumn.

Results

GNSS locations database

A total of 16,389 GNSS location records were collected for the goat herd during the monitoring period. These records represent the goat herd's detailed movements and grazing patterns across different terrains and times. After the data cleaning process, which is essential to remove errors, inconsistencies, and irrelevant data points (such as outliers or points recorded during non-grazing activities), the dataset was reduced to 14,929 valid records, meaning 1,460 records were excluded for better accuracy and reliability of the analysis. This refined dataset ensured that only meaningful and relevant data were used to examine grazing behaviours and environmental interactions.

In the sheep herd, the dataset began with 13,510 GNSS records. After a similar data-cleaning procedure to ensure analytical integrity and precision, the dataset was reduced to 5,646 records, with 7,864 records excluded. This higher exclusion rate may reflect stricter criteria or more noise in the original data, such as points outside grazing periods or inaccuracies due to technical limitations.

Figure 1 provides a representation of the distribution of these GNSS locations over time and by date. It is critical for understanding the temporal patterns of movement and identifying any gaps or irregularities in the data collection process. By reviewing Figure 1, it can be seen that the data points were spread across the monitoring period, illustrating trends like seasonal variations or specific periods of intense activity.

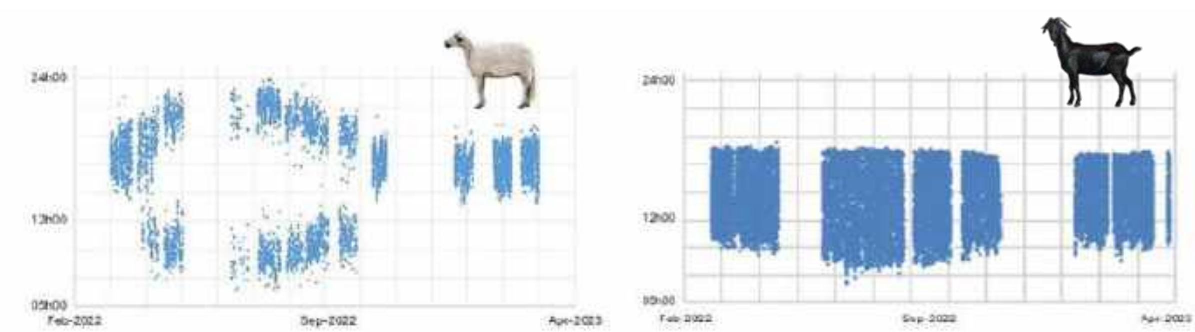

Figure 1 - Distribution of GNSS location records over time and dates for sheep and goat herds in Montesinho Natural Park.

These findings highlight the importance of data cleaning in GNSS-based studies to enhance the reliability of results and ensure that conclusions are drawn from accurate and meaningful data. The difference in the numbers before and after cleaning underscores the challenges in livestock movement tracking and the necessity of rigorous preprocessing.

The goat herd's first principal component (Dim1) is primarily influenced by physical, land use, temporal, and seasonal variables. These include the length of grazing paths (LGT), altitude (ALT), and diverse land use types like chestnut forests, oak forests, and orchards. Additionally, the Shannon Diversity Index (H') and grazing duration (DRT) contribute significantly, alongside seasonal markers such as proximity to the autumnal equinox (AE). The second principal component (Dim2) is shaped mainly by grazing duration and timing, particularly the differences in start and end times relative to 6 AM and 6 PM, which reflect temporal patterns of grazing behaviour. The third component (Dim3) highlights the influence of specific land uses like shrublands and temporary rainfed and irrigated crops. These variables are visually represented in Figure 2, where these grazing variables' spatial and temporal patterns can be observed across the goat herd's movement paths.

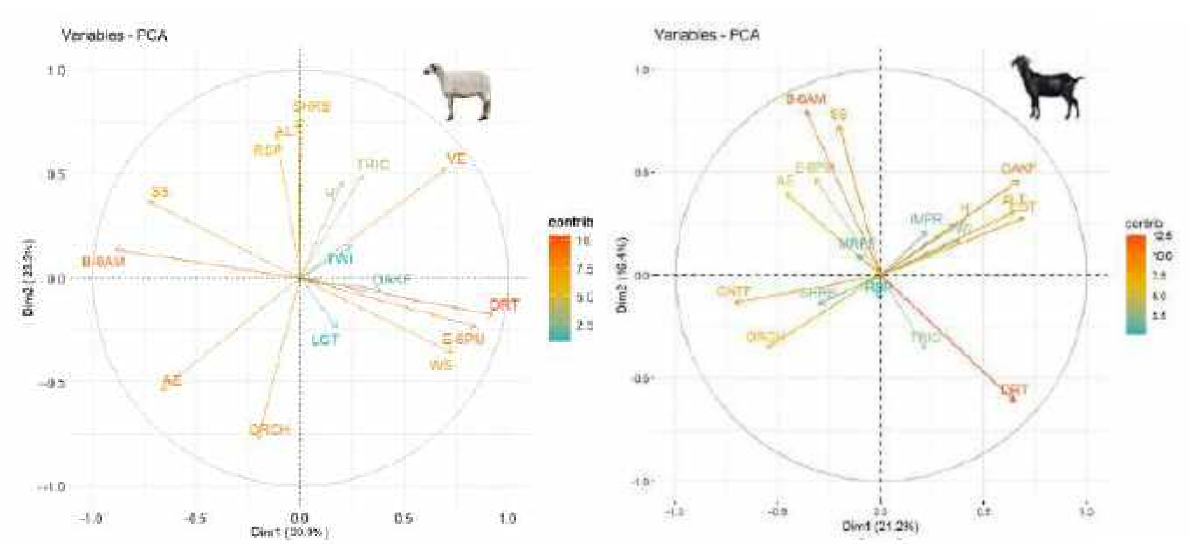

Figure 2 - Spatial and temporal patterns of grazing variables for sheep and goat herds in the Montesinho Natural Park along the first two PCA components for both herds.

In the sheep herd, the first principal component (PC1) is dominated by temporal variables, including grazing duration, the difference in grazing start times relative to 6 AM, and seasonal markers like proximity to the winter and summer solstice (WS and SS). The second principal component (PC2) emphasizes land use and topographical features such as orchards, shrublands, altitude, and relative slope position. These variables illustrate how sheep movements are influenced by terrain and land cover types. The third principal component (PC3) reflects topographical features like elevation and slope, diversity indices such as H', and seasonal proximity to the vernal equinox (VE). Figure 2 illustrates these dynamics by showing the distribution of grazing locations over different terrains and seasons, providing a comprehensive view of how these variables interact to shape grazing patterns in the sheep study.

Discussion and Conclusion

Both the goat and sheep GNSS locations reveal detailed insights into how these herds interact with their environments, highlighting differences in their behavior concerning terrain and land use throughout the year. Goats tended to explore diverse terrains, particularly for elevated areas and extended grazing paths. They relied heavily on land use types such as chestnut forests, oak forests, and shrublands, indicating their adaptability to rugged terrains and varied vegetation. This behavior was particularly evident in summer and autumn, when goats utilized high-altitude areas for longer grazing routes, reflecting their inherent ability to browse shrubs and foliage in challenging environments. In contrast, the sheep herd demonstrated more concentrated grazing patterns, favoring gentler slopes and areas with consistent vegetation. Their preference for orchards and temporary crops suggests a reliance on structured agricultural landscapes where nutrient-rich forage is readily available. Seasonal variation was marked in the sheep study, with grazing patterns closely tied to vegetation availability, particularly in spring and fall when conditions were favorable. Sheep showed reduced activity during harsher seasons, such as summer and winter, emphasizing their dependency on predictable resources and more accessible terrains than goats.

The comparative analysis highlights significant behavioral differences, as previously reported by several authors (e.g. Castro, 2004; Castro and Fernández-Núñez, 2016). Goats displayed greater adaptability to rugged terrains, utilizing steeper slopes and higher elevations, consistent with their physiological traits and foraging behavior. They were also more versatile in their land use, exploiting a broader range of vegetation types, including shrublands and forested areas. On the other hand, sheep concentrated their grazing in more controlled and accessible areas, thriving in environments with dense vegetation and less topographical challenge.

Both herds exhibited seasonal variations in grazing behavior; however, sheep were more directly influenced by climatic conditions and vegetation cycles, whereas goats maintained consistent foraging patterns across seasons. This adaptability of goats makes them particularly suited for managing vegetation in rugged and heterogeneous terrains, whereas sheep are better suited to structured landscapes like agricultural zones.

In conclusion, the results emphasize the ecological roles of each species in pastoral systems. Goats effectively manage vegetation in challenging and underutilized terrains, while sheep excel in agricultural settings where forage is predictable and abundant. These findings provide valuable insights for sustainable land management and adaptive strategies to address changing environmental conditions, ensuring the resilience and productivity of pastoral practices.

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Decision support tools for pastoralists and grazing systems

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Big landscapes meet big data in StockSmart--grazing decision support with temporally and spatially explicit annual net primary production data

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Key words: stocking rate; remote sensing; decision support tool; rangeland production; grazing

Abstract

Grasslands, shrublands, and savanna ecosystems worldwide are often grazed by domestic livestock. These vegetation types are critical for human flourishing and are vulnerable to overuse and degradation when local socio-economic conditions or misunderstanding of plant ecology leads to overuse. On large grazing areas, whether used as private property or as common pool resources, the ability of plant communities to retain rangeland health attributes of soil stability, hydrologic function, and biotic integrity depend on both stocking rate and careful application of patterns of grazing timing, duration, severity, and frequency. Sustainable stocking rates depend on judicious allocation of available forage. Historical stocking rate tools have assumed that land managers have accurate information on forage quantity and that a static sustainable stocking rate can be developed. But in non-static arid and semi-arid ecosystems already defined by resource scarcity and prone to threshold events driven by abiotic variables, the inherent interannual variability of precipitation and unpredictable net primary herbaceous production pose particular challenges for pastoralists. Washington State University Extension, in partnership with the University of Arizona and the United States Forest Service, developed a free grazing decision support tool that incorporates historical forage production and variability with user-defined animal behavior parameters and spatial distribution to estimate livestock terrain use. We show how StockSmart allows stocking calculations and grazing planning based on spatially-explicit estimates of available forage rather than total forage. It also allows testing infrastructure investments against resulting increases in forage availability. These considerations are critical for avoiding ecological state changes through overgrazing into degraded but stable conditions.

Introduction

Ranchers and public land managers collectively make land use decisions on over 700 million acres of rangelands in North America (Havstad et al., 2007). These lands provide a broad array of ecosystem services critical to human flourishing. In addition to food, fiber, and habitat (SRM 2022), humans have connection to land that is hugely influential on physical health, mental health, and social cohesion (Dean et al., 2021). Maintaining the ecological integrity of the nation’s rangelands is extremely important and the management actions influencing ecosystem processes and attributes are made predominantly by ranchers and public land managers. Grazing is a significant and visible management factor influencing plant community trajectories, wildfire mitigation, wildlife habitat, water relations at the plant-soil interface, pollinators, and more. The most basic grazing decision is "how many animals can be grazed for how long?" Although numerous factors contribute to the effects of grazing over time, the decision of stocking rate is unavoidable; literature syntheses indicate it is critical to rangeland health, independent of intensity of animal distribution (Bestelmeyer & Briske, 2012; Briske et al., 2008; Provenza et al., 2013).

More broadly, rural communities depend on the financial viability and resiliency of pastoralists and related businesses. Agricultural businesses, especially rangeland-based livestock production, depend on protecting the productive capacity of the land and sustaining ecosystem functions. Profitable businesses enable family stability and farmer mental wellness at the individual scale and social resiliency at the community scale, contributing to quality of life. The nearly inevitable result of ranch failure is fragmentation and environmental degradation of various kinds. The less common trajectory of land purchase and passive management can be ecologically dysfunctional as well. There is tremendous need to enable economically sustainable grazing use of private and public lands, and StockSmart can contribute to ensuring that good data underlie key sustainable stocking decisions. Federal, state, and tribal land managers make decisions about grazing on extensive, heterogenous rangelands, and these decisions are sometimes controversial. Ranchers make decisions on private lands and contribute to decisions and plan execution on private and public lands. All of these decisions directly impact rangeland resources. Stocking rate is a primary management variable in grazed rangelands. Poor grazing management, which includes excessive stocking rates, can have cascading negative environmental effects. Climate smart grazing management, which begins with an adaptive stocking rate, can maintain and improve various ecosystem services and values through promoting biodiversity, heterogeneity of plant community types and seral stages, limiting wildfire risk, and enhancing wildlife habitat attributes. Improved management may depend on investment in grazing infrastructure, practices that must be effective in order to justify the cost. StockSmart allows users to quantify the increases in accessible forage production due to proposed infrastructure development, including watering sites, virtual fencing boundaries, or physical cross-fence to better control timing of grazing.

Methods

StockSmart, a web application developed by the authors and University of Arizona Communications & Cybertechnologies, allows users to access accurate, spatially-explicit forage production data and combine it with spatially-explicit predictive terrain use by livestock to develop reasonable starting stocking rates that are responsive to interannual variation in herbaceous above-ground biomass and are based on calculations of forage in the areas actually accessed by grazing animals (Hudson et al., 2021). StockSmart addresses key challenges in landowners' and managers' abilities to accurately estimate grazing capacity on rangelands under their control, to track and monitor changes in the vegetation under a particular set of management decisions, and to prepare for and adjust their management as forage availability changes with climate change. Development of StockSmart had three sequential elements: 1) Develop a spatially-explicit, web-based decision support tool (DST) that accesses Normalized Difference Vegetation Index (NDVI)-based rangeland forage production data for an area of interest, allows the user to define key factors that determine rangeland accessibility, and produces maps of stocking rate and other synthetic metrics showing variation through the growing season and from year to year. 2) Convene an advisory group of rangeland owners and managers to provide actionable input and real-life pilot cases to test the tool on, ensuring that the DST provides relevant and actionable information needed for improved grazing management decisions. 3) Engage with Extension agents and specialists, public land managers, and other rangeland advisors through existing communication networks to build awareness, collect valuable feedback, and encourage early adopters to use the DST. The access to data characterizing variations in forage availability and other key factors will improve private landowners' and public land managers' ability to enhance the sustainability of the nation's forests and rangelands, provide ecosystem services and market goods, improve ecological and operational resilience to climate change, and support rural livelihoods.

Results

Forage production data

Advances in remotely-sensed data and enhanced access to these data by ranchers and public land managers offer opportunities for improved calculations of stocking rates across vast rangeland environments. The primary data that StockSmart uses emanate from the Rangeland Production Monitoring Service (RPMS) (Reeves et al., 2021) and the Rangeland Analysis Platform (Allred et al., 2021). Based on the RPMS data, StockSmart computes the historical mean and standard deviation of total annual production from 1984 to 2024, giving one value for each 30x30m square (less than a quarter of an acre, approximately one tenth of a hectare). It then uses the most recent Vegetation Cover data from the Rangeland Analysis Platform (RAP) to apportion total production into shrubs, herbs (annual and perennial), and tree growth.

Users identify an area of interest, including multiple pastures, enter on the map where water sources are (point, polyline, or polygon), select a harvest coefficient (how much of ANPP one wishes to allocate to grazing consumption), and calculate available forage based on the historical mean 1984-2024 and one standard deviation above and below the mean.

Accessibility of forage

To determine what forage is actually accessible to the animals grazing these rangelands, StockSmart corrects the forage production values based on tree canopy cover, terrain, and distance to water. Where remotely sensed estimates of understory forage are unreliable because of the interference of tree canopies, some basic linear models are used to estimate forage growing beneath the trees. All the edible forage is then corrected, accounting for how steep a slope your livestock will traverse, and how far from water they will disperse. After also adjusting the accessible forage using a harvest coefficient—the fraction of total forage produced that is assigned to grazing animals for consumption—and a shrub utilization fraction (some animals browse shrubs, some don't), StockSmart provides the user with a final number. This can be either the number of days your herd of cattle could graze, or the number of head of cattle that could graze there for a predefined length of time.

Decisions StockSmart can inform

With access to accurate, spatially explicit historical forage production data, ranchers and other rangeland managers can fine tune grazing management decisions and compare scenarios (and save them, if one creates an account). One can visualize what areas are too far away from water to be accessed by livestock and explore how stocking rate changes by adding a source of water in that part of a pasture. One can explore whether dividing pastures as well as developing water would make a big enough difference in terms of available forage to be worth the investment in fencing. The historical variations in forage production—and therefore stocking rate—are particularly valuable as the climate continues to change. StockSmart will not indicate when, how, and how much to graze, but it will provide robust estimates of how much forage is available with realistic parameters on where animals will graze and will provide clarity on how variable that forage is likely to be from year to year. When paired with careful grazing planning and monitoring of rangeland health, it provides a very useful additional tool in the rangeland manager's toolbox, to help understand and deal with the complexities of maintaining healthy herds and healthy rangelands, now and under a changing climate.

Discussion

StockSmart is available now at Stock-Smart.com; the geographic range is currently limited to the 11 Western U.S. states, but efforts are underway to expand StockSmart to the rest of the U.S. and a few other countries, including Australia. It is currently being used by federal, state, and tribal entities to plan grazing on large landscapes. It has been used in throughout the Western US in public land management scenarios. Uses have included quantifying appropriate stocking rates from Arizona to Canada and for evaluating the value of grazing lands for the purposes of land purchases. The main uses thus far have been for evaluating federal allotment management plans as well as providing a "second opinion" to evaluate field observations obtained by consultants and managers alike. In addition, it offers a unique platform for teaching range management concepts to various age and user groups.

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Plant production forecasting; current state and opportunities for advancing grazing land management

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Key words: weather and climate; forecasting; region; biomass; rangeland

Abstract

Forecasting climate and plant production provides an advantageous way to move from reactive to proactive grazing land management. Throughout grazing lands water availability and temperature are primary drivers of annual net primary plant production (ANPP) and total annual precipitation is a fundamental indicator of ANPP in native plant dominated communities that receive less than 500 mm of precipitation. In this paper we review the process by which forecasts are produced and showcase several examples of where climate and plant production forecasts can be useful in diverse US rangeland ecoregions. While forecasting is probabilistic and may not be beneficial in all circumstances, our results suggest that if forecasts are used over time, they can provide higher quality information than just chance alone. Collectively, climate and plant production forecasting could aid in moving grazing land management from a reactive to a proactive discipline by allowing producers to prepare for drought or flooding events, set appropriate stocking rates and avoid inflated hay costs, select the most appropriate crop species for annual conditions, and improve rangeland success by only seeding when weather conditions are suitable for establishment.

Introduction

Water availability and temperature are primary drivers of annual net primary plant production (ANPP) across rangelands (Bradford et al. 2006; Swain et al. 2016). Rangeland plant production is particularly affected by these factors as total annual precipitation is a fundamental indicator of ANPP in native plant dominated communities that receive less than 500 mm of precipitation (Huxman et al. 2004; Hsu et al. 2012; Williams et al. 2023). While climate can be used to produce reliable rangeland plant production forecasts, spatiotemporal climate forecasts first need to be tested for accuracy against historical weather data to ensure quality model output.

Historical climate data

Historical climate data can be acquired in various formats. The highest quality historical climate data are from stationary weather stations (Stawowy et al. 2021; Daly et al. 2008). Weather stations are, however, expensive to acquire and maintain. Across rural grazing land regions, few and sparsely dispersed meteorological tracking has limited quality spatiotemporal climate data to widely distributed point-scale locations (Hardegree et al. 2018). To overcome this limitation, scientists have used gauge data, remote-sensing inputs, and both data interpolation and disaggregation schemes to produce daily historical climate estimates of precipitation, temperature, relative and specific humidity, dew point, radiation and wind velocity, as well as derived estimates of reference evapotranspiration data at 1-4 km gridded spatial resolutions across the contiguous US (Daly et al. 2008; Thornton et al. 2014; Mourtzinis et al. 2017). These gridded databases include PRISM (Daly et al. 2008), DayMET (Thornton et al. 2014), GridMET (Abatzoglou 2013) and others (Mourtzinis et al. 2017). Gridded climate databases like these provide historical data continuity from 1979 until present and can be used across extensive or multi-site field studies where the deployment of weather stations is impractical (Hardegree et al. 2018). While these data have helped overcome data limitations across space, they are still imperfect. The process of statistical data downscaling, for example, can result in significant modelling uncertainty, as averaged and interpolated values cannot reflect complex spatial and temporal variations in climate variables at sub-daily scales. This limitation particularly applies to soil erosion applications that require fine-scale estimates of precipitation timing and intensity (Fullhart et al. 2024).

Stochastic weather generators are another modelling tool that can be used to simulate probabilistic estimates of daily weather time-series that capture additional features of daily and sub-daily climate dynamics (i.e., daily means, variances and covariances, frequencies, extremes, etc.) (Wilks and Wilby 1999). While initially used in association with individual weather stations to simulate probabilistic estimates of historical weather data, Fullhart and his colleagues have expanded the utility of one of these models, i.e., the CLIGEN climate GENerator, for estimating weather time-series across large spatial regions, from hourly to annual temporal scales (Fullhart et al. 2023; Fullhart 2023; Fullhart et al. 2022; Fullhart et al. 2021). Given the spatial and temporal availability of historical weather data and probabilistic scenarios from stochastic weather generators, reliable climate and plant production forecasts, and probabilistic plant-production scenarios can be developed.

Forecasting application and process

Seasonal climate forecasts are being used in a growing number of agricultural and natural resource modeling applications (Mo and Lettenmaier 2014; Klemm and McPherson 2017). These applications have been facilitated by the availability of seasonal forecasts of monthly temperature and precipitation from the North American Multi-Model Ensemble (NMME) program (Kirtman et al. 2014; Becker et al. 2014; Schantz et al. 2024; Roy et al. 2020). To test forecast skill (or reliability as measured via a P-value of $P<0.10$), hindcasts (or retrospective forecasts) are regressed against historical climate data. For this process, hindcasts from models used in the NMME program are acquired, as described by Kirtman et al. (2014) and matched to the spatial resolution of historical climate data at the appropriate grid scale, following a Bias Correction-Spatial Downscaling (BCSD) procedure such as in Barbero et al. (2017). For the studies we showcase here forecast model output from NMME was downscaled to match the 4-km resolution of historical gridMET weather estimates.

Climate forecast skill

In our first study, we evaluated the quality of point-scale forecasts across four US rangeland ecoregions (Fig. 1; Schantz et al. 2024). Key take aways from this study were that 1) forecast skill varies by region with the highest forecast skill in the Desert Southwest and relatively poor forecast skill in the Southern Great Plains; 2) temperature forecasts were found to have higher relative skill than precipitation forecasts; 3) we found no differences in forecast skill as a function of the forecast lead time but forecast skill varied strongly with the season for which the forecast was made; and 4) multi-model aggregate forecasts often had synergistic skill when compared to both individual model forecasts and forecasts based on the ensemble mean of all available models (Schantz et al. 2024).

Plant production forecast skill

Additional region-specific studies have shown that climate forecasts could be used as input into plant-production models to produce reliable estimates of forage yields (Fig. 2,3; (Schantz et al. *In Press-b;* Schantz et al. 2023a). In the California Annual Grassland, for example, forecasts reliably estimated plant production across most of the growing season at two sites and in three of the seven forecasting months at an additional study site (Schantz et al. 2023a). Forecast skill was shown to vary seasonally (Fig. 2) with the best forecasts produced in February following winter precipitation inputs (which is the dominant precipitation time in these regions) and when annual grasses are just beginning growth (Schantz et al. 2023b; Schantz et al. 2023a). This finding has practical application for livestock production systems as most cow-calf operations make stocking decisions in winter (January and February) and having an estimate of potential plant production would aid in the ability to justify alternative stocking decisions. Similarly, in the Great Basin we found that skillful plant-production forecasts were possible, but that forecast skill varied by inherent site conditions, such as, aspect, slope and dominant plant community (Fig. 3: Schantz et al. *In Press a,b*).

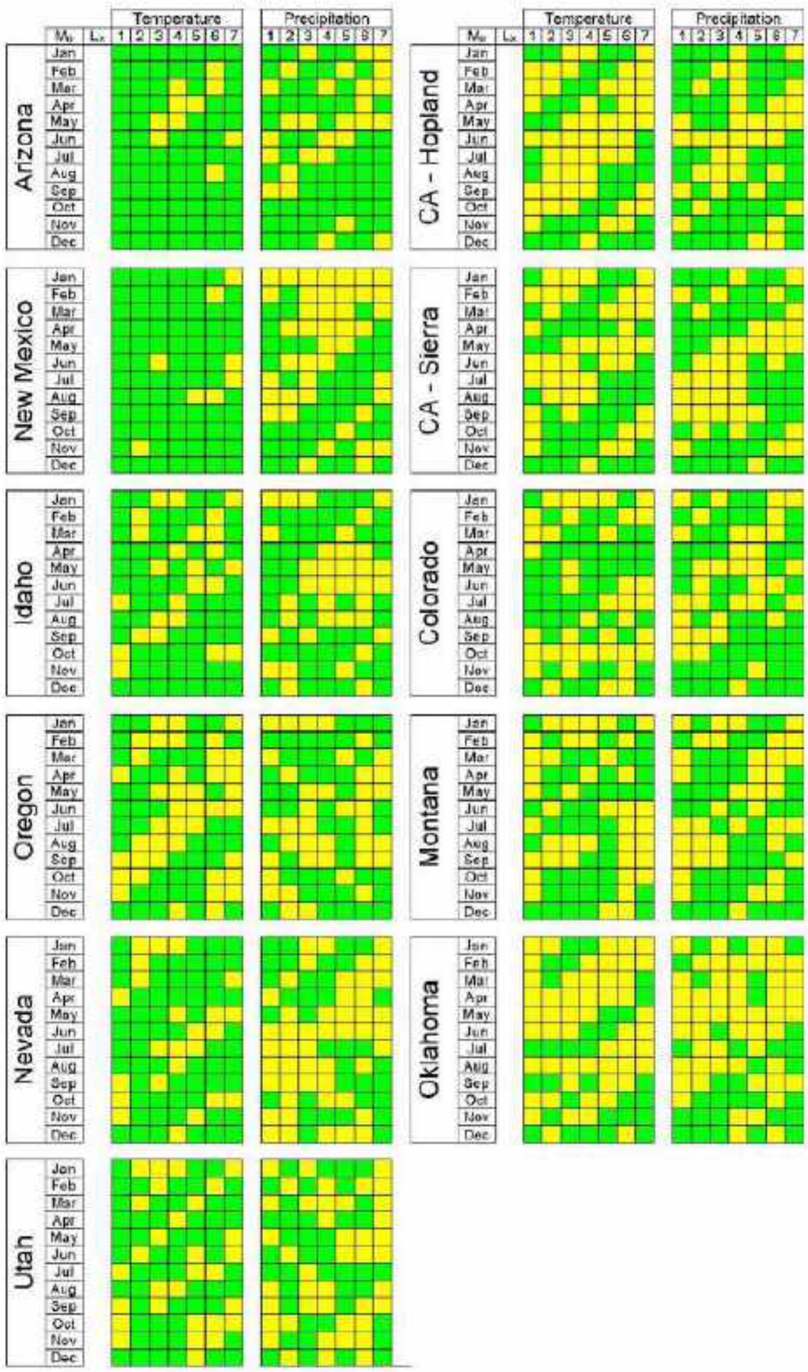

Figure 1. Skill map of 84 temporal scenarios for estimating monthly mean temperature and total precipitation at each point scale rangeland site as a function of the month in which the forecast was made M_0: Jan-Dec) and the forecast lead time L_x 1-7 months. This figure is from Schantz et al. 2024a.

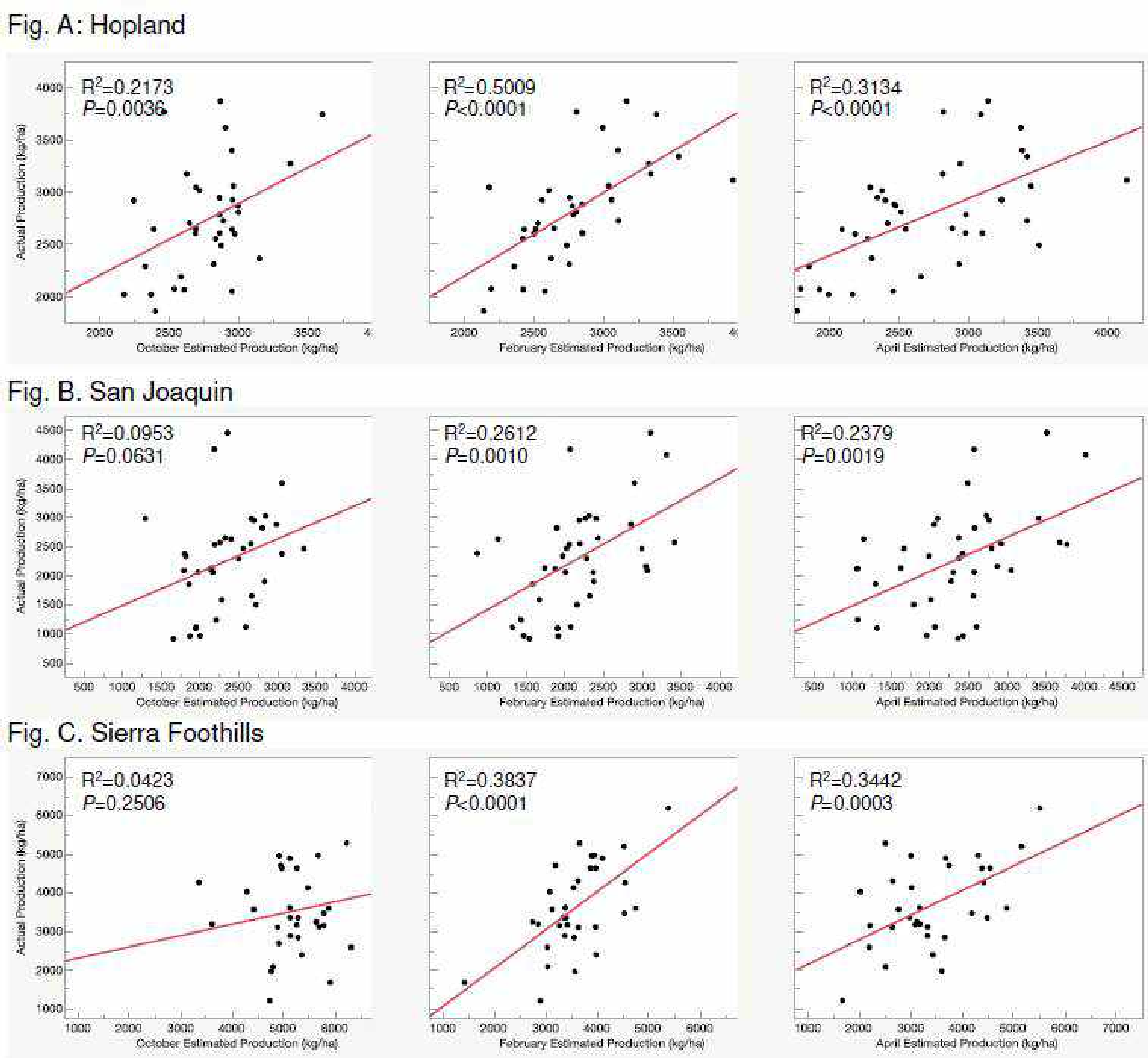

Figure 2. Regressions of actual to forecasted plant production across the study years 1982-2022 for the months of October, February, and April at three California Annual Grassland study sites. Fig. A refers to the Hopland site, B to the San Joaquin site, and C to the Sierra Foothills. This figure is from Schantz et al. 2023b.

The Future of Forecasting

Currently our team is working to provide better forecasting data access and improved tools for using forecasts in diverse agricultural and natural resource modeling applications. Upcoming projects include additional regional assessments of seasonal forecasting skill and evaluations of the utility of climate data type (i.e., stationary weather station, gridded and model-generated climate scenarios) across land use application and ecoregions associated with the Long-Term Agroecosystem Research (LTAR) network.

Conclusions and Implications

Forecasting provides an advantageous way to move from reactive to proactive management. Proactive management would allow producers to better prepare for drought or flooding events, set appropriate stocking rates and avoid inflated hay costs, select the most appropriate crop species for anticipated seasonal conditions, and provide recommendations for rangeland seeding. The process of forecasting begins by accessing high quality climate data. While stationary weather stations provide the highest quality data, they are limited to point-scale locations. Gridded and hybrid gridded stochastic weather generators can help overcome this limitation by providing quality weather information across space. Even with the best historical climate data inputs, forecasting skill will be dependent upon the interaction between region and time of the year. Similarly, the skill of plant production forecasts will depend on the interactions of area of interest, time of year, and plant species phenology. While forecast utility is probabilistic and may not be beneficial in all circumstances, our results suggest that consistent use of climate forecasts could improve the efficiency of agricultural management practices.

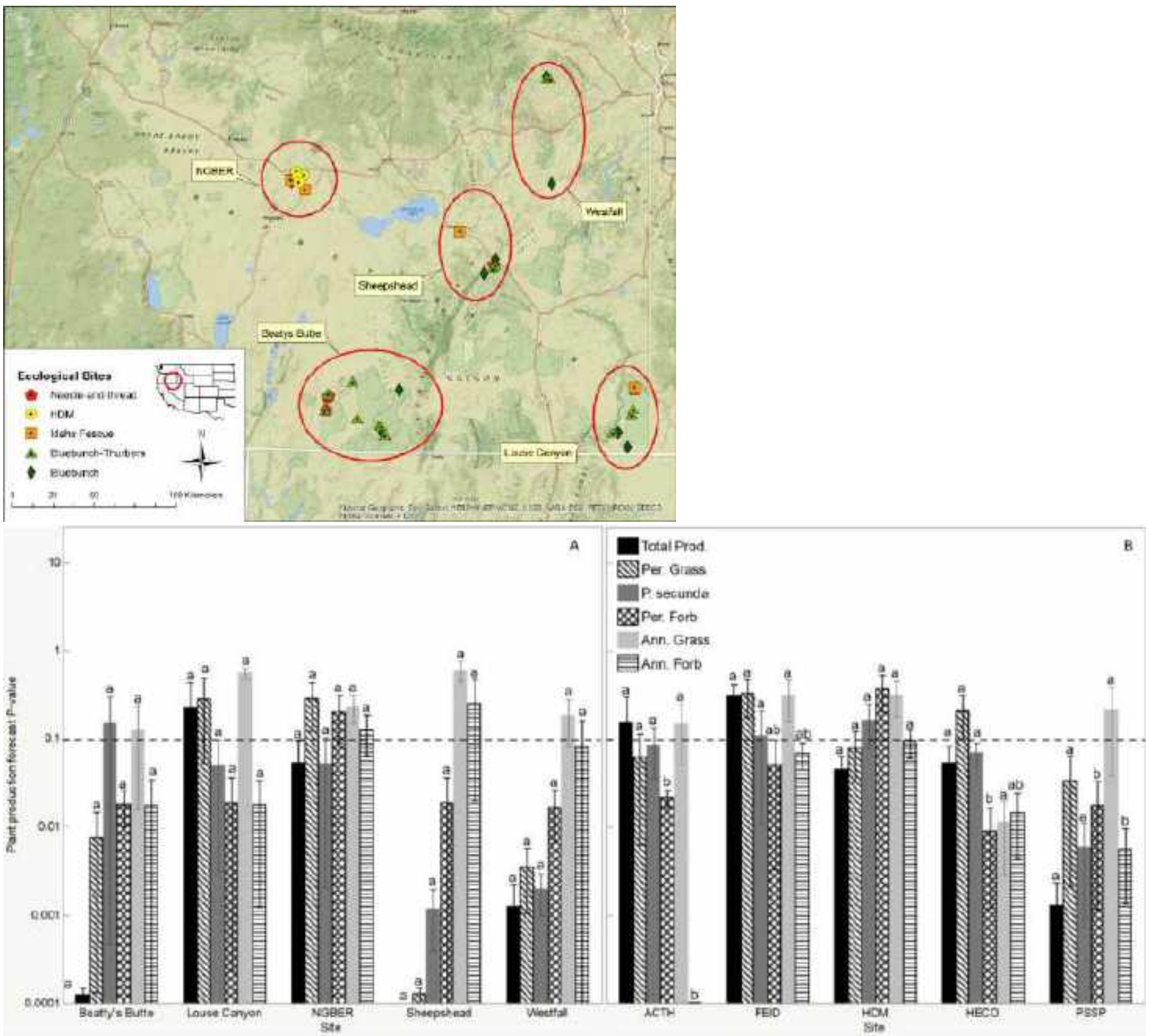

Figure 3. Upper figure refers to the geographical sites and the associated ecological states within those sites.

Lower figure refers to the skill as measured via a *P*-value ($P<0.10$) of forecasts. Figures are from Schantz et al. *In Press*.

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Empowering producers with a national grassland biomass service

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Key words: Pasture Biomass; Remote Sensing; Data Analytics; Sustainability; Decision-making

Abstract

The Australian Feedbase Monitor (AFM) is a new grazing management tool that gives Australian land managers satellite insights into their feed capabilities. It is an online portal codeveloped between CiboLabs and Meat and Livestock Australia (MLA) to improve the understanding and management of Australia's pasture and fodder feed base. The portal is free to MLA members and supported through a broad-based extension program. We used over 5000 site-based total standing dry matter (TSDM) measurements from pasture cuts, rising plate meter transects and expert observation to build a satellite-based TSDM estimate with similar accuracy to the field observations.

This model produces national TSDM estimates every five days based on the previous 30 days of imagery. The coincident application of a fractional cover model allows the TSDM estimates to be partitioned into green and dry components, allowing additional applications such as pasture quality estimation, bushfire risk assessment and ground cover analysis. Based on the European space agency Sentinel-2 satellite, these products are available back to 2017. This enables producers to understand the trends in their farms' pasture production, including rainfall, ground cover, and biomass, to place this season in the context of previous years.

As part of this tool, training and extension programs have been developed to support producers using the data for feed budgeting and to improve planning to respond to seasonal changes. This data is also used to identify underperforming areas of the farm or areas that may benefit from management changes. Further enhancements are planned to support a greater range of visualisations, farm metrics, and comparisons, which will drive adoption and help producers understand this tool's benefits and limitations.

Introduction

The Australian red meat industry needs help meeting market demands due to fluctuating livestock availability, influenced by variable pasture resources. This variability stems from rainfall, grazing pressure, and land conditions. Innovative technologies are being developed to enhance feedbase and animal management for improved productivity and sustainability.

In partnership with Meat and Livestock Australia (MLA), Cibo Labs has developed the Australian Feedbase Monitor (AFM). This groundbreaking grazing management tool leverages satellite imagery to give land managers valuable insights into their feed capabilities. This online portal aims to enhance the understanding and management of Australia's pasture and fodder resources, ultimately supporting a more profitable and sustainable red meat industry.

Methods

The development of the Australian Feedbase Monitor (AFM) followed a comprehensive process to ensure its effectiveness and applicability.

Data Collection and Preprocessing:

We collected and curated 5,100 Total Standing Dry Matter (TSDM) measurements from diverse locations across Australia, including sites collected by Cibo Labs, clients and collaborators. These field data were guided by a dedicated field data collection app that assists the user in collecting field data along a 50m transect, suitable for calibrating Sentinel-2 10m spatial resolution imagery and aimed to capture variability within and between species, growth stages and land types in the grazing regions, ensuring the model's robustness. Measurements were obtained through multiple techniques, including pasture cuts (31%), rising plate meter transects (9%), and expert observations (60%), allowing for a broad analysis of measurement types and variability. We acquired the five closest cloud-free Sentinel-2 satellite images for each site, giving us an effective window of 20 days around the field date. Coincident photography and GPS locations enable Rigorous quality control to be applied to the field and satellite data to remove outliers and address inconsistencies, such as cloud contamination and location error.

Model Development:

We used a five-hidden-layer, multilayer perceptron regression model for TSDM prediction, known for its capacity to learn complex relationships between input (satellite features) and output (TSDM) variables. The dataset was split into 50% training and 50% validation subsets to prevent overfitting and ensure generalizability. We optimised parameters using the Adam optimiser coupled with 50% layer dropouts, a layer norm constraint of 1.0 and a robust Huber loss function to enhance accuracy and prevent over-prediction. The model's performance was evaluated using metrics such as Mean Absolute Error (MAE) and Mean Absolute Percentage Error (MAPE).

Model Validation and Refinement:

A 10-fold cross-validation method ensured robust validation, dividing the data into subsets to iteratively train and test the model. We generated 16 initial realisations of the model to assess hallucinations and used an adversarial method to select the four best candidate models for additional expert evaluation. We adopted a "living model" approach, using an ML Ops framework to continuously update the model with new field data to maintain accuracy and relevance as conditions evolve.

Extension and Training:

The extension program of Cibo Labs commenced in March 2022, with activities increasing following the formal launch of the Australian Feedbase Monitor in November 2022. As of December 2024, the Cibo Labs extension team had facilitated 236 engagement events, connecting with 16,700 producers and 3,486 consultants through various platforms like field days, conferences, and webinars to boost pasture assessment and grazing management awareness. These figures reflect program activities conducted over a 33-month period from March 2022 to December 2024. The team was crucial in industry initiatives such as NT TRM Rain Ready Rangelands and MLA EDGE Grazing Fundamentals. They also developed the

'Grazing for Growth' workshop to enhance producers' confidence using pasture assessment and forage budgeting tools.

Results

Table 1 shows the cross-validated satellite TSDM error metrics for various ranges of TSDM values. Figure 1 shows the cross-validated results and associated confidence envelopes for the field data and the predictions. The median absolute percentage error of less than 30% over most of the model's range aligns closely with field measurement error and demonstrates its reliability in offering critical data to producers. There is still a significant error in the 0 to 1000kg/ha range, which reflects the variability of field estimates and difficulties associated with some soil colours when the estimation area is predominantly bare ground. Additional field sites are being collected to better sample these environments and update the model in early 2025. The model is used to supply rolling monthly pasture biomass estimates that are updated every five days. This enables producers to make informed decisions regarding grazing management, stock movements, and supplementary feeding, optimising their operations.

Table 1 - Cross-validation metrics for selected TSDM ranges.

TSDM range	Mean Error (kg/ha)	StDev (kg/ha)	RMSE (kg/ha)	MAE (kg/ha)	MAPE (%)
0 - 1000	287	543	618	184	90.5
1000 - 2000	35	563	564	235	25.7
2000 - 3000	268	735	783	453	24.0
3000 - 4000	618	892	1085	637	24.3
4000 - 6000	1218	1193	1705	1073	27.9
6000 - 10000	2404	1915	3074	2263	35.1

Producers who have participated in extension activities were surveyed before and after the event, focusing on their confidence in developing forage budgets. Participants, particularly those attending Grazing for Growth, showed significant increases in their understanding and confidence in forage budgeting, specifically in accessing and applying data provided by the AFM or PastureKey.

Additionally, the AFM enriches producers' understanding of pasture trends by providing historical data since 2017. This allows for a comprehensive analysis of factors such as rainfall, ground cover, and biomass, helping producers make informed decisions for the current season while also planning for the future. The tool's broad industry adoption reflects its perceived value, with over 4,400 registered users managing more than 52 million hectares as of December 2024.

Furthermore, extension activities have equipped producers with practical tools and knowledge to integrate this data effectively into their strategies, leading to a measurable 58% increase in confidence in forage budgeting. This increase is benchmarked against pre-event survey responses, where participants rated their confidence in key areas such as estimating available feed, calculating livestock demand, and making stocking decisions based on AFM or PastureKey data. Post-event surveys substantially improved participants' ability to apply these skills independently. These efforts have heightened awareness and enabled actionable improvements in grazing management practices, enhancing efficiency, resource utilisation, and resilience against climate variability across diverse production systems

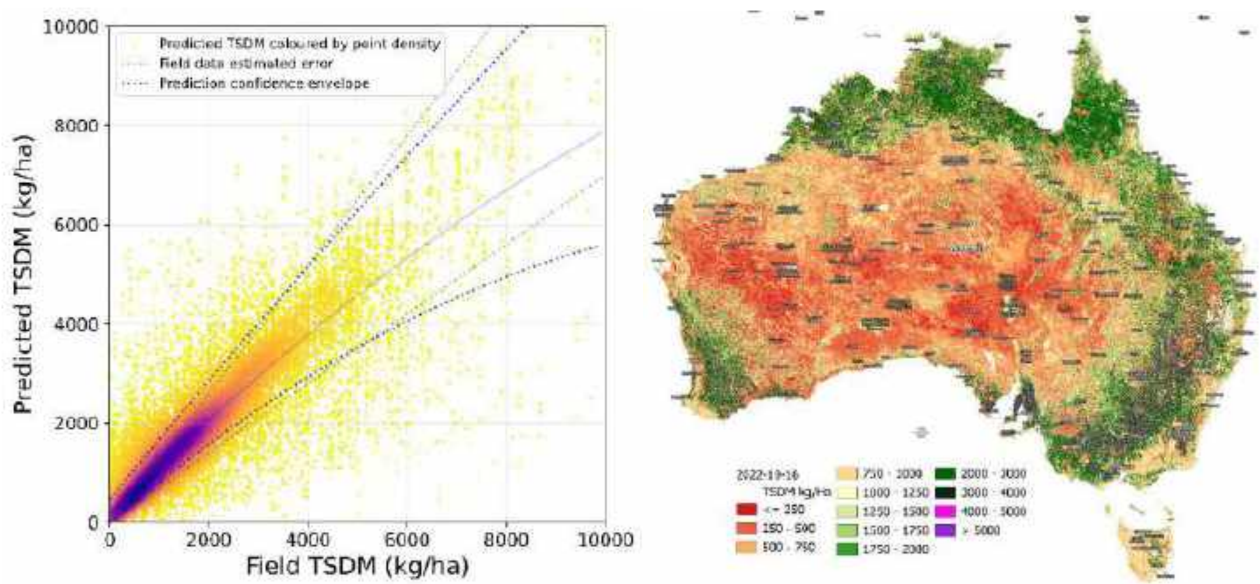

Figure 1 - Australian feed base monitor predictions vs field-based estimates (left) and example model output for 16 October 2022 (right).

Implications

The Australian Feedbase Monitor represents a significant step forward in grazing management. It gives producers powerful data-driven insights to optimise their operations and contribute to a more sustainable and profitable red meat industry. Continued research, development, and ongoing producer engagement will further enhance the AFM's capabilities and accuracy and ensure its long-term impact.

Acknowledgements

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XII INTERNATIONAL RANGELAND CONGRESS AUSTRALIA 2025

Collaborative intelligence: AI-driven decision support for beef production

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Key words: Beef production; Domain-specific AI; Collaborative intelligence; AI decision support; Agricultural innovation

Abstract

The agricultural industry is confronted with an ever-expanding array of innovations, technologies and scientific knowledge. Despite the availability of these solutions, the knowledge exploration process is time-consuming and cognitively demanding due to the volume and variability of information – this often leads to inconsistent advice, non-adoption, or suboptimal decision-making. BeefVantage aims to bridge this gap by providing a tailored AI-powered decision support system designed specifically for beef producers in Queensland – the first of its kind.

BeefVantage utilises advanced Natural Language Processing (NLP) techniques and fine-tuned Large Language Models (LLMs), focusing on trusted domain-specific data. This approach ensures high relevance and accuracy in its recommendations, moving beyond the limitations of generic AI tools, which often suffer from hallucinations and lack of domain-specific knowledge. The tool is in development, with a Minimum Viable Product (MVP) anticipated six months prior to the congress. The presentation will introduce the groundbreaking concept behind BeefVantage, detailing its initial validation processes, and explore the anticipated transformative impacts of this AI-driven tool on beef production.

BeefVantage represents a significant advancement in the application of generative AI in agriculture, tailored specifically to meet challenges faced by beef producers. By offering real-time, context-sensitive, actionable insights, it supports not only immediate problem-solving but also long-term strategies for sustainable and resilient operations. The scalability of BeefVantage suggests potential applicability to other regional contexts and agricultural sectors, promising broader impacts across rangelands.

Attendees will gain insights into cutting-edge generative AI applications in agriculture, understanding both the technological underpinnings and practical benefits. The session will invite discussion on how the collaborative intelligence of human experts and AI can be harnessed to improve the future of rangelands.

Introduction

The northern Australian beef production sector encounters distinct challenges in rangeland systems, where climate variability, environmental degradation, complex grazing land management, and market fluctuations place significant pressure on producers. While rapidly evolving agricultural technologies, innovations, and scientific knowledge offer potential solutions, they are often inaccessible or impractical for direct application (Knickel et al. 2009; Klerkx and Proctor 2013). The sheer volume and complexity of available information can overwhelm producers, complicating decision-making and leading to inconsistent adoption of innovations (Bronson and Knezevic 2016; Eastwood et al. 2019).

While tools like ChatGPT serve broad queries, they lack the precision and contextual relevance required for rangeland beef production, often generating plausible but inaccurate outputs—referred to as hallucinations—that undermine reliability (Bender et al. 2021; Balaguer et al. 2024). BeefVantage addresses these gaps by leveraging collaborative intelligence—a synergy of human expertise and advanced AI technologies—to provide tailored decision support. By integrating fine-tuned Large Language Models (LLMs), and advanced AI techniques, the system offers contextually relevant advice aligned with real-world on-farm challenges in rangeland systems.

Methods

Development followed a systematic workflow, beginning with problem definition and the collection and pre-processing of domain-specific data. The data was curated from trusted sources, including scientific journal papers, reports, case studies, fact sheets, conference proceedings, and industry guidelines. Multimodal content, such as podcasts and videos, was transcribed using Whisper (Radford et al. 2022) and integrated into the dataset.

Foundational models were identified and evaluated for integration with advanced AI techniques. Initial experiments focussed on fine-tuning Large Language Models (LLMs) (Ding et al. 2023) to generate nuanced domain-specific responses. Subsequently, advanced AI techniques were explored, included Retrieval-Augmented Generation (RAG) (Lewis et al. 2021) to retrieve relevant content from a vector database of domain-specific documents, and Graph Retrieval-Augmented Generation (GRAG) (Hu et al. 2024), which utilised a knowledge graph with 118,000 nodes and 508,000 edges to provide relational insights into critical topics. Additionally, an Agent Flow mechanism (Park et al. 2023) was also implemented to address knowledge gaps, conducting constrained web searches to deliver contextually relevant recommendations when the system could not generate a suitable answer.

Evaluation involved automated Q&A testing with 127 domain-specific question-answer pairs, assessing three metrics: relevance, groundedness, and helpfulness. All configurations were evaluated alongside foundational models. The highest-performing configuration was integrated into a Minimum Viable Product (MVP) with a user-friendly interface, allowing users to rate responses and provide descriptive feedback to support iterative improvements.

Results

BeefVantage demonstrates significant potential as a transformative decision-support tool for beef producers. The system functions as an interactive AI assistant, generating context-specific recommendations for challenges such as drought management, sustainable grazing practices, biosecurity measures, and reproductive efficiency. By providing accessible domain-specific knowledge, it enables producers to make informed, strategic decisions that address regional challenges and environmental demands.

Experiments with fine-tuning Large Language Models (LLMs) (Ding et al. 2023) demonstrated no significant improvement over the original Llama 3.1 model, leading to the decision to retain the original model. Performance evaluation indicated modest improvements across techniques explored, namely RAG, GRAG, and Agent, in terms of relevance, groundedness, and practical utility when compared to foundational AI models.

Combinations of techniques yielded mixed results. For example, integrating RAG with Graph RAG, despite its theoretical potential, resulted in decreased performance. This decline may be attributed to catastrophic forgetting, a phenomenon where a model loses general reasoning capabilities while acquiring new domain-specific knowledge (Luo et al. 2024). Ultimately, the highest-performing configuration was Llama-3.1-70B with Agent-RAG-Web, achieving a strong balance of domain relevance, groundedness, and practical utility.

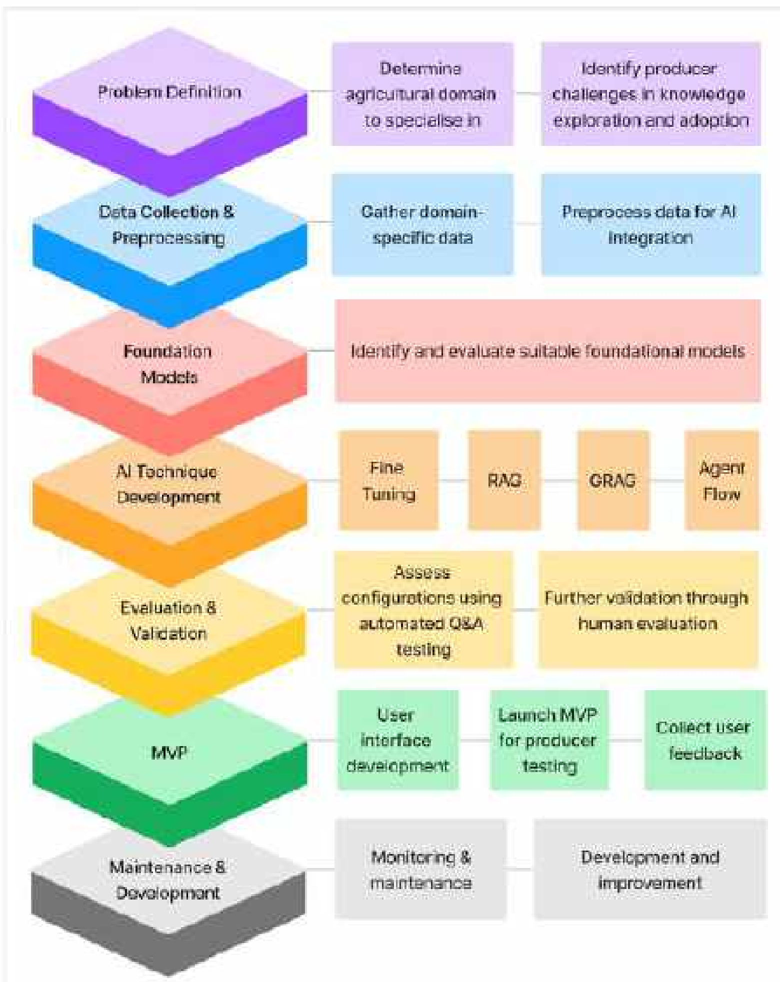

Figure 1. Development & Implementation Workflow

Key features of the MVP include a user-friendly interface with personalised accounts, saved chats, conversational memory, and the ability to download conversations. For example, producers can review previous queries related to grazing strategies, enabling continuity in decision-making. Preliminary testing has demonstrated its effectiveness in presenting complex scientific insights in an actionable format, successfully bridging the gap between academic research and practical applications.

Discussion

BeefVantage empowers producers to transition from reactive problem-solving to strategic planning by providing accessible knowledge and immediate, actionable insights. While trust in AI remains essential for widespread adoption in agricultural communities, transparent validation and producer-driven improvements can foster acceptance and encourage long-term engagement.

The system faces several challenges, including context window constraints, RAG/GRAG scalability, and adoption barriers such as digital literacy and connectivity literacy. Additionally, the platform includes a clear disclaimer, advising users to consult qualified professionals for veterinary or animal welfare concerns, ensuring clarity about its scope and limitations.

The next phase involves human evaluation to compare and validate results against automated metrics, ensuring practical utility. Feedback gathered upon the release of the Minimum Viable Product (MVP) will further refine the system, enabling continuous improvement and broader adoption. As foundational models and AI techniques continue to advance, significant improvements in system performance, scalability, and domain relevance can be expected, further enhancing the impact of tools like BeefVantage.

Future opportunities include adapting the system to other agricultural sectors and collaborating with technology partners to enhance capabilities, extend its relevance to full supply chain systems, and address broader agricultural challenges. Realising these possibilities will require sustained collaboration among researchers, producers, and industry stakeholders to overcome current limitations and amplify its impact.

Through the synergy of AI and human expertise, BeefVantage empowers producers to transform specialised knowledge into actionable insights, fostering sustainability, productivity, and resilience in rangeland systems. Its continued development and deployment hold the potential to redefine agricultural innovation, enabling beef producers to tackle pressing challenges and shape a more sustainable future.

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Evolving VegMachine.net: enhancing a successful tool for Australian rangeland cover analysis

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Key words: ground cover; digital tools; rangeland management

Abstract

VegMachine.net is a free online platform for analysing long-term vegetation trends across Australian landscapes. Since its launch in 2016, the platform has been used for thousands of site-specific cover analyses, been a feature of numerous NRM and extension projects, and contributed to more than 30 peer reviewed studies. While VegMachine® has proven valuable to land managers, scientists, and environmental organizations, user feedback has highlighted potential improvements around more reliable data access, better mobile access and improved interface stability of the platform.

A recent upgrade to VegMachine has addressed these user requests by prioritising mobile accessibility and user experience. This upgrade includes a responsive mobile-first design, new tools for efficient data collection of user features, and data persistence for seamless use across sessions and when offline. Additionally, the backend infrastructure has been overhauled, resulting in improved data stability and robust access through a revamped Application Programming Interface (API) and improved data storage.

This paper discusses the improvements to the interface, backend API and improved data storage in detail. These changes will significantly improve the VegMachine user experience and make the application more accessible to a broader user base across Australia.

Introduction

Remote sensing provides land managers and researchers with a potentially useful source of time series vegetation data. However, accessing and interpreting these massive datasets requires specialised skills and processing capability. VegMachine is an online platform that simplifies this process by extracting and summarising subsets of these datasets, in a non-commercial, user-friendly way. Users can define an area of interest and then receive many years of vegetation cover data for that location without being required to download or process any datasets themselves.

After initial development in 2002 (Beutel et al., 2004), an expanded online version, VegMachine.net was launched in 2016 (Beutel et al., 2019). Since then, the number and variety of datasets provided has expanded to include a variety of monthly and seasonal vegetation cover products, persistent green cover, fire scars and rainfall. As well as supporting land managers to easily access data, the online version of VegMachine has been utilised for research projects in areas as diverse as grazing, ecology, hydrology and primary productivity. VegMachine has also been identified as a key digital resource for earth observation data by various state and national agencies.

VegMachine's success has occurred despite ongoing data service interruptions, outdated data access methods and limitations with the interface design. In recent years, VegMachine has been upgraded to address these issues. A new version of VegMachine will be released in 2025 with significant improvements.

Methods

Data Storage and Service Improvements

All datasets available through VegMachine are provided under the Queensland Government's open data policy. These valuable datasets are delivered via Terrestrial Ecosystem Research Network (TERN) infrastructure (TERN Queensland Node) on a non-commercial basis.

The infrastructure has undergone significant updates in recent years. The time series datasets have been transitioned onto a more stable platform and are now stored as Cloud Optimised GeoTIFFs (COGs) within an OpenStack Swift object-based storage system. Additionally, the GeoServer instance, providing Web Mapping Services (WMS), has been reconfigured to improve stability and data discoverability. Web Mapping Service Tiles (WMST) have also been implemented for scalability. This new architecture enables efficient data access within the updated VegMachine API and will significantly improve the stability and reliability issues previously experienced by VegMachine users.

Application Programming Interface (API) Redevelopment

The VegMachine API specialises in extracting vegetation data from time series raster files. Upon receiving a polygon, and a specified time series dataset, the API rapidly returns spatial summary statistics for each date, including monthly rainfall (Scarth et.al, 2017). The API is hosted on Digital Ocean virtual machines, supported by the Joint Remote Sensing Research Program (JRSRP). The machines have fixed capacity and lack scalability, so the speed of the API depends on efficient asynchronous data access rather than computing power.

The previous API relied on the use of WMS to enable asynchronous access. In a significant redevelopment, the API has been implemented as a custom Python package (JRSRP, 2024 (https://gitlab.com/jrsrp/sys/asyncog)) designed to asynchronously extract information directly from the COG files via an HTTP session. HTTP range requests minimise the amount of data transferred by spatially constraining the data. Directly accessing the underlying COGs additionally eliminates restrictions on data types that are inherent in WMS.

The VegMachine API also utilises raster overviews to reduce the volume of data read and processed. Overviews are resampled versions of the data at coarser resolutions. While employing overviews typically yields an unbiased estimate of the spatial mean, reducing raster resolution can also decrease variance within the data, as extremes in pixel values tend to be averaged out (see Figure 1). This smoothing effect may obscure the variability present in the original data, especially for larger regions. The level of resampling is determined by an input parameter in the API, which users can adjust. Currently, the API does not provide users with information about overviews or the resampling level, but this functionality will be made available to advanced users with the 2025 release of VegMachine. The VegMachine developers are also considering adapting the interface to allow users to opt for increased precision at the cost of processing speed.

Figure 1. The effect of raster resampling in VegMachine on the bare ground minimum-maximum range (blue and orange regions) for a larger property (~90,000 ha) is shown. Data variability reduces with increasing site area because VegMachine utilises coarser resolution rasters for large-scale analyses to ensure timely processing. Mean values remain unbiased (represented by the dashed and dotted lines).

Interface redesign

To enhance the accessibility of the VegMachine site, the interface has been redesigned as a responsive mobile-first web application. This redesign will enable users to access the full suite of VegMachine tools on any device. The desktop interface retains all previous functionality (Beutel et al., 2019), and existing users should find the transition to the new site straightforward.

In response to user feedback, a wide variety of additional features have also been incorporated into the updated version of VegMachine (Table 1).

Table 1. Major additional functionality for new VegMachine.net version release.

New Functionality	Description
Interactive Digital Cadastral Database (DCDB) overlay	Allows Queensland users to select a lot on plan to use as an assessable feature.
Enhanced download capacity	Downloads now include the assessed features as a vector file.
Persistent data storage	Vector map features from previous sessions are retained on refreshing the application, until manually deleted.
Advanced custom chart	Allows users to select three data series statistics from all available product statistics and create a custom chart.
‘Point’ features	Instant 1 ha circle feature creation, in addition to user drawn polygons.
GPS logger with offline capability (mobile only)	Allows users to record location as a point using device GPS. Functions offline for users out of internet range.

Results

The improvements have significantly stabilised the VegMachine platform, while the redesign of the interface has provided considerable additional functionality.

While most additional interface features are aimed at simply improving user experience, the advanced custom chart (Figure 2) and mobile interface (Figure 3) are significant additions to VegMachine functionality.

The advanced custom chart feature allows users to create a chart specific to their analysis from all available data products. Map and chart are synchronized, which facilitates the easy interrogation of the chart series against the underlying raster data. Figure 2 illustrates an example chart.

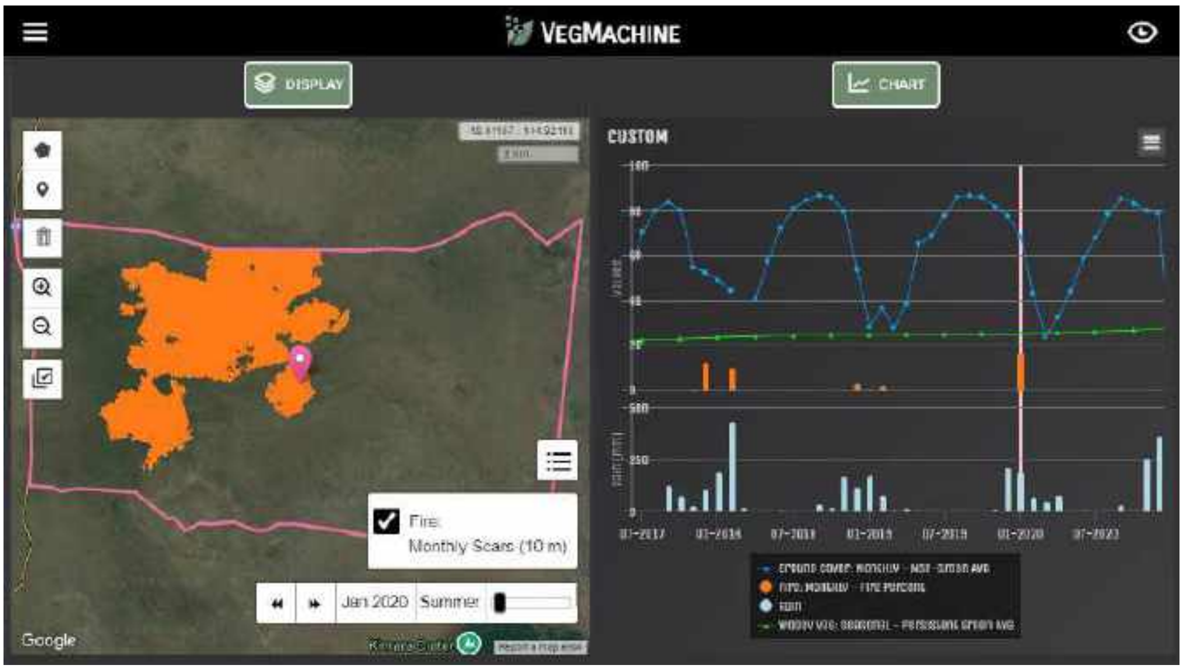


Figure 2. A screenshot of the updated VegMachine interface, showing output from the advanced custom chart feature, displaying three time series statistics (average non-green ground cover (blue), fire scar percentage (orange) and average persistent green (green)). Rainfall is also shown (light blue). By clicking on an observation in the chart, the synchronized map displays the relevant product for that date. In this instance a fire occupying 17 percent of the property for January 2020 is displayed.

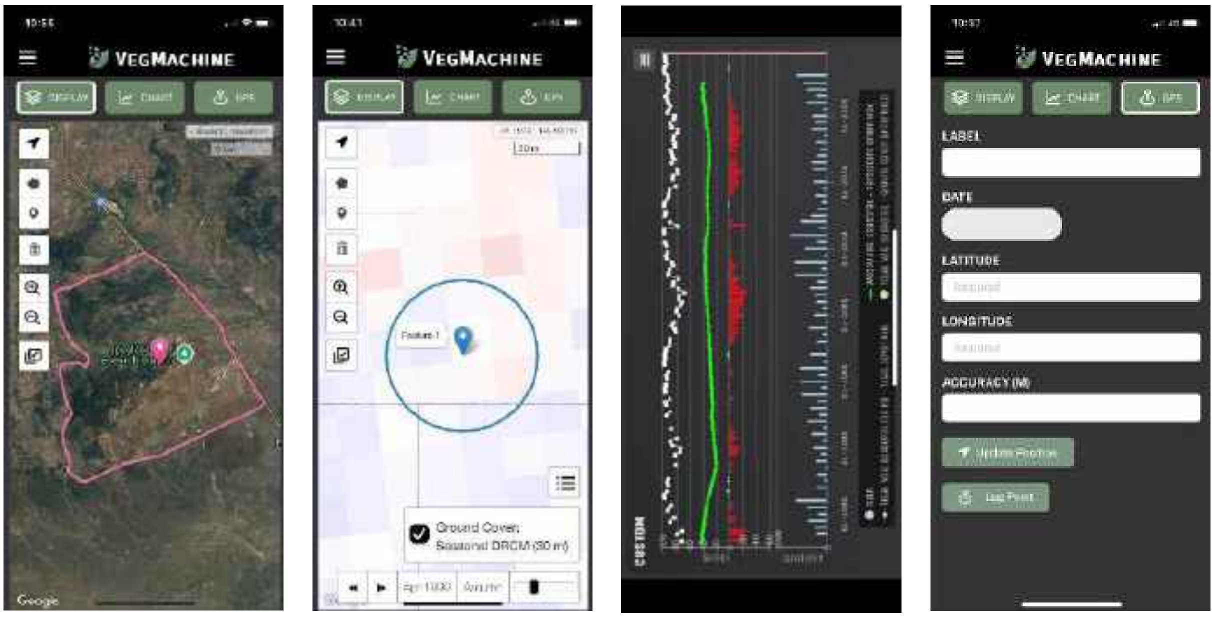
Two specific features have been added with mobile use in mind. The addition of point features (1 ha circles) will be useful for site assessments using mobile devices. The point features are optimised for straightforward application and 1 ha is a common site size. The GPS logger, with offline functionality, allows for easy point capture at locations even when out of internet range.

Discussion and Conclusion

VegMachine is a dynamically evolving platform undergoing continuous improvement. While major changes to its function and design are not anticipated for some time, incremental changes will continue to occur. Additional time series datasets will be considered for inclusion in the API and VegMachine interface if suitable. Additional publicly available APIs are expected to be developed, to meet user demand. These

APIs will be incorporated into VegMachine as additional tools and be made available for use in other 3rd party applications.

With these recent improvements, user demand is expected to increase. The degree to which the VegMachine API can scale to support additional demand, including the use of the API for 'batch' processing, is uncertain. However, VegMachine will continue to make valuable remote sensing time series data as easily accessible as possible to a broad cross section of users at no cost to them.



Map screen with a lot on plan displayed, selected from an interactive DCDB vector overlay.

Image time series overlay with time slider and point feature displayed.

Advanced custom chart with output optimised in landscape view.

GPS logger screen.

Figure 3. Selected screen shots from the VegMachine mobile interface.

Acknowledgements

VegMachine currently exists as a collaborative project between Queensland Government (Department of Primary Industries (DPI) and Department of Environment, Tourism, Science and Innovation (DETSI)), The Joint Remote Sensing Research Program (JRSRP) and the Terrestrial Ecosystem Research Network (TERN).

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Poster presentations – Theme 3

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Carbon exported in runoff from grazed semiarid lands in the Fitzroy Basin, Queensland, Australia

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Key words: Great Barrier Reef; erosion; organic carbon; water quality

Abstract

The complexities of nutrient cycling in grazing systems are influenced by management practices and soil characteristics. Grazed land accounts for approximately 71% of the total land area in the Great Barrier Reef (GBR) catchment and plays an important role in soil organic carbon storage and cycling. This study investigates the effect of vegetative ground cover and soil properties on the export of carbon fractions in runoff from grazed land in the Fitzroy and Burdekin Basins of the GBR catchment under simulated rainfall.

Particulate organic carbon (POC) in runoff was driven by fluctuations in ground cover, where POC increased as ground cover declined. Soil type and texture, specifically clay fractionation, also contributed to the export of POC. In contrast, dissolved organic carbon (DOC) exports were independent of ground cover condition and instead linked with soil type; these being Dermosols, Sodosols, and Vertosols. Clay content less than 50% in the parent soil influenced DOC load, especially as an interaction with ground cover. The enrichment of DOC in runoff as clay increased and ground cover decreased suggests soil type, and associated texture properties, facilitate DOC mobilisation, and is enhanced by the disaggregation of soil particles as driven by the erosive action of raindrops and overland flow.

Raindrop impact, runoff, and entrainment of sediment are the primary drivers for POC losses, particularly where ground cover is scarce. However, the presence of DOC in runoff is influenced by the inherent characteristics of the surface soil. Interestingly, the organic matter content of the surface soil had little influence on the carbon fractions in this study. These findings highlight the importance of vegetative management in reducing POC losses from hillslopes through runoff. The lateral movement of soil organic carbon because of depletion in POC and DOC is an important aspect of the terrestrial carbon budget.

Introduction

Soil plays a central role in regulating the global carbon cycle, storing approximately 300 times the equivalent emissions from fossil fuels as soil organic carbon (Schulze and Freibauer 2005). As the largest terrestrial carbon pool, soil contains up to three times more carbon than the atmosphere and vegetation, making it a critical component of climate regulation and ecosystem functioning (Jobbágy and Jackson 2000;

Lal 2003). Research has discovered that agricultural practices have caused a decline of organic carbon from terrestrial systems (Kirschbaum et al. 2008; Thornton and Shrestha 2021). Organic carbon is an integral component of soil fertility and marine ecosystems, and understanding its fate through the hydrological cycle is receiving attention in research (Lal 2005; Berhe et al. 2007; Garzon-Garcia et al. 2015; Burrows et al. 2023).

Coastal waters of the GBR, Australia, showed an increasing trend of POC and DOC over a twelve-year period from 2005 to 2017 (Lønborg C. 2016; Waterhouse et al. 2018). Thornton and Elledge (2022) observed that heavy grazing pressure significantly increased the amount of runoff above that attributed solely to land use change, thus increasing the amount of sediment (including POC and DOC) being exported. The erosion of fine sediment is well documented from grazing lands and is associated with carbon both in runoff and as a component of declining soil fertility (Thornton and Shrestha 2021; Elledge and Thornton 2022; Thornton 2022).

End of catchment sediment loads are exacerbated by runoff and erosion processes, and contribute significant nutrients, including carbon, to stream systems and the marine environment (Ludwig et al. 1996; Bianchi 2011; Garzon-Garcia et al. 2015; Bainbridge et al. 2018). Greater understanding of terrestrially generated organic carbon loads will help quantify exports to the GBR (Lønborg C. 2016; Nachimuthu and Hulugalle 2016; Bainbridge et al. 2018), especially considering grazing is a significant portion of land use in the GBR catchment (71%). This study documents the mobilisation of POC and DOC in runoff from plot-scale rainfall simulation trials on grazing land in two GBR catchments.

Methods

The soil types included in this investigation are classified as Dermosols, Sodosols, and Vertosols, and represent 67% and 19% of the soils found in the Fitzroy and Burdekin Basins under grazing, respectively. The Fitzroy and Burdekin are the two largest basins in the GBR catchment, which combined, represent 70% of the total catchment area. Data was collected *in situ* on hydrologically bunded plots for each soil type under simulated rainfall with various ground cover conditions. Rainfall intensity applied averaged 81 mm/hr across 89 plots. Runoff from these sample plots (1.7 to 3 m^2) was collected from a galvanised flume draining into a connection pipe. Sample collection, water quality and soil chemical analysis methods are outlined in detail in Bosomworth et al. (2018), Bosomworth (2022), and Cowie et al. (2013). A two-way ANOVA was used to examine the effects of ground cover, clay, and silt content on POC and DOC. For POC data, analysis was performed on log-transformed to meet normality assumptions.

Results

Particulate Organic Carbon in Runoff

Ground cover had a significant influence on POC loads ($P<0.001$) where increased ground cover was associated with decreased POC loss. A similar effect was associated with the presence of clay ($P<0.03$) (Figure 1). Silt had no statistical effect ($P=0.2$). Soil type also had a significant effect ($P<0.001$), particularly where there was a high percentage of fine fractions in the parent soil. Where ground cover was <10%, Sodosols exhibited the highest mean POC load (28.9 kg/ha) followed by Vertosols (23.5 kg/ha) and Dermosols (6.0 kg/ha). As ground cover exceeded 10% total cover, POC loads decreased significantly by up to 88%, depending on soil type. POC was 2 to 99% of the total organic carbon fraction depending on soil type, ranging from 2 to 82% for Dermosol, 62 to 99% for Sodosols, and 2 to 99% for Vertosols. Soil organic matter in the parent material was not significant for POC load.

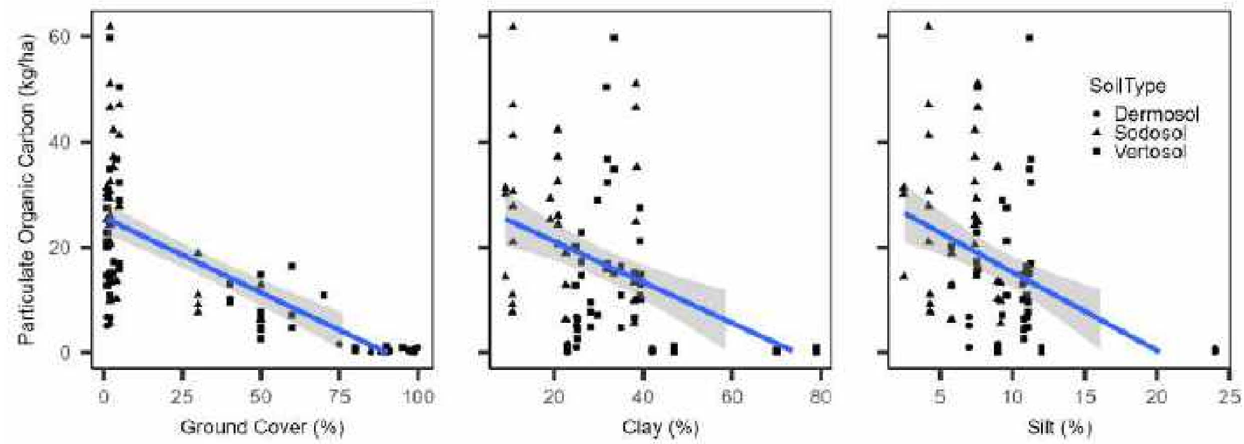

Figure 1: Particulate organic carbon (POC) loads in runoff (kg/ha) and the relationship to ground cover (left) and fractions of clay (centre) and silt (right) in the parent soil. Data points represent raw observed values, with the trendline based on log-transformed data to meet normality assumptions for statistical analysis.

Dissolved Organic Carbon in Runoff

Ground cover had no significant effect on loss of DOC in runoff (P>0.8) (Figure 2). Clay content was marginally significant (P=0.06), and silt content had no effect (P>0.2). Soil type was the main driver for DOC loads (P=0.002). An effect between ground cover and soil type was significant for DOC loads (P<0.001). Results suggest as clay fractions in the soil increase, the DOC loads tend to increase. However, once clay exceeds 50%, an inverse relationship was found. Where soils had <50% clay, clay content had a significant effect on DOC load (P<0.001). DOC was 1 to 98% of the total organic carbon load, ranging from 18 to 98% for Dermosol, 1 to 38% for Sodosols, and 1 to 98% for Vertosols. Soil organic matter in the parent material was not significant for DOC load.

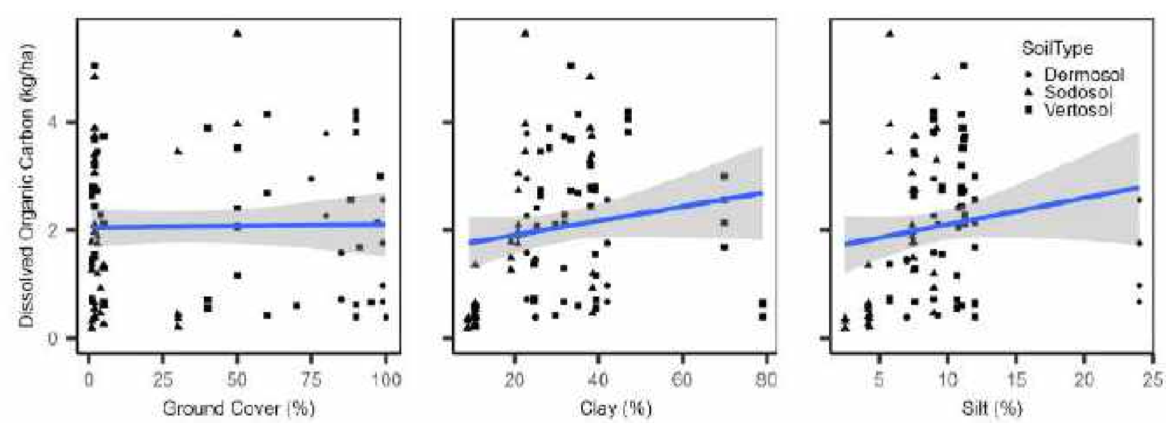

Figure 2: Dissolved organic carbon (DOC) loads in runoff (kg/ha) and the relationship to ground cover (left) and the fractions of clay (centre) and silt (right) in the parent soil.

Discussion

POC mobilisation in runoff was driven by erosion processes including raindrop impact and subsequent sediment entrainment. Where there was minimal vegetative protection, these processes facilitated the detachment and transport of fine soil particles, thereby increasing sediment and associated POC loads.

Managing ground cover will influence the contribution of this labile fraction of organic carbon. Many studies have shown variation in ground cover because of agricultural impacts such as grazing is strongly related to sediment export (Bosomworth et al. 2018; Thornton and Elledge 2021), and our results reinforce the importance of cover.

DOC mobility is primarily driven by soil type and the detachment and transport of finer particles associated with the parent soil. DOC loads are also influenced by the interaction between bare ground and clay fractions present in the *in situ* soil. Managing the DOC contribution isn't as easily achieved as it is for POC because of the variable nature of soil texture; however, increasing ground cover reduces fine particle detachment from raindrop impact and will impede both POC and DOC export.

The soils used in this study were located within the Fitzroy and Burdekin Basins, which, combined, represent 70% of the GBR catchment, from which 1300kt of fine sediment is exported annually (Prosser and Wilkinson 2024). Fine sediments, <20 µm, are easily suspended and transported, which includes the DOC fraction. Studies by Bainbridge et al. (2012) show that particles <16 µm are capable of sustained suspension and discharge from the end-of-catchment well into the Reef lagoon.

Packett (2017) showed that rainwater also serves as an additional source of DOC which could have impacts on the GBR, but also the terrestrial carbon pool. While concentration of DOC in rainfall from that study (range 0.7 to 2.3 mg/L) is lower compared to the mean soil-derived DOC reported here (8.1 mg/L; range 0.9 to 22.4 mg/L), its contribution to the total carbon budget should not be discounted. Given the nature of eroded organic fractions, which are prone to rapid mineralisation, quantifying their contribution in runoff from GBR catchments would provide further important insight into the carbon budget.

Acknowledgements
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Ecosystem integrity index (EII) in ranchers of the "grass management" project in Uruguay

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Key words: Grassland; conservation; index; livestock

Abstract

Grasslands cover about 60% of Uruguay and are the main forage for cattle and sheep production. This ecosystem and the other natural resources of livestock systems show great variability in their conservation status and little information is available. The Ecosystem Integrity Index (EII) is an indicator that assesses the state of a specific ecosystem under agricultural use, with reference to an optimal state that should be established for the ecoregion. Its application involves a qualitative and quantitative visual assessment, it has a scale of points (from 0 to 5) that includes four aspects: vegetation structure, species diversity, soil erosion and condition of watercourses and riparian zones. We carried out the EII in 12 ranches distributed throughout Uruguay, as part of the Grass Management Project of the Institute Plan Agropecuario, in the spring and summer of 2021 and 2022, years with below-average rainfall. A total of 10,808 hectares were studied. The EII showed different starting situations among the ranches. Within ranches, the EII showed differences between plots, and plots also showed differences in index composition. The EII was able to assess the conservation status of livestock systems in a simple way. The results made it possible to objectively characterise, target and localise restoration and conservation activities and make them more effective. It is planned to repeat the indicator at the end of the project to compare the ranchers' assessments.

Introduction

Uruguay is included within the grasslands of the Río de la Plata (Soriano, 1991), where they occupy 60% of the territory and are the main nutritional support for livestock production. Livestock systems present great variability in the state of conservation of grasslands and other ecosystems that need to be evaluated. To meet this objective, the Ecosystem Integrity Index (EII) was developed within the framework of the extension project of the Institute Plan Agropecuario (IPA) called Grass Management Project.

The EII is a point scale index (from 0 to 5) that includes four aspects: vegetation structure (VE), species diversity (SP), soil erosion (S) and condition of watercourses and riparian zones (RZ) (Figure 1). The index evaluates the state of a specific ecosystem under agricultural use, referring to an optimal condition to be established for the ecoregion (Blumetto et al., 2019). Its application involves a qualitative and quantitative visual assessment. The value is calculated for each paddock and an overall value weighted by the size of each paddock using the following equation:

$$EII = \sum_{n=1}^{n} \frac{(VE_i + SPp_i + S_i + \ RZ_i\ )APi}{4RA}$$

Fig 1. Where, VEi = vegetation structure score for paddock i, SPpi = species presence score for paddock i, Si = soil score for paddock i, RZi = riparian zone score for paddock i, APi = area of paddock, and RA = total ranch area, adapted from (Blumetto et al., 2019).

Methods

The EII was obtained in 12 ranches. The survey was carried out in the springs and summers of 2021 and 2022, totalling some 10,808 hectares distributed throughout Uruguay. Four ranches were selected for a second evaluation in the spring of 2024.

During the years 2021 and 2022, there were negative anomalies in precipitation indicators in all livestock regions of the country (MGAP, 2023), an aspect that is being reversed in the spring of 2024 (INUMET, 2024).

The relation between land use and the values of EII and they components was evaluated by regression coefficient. The general comparison between years of the EII and its components was performed by paired two-tailed t-test. The comparison within each ranch was performed by Fisher's test, the measurement site effect was considered a random effect, and the difference was significant when the p-value was less than 0.05.

Results

The Ecosystem Integrity Index and its four components are presented separately for each facility.

Table 1 Ecosystem Integrity Index and its components by ranches at the beginning (2021 and 2022) and at the end (2024).

	————— Initial (2021/2022) —————					————— Final (2024) —————				
Ranches	**EII global †**	**VE**	**SP**	**S**	**RZ**	**EII global**	**VE**	**SP**	**S**	**RZ**
G I	3,5 (0,22) A‡	3,7 (0,36) A	3,1 (0,21) A	4,2 (0,42) A	2,9 (0,37) A	3,6 (0,31) A	3,9 (0,30) A	3,1 (0,52) A	4,2 (0,42) A	3,0 (0,48) A
Bar	3,4 (0,39) A	3,6 (0,49) A	2,5 (0,65) A	4,2 (0,38) A	2,9 (0,40) A	3,3 (0,37) A	3,6 (0,38) A	2,3 (0,77) A	4,2 (0,29) A	2,9 (0,33) A
L. P	2,9 (0,47) B	2,7 (0,68) A	1,7 (0,49) A	3,9 (0,63) A	3,0 (0,61) A	3,0 (0,34) A	3,1 (0,51) A	1,7 (0,56) A	4,1 (0,49) A	3,0 (0,61) A
AA	3,4 (0,05) B	3,5 (0,31) A	2,8 (0,22) B	4,3 (0,15) A	3,0 (0,19) A	3,5 (0,34) A	3,8 (0,51) A	3,2 (0,56) A	4,2 (0,49) A	3,1 (0,61) A
De B.	3,4	3,2	2,0	4,0	3,0	nd	nd	nd	nd	nd
Ver.	3,3	3,9	2,6	3,7	3,0	nd	nd	nd	nd	nd
And.	3,2	3,2	2,5	4,1	3,1	nd	nd	nd	nd	nd
Sang.	3,0	3,4	1,9	3,5	2,8	nd	nd	nd	nd	nd
L. D	3,4	3,9	2,3	4,4	2,8	nd	nd	nd	nd	nd
S. R	2,8	3,7	1,2	3,3	2,5	nd	nd	nd	nd	nd
F.E	2,7	2,6	1,5	4,1	1,8	nd	nd	nd	nd	nd
Tro.	2,6	2,5	1,7	3,6	2,9	nd	nd	nd	nd	nd

†: Mean value and between parentheses the standard deviation. ‡ The letters indicate comparison of means between years for the same variable and ranches, the procedure of different means test of Fisher LDS was used whit alfa = 0,05.

In the evaluation 2021/2022 the average EII of the 12 ranches was 3.1, a standard deviation of 0.31 and a variance of 9%. On average, the EII had a significant increase of 0.10 points from 2021/2022 to 2024, in the ranches evaluated in both instances. The increased observed to VE was no significant (0,43). To the components RZ, S and SP, the means values had a significant increase of 0.05, 0.14 and 0.15 respectively.

The proportion of grassland increase the EII values (regression coefficient = 1.05, p-value=0.02), the VE values (regression coefficient = 1.71, p-value=0.02) and SP values (regression coefficient = 1.81, p-value=0.02). No significant coefficient regression coefficient was observed between proportion of grassland and S or ZR.

Fig. 2: EII per ranch and per paddock

Discussion

The EII obtained was above its mean value in all the ranches, showing different starting points between ranches and differences in the internal composition of the index (Table 1). On the other hand, differences were observed within each ranch; these findings allow focusing and locating restoration and conservation measures, and to this end maps were generated for each cattle farmer (Figure 2).

On the other hand, the data on land use in each ranch were related by regression with the EII obtained, resulting those ranches with a higher proportion of grasslands obtained a higher value of EII, this was explained by its positive and significant coefficient regression of the structure (VE) and species (SP) components, which highlights the environmental importance of grasslands for livestock systems.

In the four ranches where the index was performed again in 2024 the results indicate that in general terms there was a positive evolution of the overall EII and also in most of its components (p value<0.05), this coincides with what was found by Blumetto et al., 2019. and shows a positive effect of the project on the environmental quality of the ranches, although there may also be an effect of the change in the rainfall regime existing in the period.

Conclusions

The EII was able to evaluate the conservation status of livestock systems in a simple way. It allowed characterizing the different systems and having objective criteria to locate and focus restoration and/or conservation actions. The grassland showed a great importance in the environmental quality of the ranches. Moreover, the index showed significant changes between the beginning and the end of the project in four selected ranches, which shows a positive effect of the project and/or an effect of improved rainfall, it would be important to continue monitoring these ranches.

Acknowledgements

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Digital virtual fence user guide for rangeland management

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Key words: virtual fence; precision agriculture; livestock management; professional development

Abstract

Virtual fence (VF) is an expanding technology used on rangelands around the world. The system uses invisible barriers established by Global Navigation Satellite System (GNSS) coordinates to influence livestock movement without a physical fence. VF systems use a combination of auditory and electrical cues (i.e., beeping noises, benign electrical shocks) that originate from a wearable, GNSS-enabled VF collar. This emerging precision livestock management technology has the potential to change grazing systems by improving livestock control and distribution. Collars also generate livestock location data, which can provide information about grazing behaviour and support decision-making. Despite these opportunities, VF systems can be complicated and expensive to adopt. To address these challenges, researchers at the University of Arizona and the Southern Arizona Experiment Station have developed a digital Virtual Fence User Guide based on ongoing field trials at the University of Arizona's Santa Rita Experimental Range (Green Valley, Arizona, USA) in collaboration with the Rangelands Partnership (RP) and members of the Virtual Fence Working Group. Available on the RP's Rangelands Gateway (https://rangelandsgateway.org/virtual-fence), the guide includes practical information about VF adoption, learning modules, early adopter videos, recordings and handouts from past webinars, and answers to frequently asked questions. Tools for comparing costs between the various vendors and instructions on how to mobilize a base station to optimize coverage are also available. This comprehensive guide of digital support tools empowers land managers to effectively evaluate and use VF to improve rangeland management.

Introduction

Precision livestock management is becoming an increasingly appealing opportunity for land managers as climate change, severe drought, and unpredictable extreme weather events pose growing challenges for land managers on rangelands around the world. Virtual fence (VF) systems are precision management tools that use invisible barriers to manage livestock distribution on a ranch. When used with a grazing management plan, VF has the potential to change grazing systems by allowing novel influence over livestock movement with a combination of auditory and electrical cues (i.e., beeping noises, benign electrical shocks) that originate from a wearable GNSS-enabled collar (Antaya et al. 2024a). These systems rely on three interconnected components (1) software to draw VF boundaries on a digital map, (2) GNSS-enabled collars worn by livestock that deliver an auditory and/or electrical cue when an animal approaches the invisible VF barrier, and (3) base stations or cellular service to relay information about the invisible VF boundaries to the collars (Antaya et al. 2024a; Ehlert et al. 2024). While VF systems were first described decades ago, improvements in technology have brought VF to the forefront of ranching with the launch of several commercial VF systems by different vendors (Anderson 2007). However, as an emerging technology, there has been limited information available from unbiased sources to help land managers effectively evaluate and implement VF for sustainable rangeland management. As more VF vendors enter the market, interest and excitement over VF technology is likely to increase. Because of this, we developed an impartial VF outreach and educational resource so prospective users can make informed decisions before investing time and money in novel VF technology.

The challenge of finding accurate science-based rangeland information is the foundation of the Rangelands Partnership (RP), a group of rangeland professionals, agricultural librarians, and technology experts from across the United States (Hutchinson and Ruyle 2002; Hall et al. 2022). Since 2002, the RP has worked to bridge the gap between peer-reviewed content and on-the-ground land managers by maintaining an online portal called Rangelands Gateway (https://rangelandsgateway.org/). Rangelands Gateway provides access to a database of quality and peer-reviewed information related to rangeland ecology and management. The portal also provides access to new cutting-edge educational resources through diverse platforms including decision support tools and videos (Hall et al. 2022). The RP and Rangelands Gateway provide a unique opportunity to create and distribute information about VF.

Within Rangelands Gateway, the Virtual Fence User Guide (https://rangelandsgateway.org/virtual-fence) is designed to empower land managers to effectively evaluate and use VF for improved rangeland management by providing access to comprehensive information and resources. This article introduces the VF User Guide and describes the digital resources that it provides through diverse platforms including factsheets, videos, webinars, and support tools.

Methods

The VF User Guide is a digital resource created within the RP's Rangelands Gateway. The platform was designed to synthesize rangeland information and provide an opportunity to learn about emerging technologies through articles, factsheets, videos, webinars, and additional resources (Hall et al. 2022).

The primary resource in the VF User Guide is a collection of VF articles, called the *Foundations of Virtual Fencing*, based on real-world field trials at the University of Arizona's Santa Rita Experimental Range (Green Valley, Arizona, USA). Through a collaboration between the Marley Endowment for Sustainable Rangeland Stewardship, Arizona Cooperative Extension, and the Santa Rita Ranch LLC, researchers deployed a ranch-scale VF system (Vence™ CattleRider™ ver. 2 rev. c-g, Vence Corporation, San Diego, CA, USA) on the Santa Rita Experimental Range, a working research ranch, in 2021. From these early experiences, a variety of opportunities and challenges associated with VF adoption were documented. Additional early adopter experiences were gathered from the VF Working Group (VFWG), a community of practice primarily made up of researchers from USA land-grant Universities and non-governmental organizations formed to address knowledge gaps (Ehlert et al. 2024). Implementation and ongoing issues were documented and organized into overarching themes. With a diverse set of experiences and recurring problems, factsheets were developed to explain, offer solutions, and acknowledge the challenges of implementing VF so future users would be more prepared than the initial group of early adopters.

A multimedia approach was taken to develop the VF User Guide, incorporating learning modules, videos, webinars, and interactive decision support tools. Learning modules were collaboratively developed with VFWG members and created using Google Earth, an open access software. The intent was to provide prospective users with an instructional reference without needing access to the proprietary, vendor-specific VF software. This allows prospective users to understand what is required to set up and manage a VF system without having to first purchase a system. To share the experiences and insights of early adopters, the guide includes a four-part video series designed to help prospective users understand how others have integrated VF into real-world operations. Additional videos created by other VFWG members provide additional information on other relevant topics. Three webinars were held in fall 2024 and winter 2025 focused on adoption and implementation of VF. Webinar topics were developed based on feedback from prospective users. Recordings and handouts were posted online for open access. Finally, several interactive decision support tools were either created by University of Arizona researchers or identified and compiled from VFWG members. These include answers to frequently asked questions, resources about the financial impact of VF adoption, instructions on modifying a base station to make it mobile, and access to geospatial databases.

Results

The VF User Guide contains four primary sections to help prospective users make informed decisions about VF and improve the chances of initial success if they adopt the technology. These sections are factsheets, videos, webinars, and support tools.

Factsheets

The main function of the guide is to provide users with written information about VF that can be accessed at any time. The collection of science-based, peer-reviewed open-source factsheets are focused on the foundational information needed from start to finish, and include:

1. Basics of a VF system (Antaya et al. 2024a),
2. Economic viability of VF adoption,
3. Vital role of high-quality geospatial data (Antaya et al. 2024b),
4. Collar deployment recommendations,
5. Principles of livestock training and animal welfare considerations (Mayer et al. 2024a),
6. Strategies for collar management (Antaya et al. 2024c), and
7. Complexities and challenges (Mayer et al. 2024b).

Videos

The guide includes a variety of learning modules, early adopter videos, and other videos. Learning modules include (1) how to create a VF boundary on a digital map using VF terminology and (2) what factors to consider when placing a VF (i.e., quality of the digital map, buffer zones, fence design, water sources, and locations where VF is not appropriate). There is also a four-part video series that showcases the experiences and insights of early adopters across the USA. Additionally, videos created by VFWG members filled in knowledge gaps related to collaborations, land manager experiences, applications, animal reactions to collars, and tutorials.

Webinars

Recognizing the need for an interactive component, one-hour webinars were developed to focus on high-impact VF topics. The first webinar highlighted the basic components and compared the VF vendors available at that time. Building on this introduction, an application webinar focused on three real-world examples of how VF has been used to improve rangeland and livestock management. An economics webinar outlined the benefits, costs, returns over time, and tools to make informed decisions. Recordings and handouts are available in the VF user guide for future reference and continued distribution.

Support Tools

A variety of support tools were either created or compiled to help prospective users obtain the necessary information in one place. These items include:

1. Calculators to compare the cost of VF systems and physical fences under different scenarios,
2. Concise answers to frequently asked questions,
3. Instructions on how to mobilize a base station to optimize coverage, and
4. Direct links to USA-based geospatial databases.

Discussion, Conclusions, Implications

The VF User Guide aims to assemble comprehensive, unbiased educational and outreach materials to help land managers understand the complexities and challenges of applying an expensive, unfamiliar tool on real-world ranches. Collectively, the resources should help prospective users determine whether VF is a good fit for their unique operation and what to expect and prepare for during implementation. Without this information, land managers may miss opportunities to use VF to adapt to challenges or may misapply the technology, ultimately leading to frustrations when learning and using the technology.

As of 2024, there are four companies that manufacture and sell VF hardware and software in the United States. Whenever possible, resources in the guide describe VF components in a vendor neutral fashion to avoid bias toward a particular vendor. Most resources also include a disclaimer indicating the University of Arizona and RP do not endorse a specific product. Thus, recommendations are general and may lack the specificity required for a particular vendor. Additionally, as the technology evolves over time, suggestions may slightly misalign with the VF vendor recommendations. The guide is not a replacement for manufacturer instructions. Instead, the VF User Guide is intended to provide non-vendor specific practical guidance based on our experience and the experiences of those in the VFWG.

VF is rapidly evolving as interest in precision livestock management technology increases and wearable technology improves. There is a critical need for more independent, University-led research to understand the capabilities of these systems to support rangeland stewardship and research findings must be shared so prospective users can make informed decisions. The VF User Guide is a platform to share research findings with diverse audiences. However, the guide is only useful if the resources available cover the spectrum of questions and concerns of real-world land managers. To stay up to date, we will continue to add relevant information to the guide. This will require continuing collaborations with the VFWG as well as creating new collaborations to amass open-source and public domain content. We hope the Virtual Fence User Guide on Rangelands Gateway will be the place to access unbiased, science-based information to make informed decisions about VF.

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Application of vegetation indices obtained from satellite images for the management of the Voisin rational grazing

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Key words: Cattle; mediterranean climate; NDVI; pastures.

Abstract

Cattle ranchers have problems making informed decisions for the management of natural pastures. The lack of information ends up forcing the animals to be supplemented with external feed and forage. The degradation of natural pastures, climate change, and agricultural policies aimed to make farms more sustainable. Sustainability requires improving natural resource management techniques. Voisin Rational Grazing manages grazing time based on the critical leaf area index; it has been proposed as a sustainable alternative for livestock. This method is based on optimizing the productivity of pasture and livestock but requires constant plots monitoring. The objective was to estimate through remote sensing the evolution of growth, biomass, and other pasture management parameters, which facilitate decision making in the Voisin. A real case study was chosen. The farm has 240 ha in 81 paddies in 5 counties, and 1,703 ha of communal pastures in joint use for summer use. It is in the northern of Madrid, in Central Spain under Mediterranean climate. Sentinel-2 images were used between 2017 and 2020, the processing and calculation of the vegetation indices was carried out with Sen2Cor and QGIS. In the field, biomass was sampled, and images were taken and processed with QGIS and SW Maps. A wide variety of factors affect the farmer decision, making the dynamics of the pastures between the plots heterogeneous in phenology and production. The evolution of the vegetation indices follows the dynamics of the grass logistic curve. Vegetation indices seem appropriate to detect the point of maximum grass biomass gain, necessary to apply the Voisin. Plots that are being grazed at high instantaneous stocking density, characteristic of the Voisin, can be detected using vegetation indices. Also, it was appreciated how this grazing method allows rapid regrowth. We considered that remote sensing can facilitate the application of Voisin Rational Grazing.

Introduction
Rangelands ecosystems cover more than a third of the world land surface, supporting key ecosystem services and livelihoods. The main drive variables for sustainability of rangeland are climate change, temperature and precipitation, and social-economic trends (Herrara and Davies 2014; Gartzia et al. 2016; Sanz et al. 2021). Identifying critical factors and main sources of risk into the rangelands provide useful tools for the design of mitigation measures and other measures (Iglesias et al. 2016).

Rational grazing (Worstell and Voisin 2015), specifically the methodology developed during the 1950s by researcher and farmer André Voisin (whose surname is used to commonly refer to this methodology as Rational Voisin Grazing, or RVG), is proposed as a grazing system to be implemented. While there are numerous grazing methodologies that could be considered rational—or at least account for both the development of the animal and the pasture—they all share the same foundation.

The main target of this grazing system is to optimize the production of the grazing animal and the productivity of the grazed pasture, which entails finding an optimal balance between meeting the needs of both the livestock and the pasture simultaneously. For the grazing animal, the aim is to maintain an adequate diet for the livestock in the pasture. This requires meeting the animals' needs in sufficient quantity and quality to achieve appropriate production parameters, which can only be reached if the animals' health and welfare are ensured (Pinheiro Machado et al. 2021). Our objective was to estimate through remote sensing the evolution of growth, biomass, and other pasture management parameters, focus on apply vegetation indices to facilitate decision making in the Voisin Rational Grazing systems.

Methods
We selected a rangeland from central Spain. The livestock operation under study is located at the northern mountain of the Community of Madrid. The lower parts of this area feature gentle topography, situated around 1,000 meters above sea level, while the highest peaks reach up to 2,000 masl. The operation runs a surface area of 240 hectares divided into 81 plots, of which 25 hectares equipped with irrigation. Also, it runs communal pastures covering 1,703 hectares grazing between March and October (as summer pastures). The operation includes 126 nursing cows of the native "Berrenda en Negro" Spanish breed (average 550 kg LW/cow), which are crossbred with Charolais bulls for industrial purposes.

The annual average temperature recorded is 11.3 °C, with the minimum average temperature of 4 °C in January and the maximum of 20.7 °C in July. The annual average rainfall is 637 mm, with November being the wettest month (90.7 mm) and August the driest (18.1 mm). This rainfall and temperature regime results in a dry period lasting four months: June, July, August, and September. Regarding the frost period, estimates using the Papadakis method indicate a medium frost-free season from April 21st to November 4th. The soils in the area are classified under the USDA Soil Taxonomy as Inceptisols in higher areas and Entisols in the valley floor. The soil pH is moderately acidic, ranging between 5.78 and 6.3, and the soil organic matter content varies from 0.66% to 4.3%.

In the field, biomass was sampled, data was gotten from the farmer land book and from field samples. Up to seven different types of pastures have been identified, also the agroforestry of ash (*Fraxinus angustifolia* Vahl.) and oak (*Quercus pyrenaica* Willd.), because they constitute a considerable source of food at the end of summer and beginning of autumn, when sometimes there is no grass regrowth and therefore, they represent an alternative source of great importance. The habitats present according to European Union Habitats Directive (Council Directive 92/43/EEC) are 6220 (*Festuco amplae-Poetum bulbosae*); 6310 (*Juniper oxycedri-Quercetum rotundifoliae pastures*); 91B0 (*Querco pyrenaicae-Fraxinetum angustifoliae*) and 92A0 (*Rubo-Salicetum atrocinereae*). During 2020, two types of management were studied: continuous grazing (in which areas that were being grazed during sampling were determined) and rotational grazing (areas that were excluded from grazing).

Following a literature review, seven vegetation indices have been chosen that have already been used to relate them mainly with grass biomass (Table 1).

Table 1. Vegetation indices obtained according with the literature for vegetation quantity or quality that can be calculated using pairs of Sentinel-2 bands.

Vegetation indices	Acronyms	Equations
Normalized Difference Vegetation Index	NDVI	(B08 - B04) / (B08 + B04)
Enhanced Vegetation Index	EVI	2.5 × (B08 - B04) / [(B08 + 6×B04 - 7.5×B02) + 1]
Renormalized Difference Vegetation Index	RDVI	(B08 - B04) / √(B08 + B04)
Green Normalized Vegetation Index	GNDVI	(B08 - B03) / (B08 + B03)
Sentinel 2 Red Edge Position	S2REP	705 + 35 × ([(B07 + B04)/2) - B05] / (B06 - B05)
Red-Edge Normalized Difference Vegetation Index I	RENDVI I	(B06 - B04) / (B06 + B04)
Red-Edge Normalized Difference Vegetation Index II	RENDVI II	(B07 - B04) / (B07 + B04)

*Sentinel-2 layers bands (ESA 2021): B02 (490 nm), B03 (560 nm), B04 (665 nm), B05 (705 nm), B06 (740 nm), B07 (783 nm), and B08 (842 nm).

Sentinel-2 images were used between 2017 and 2020 from Copernicus Open Access Hub to calculate vegetation indices and to monitor rangeland pastures. The processing and calculation of the vegetation indices was carried out with Sen2Cor 02.08.00 and QGIS 3.16.1. All data was processed with QGIS and SW Maps. A wide variety of factors affect the farmer decision, making the dynamics of the pastures between the plots heterogeneous in phenology and production.

Results

Pastures biomass

The farmland displays a wide variety of factors leading to heterogeneity in the phenology and production of pasture across plots. Pasture productivity ranged from 1,563 kg DM/ha in non-irrigated plots (2017) to a maximum of 4,108 kg DM/ha in irrigated plots (2020), with an average of 2,686 kg DM/ha in rain-fed plots and 3,174 kg DM/ha in irrigated plots.

The evolution of the vegetation indices

The evolution curves of the vegetation indices (VIs) showed that all indices detected changes in pasture senescence. Figure 1 illustrates how the senescence of irrigated pastures is delayed compared to non-irrigated pastures.

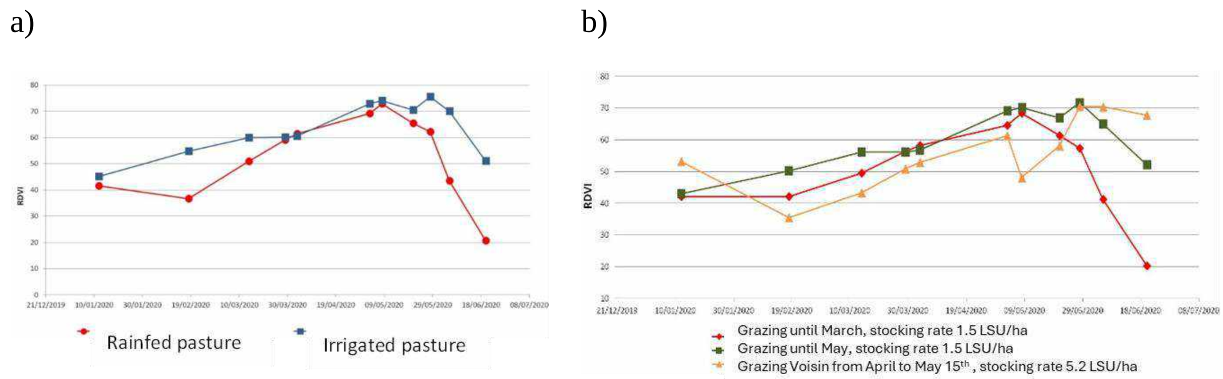

Figure 1. a) Evolution of Renormalized Difference Vegetation Index RDVI in rainfed areas and under irrigation during pasture growth periods in from winter 2019 to summer 2020; b) Evolution of Renormalized Difference Vegetation Index RDVI with different pastures management from winter 2019 to summer 2020.

When examining the effects of grazing, clear changes were only observed in plots with high instantaneous stocking rates (5.2 LSU/ha) according to Voisin. In contrast, plots with low stocking rates (1.5 LSU/ha) showed no significant differences between grazed and reserved plots (Figure 1b). From Figure 1b, it can be seen what effects are expected from PRV through the plot grazed for a short time at a high loading: the estimated production was 3,060 kg DM/ha compared to 4,060 kg DM/ha despite having been thoroughly grazed and reserved for a period at least two weeks less than the plot reserved in May. The application of rational Voisin grazing improved grass production by 24% to 76% depending on the type of grass and management (Table 2).

The evolution of VIs follows the same logistic curve dynamic as pasture growth, indicating their suitability for detecting the point of maximum biomass gain. Specifically, the RDVI index was selected for its higher sensitivity to phenological and management changes.

Table 2. Pasture productivity (kg DM/ha year) in the current and Voisin. Current management continuous grazing (in which areas that were being grazed during sampling were determined) and rotational grazing (areas that were excluded from grazing)

Management	**Current grazing** **kg DM/ha year**	**Rational Voisin Grazing** **kg DM/ha year**	**Pasture gain** **kg DM/ha year, (%)**
Continuous grazing (rainfed)	2,750	4,825	2,075 (76%)
Rotational grazing (rainfed)	3,625	4,825	1,200 (33%)
Rotational grazing (irrigated)	4,934	6,134	1,200 (24%)

Regarding the correlation of the evolution of vegetation indices with biomass in summer, it has been found that this is more adjusted in the grazing paddocks that have not been grazed since March for the set of years 2017-2019-2020. Therefore, considering the period within each season between March and the date with available satellite image following that with which the highest value of May is obtained and a linear adjustment; the cumulative or integral of the IV that has the best correlation with the estimated biomass of the pasture is the EVI ($r^2 = 0.52$).

Discussion and conclusions

It has been demonstrated that vegetation indices can identify plots grazed with high instantaneous stocking rates, a key feature of the RVG system. Additionally, this type of grazing allows for rapid pasture regrowth, achieving satisfactory productivity compared to other management approaches. The RDVI appears to be the most sensitive index for detecting changes in pasture management and phenology, making it a valuable indicator for Voisin grazing management.

Following Sanz et al. (2022) vegetation indices time series could allow us to understand better the rangelands´ evolution and the effect of management in these trends. The biomass estimation results suggest that the relationship between biomass and the accumulated VI value throughout the growth season depends on the availability of satellite imagery, particularly during critical growth periods in spring when cloud cover can limit data availability.

The best vegetation index for estimating pasture biomass in this study was the EVI. While the results could be improved with more data and biomass sampling, the index can still be used for pasture management, considering its limitations. These limitations primarily relate to the reliance on final biomass data from long growth periods without grazing. Therefore, it is proposed to use RDVI for detecting changes in pasture (management, phenology, or rest periods) and EVI for estimating available biomass after reserving pastures for cutting.

Acknowledgements

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Using optical remote sensing LAI for semi-natural grassland yields prediction in Noteć river valley

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Key words: leaf area index; remote sensing; semi-natural grassland; yield prediction

Abstract

The aim of the study was to evaluate the suitability of LAI calculated from satellite data (LAI-sat) for semi-natural grassland yield prediction in Noteć river valley based on relations between in-situ ground measured yield indicators and LAI computed from in-situ values (LAI-cept) compared to relations between those indicators and LAI-sat data. The research was carried out in the years 2020-2023 within the project GrasSAT (www.grassat.eu) on semi-natural grasslands located in Noteć river valley (Wielkopolskie region in central-western Poland). Annual yield data were collected from ca. 150 ha of semi-natural grass vegetations located on organic soils used extensively for cutting raw material for conserved fodder. In each grassland, ground measurements were carried out in a representative 30 m × 30 m plot every 2-3 weeks during the growing season. Fresh and dry matter yield was determined from biomass samples collected using a quadrat frame. LAI-cept was measured using AccuPAR LP-80 ceptometer and LAI-sat was obtained from platform Weekeo based on Sentinel-2 satellite images at 10 m pixel resolution. Statistical analysis has shown that all the tested relations had high correlation coefficients. The accuracy between LAI and FM or DM was slightly higher for for LAI-cept than LAI-sat. The optical remote sensing LAI applied for semi-natural grassland yields prediction is an efficient method that can be used to monitor the productivity of grass communities located in riparian areas of river valleys. This can help in planning for agricultural practices, can be an efficient tool in decision support system of semi-natural grassland management, and offsetting financial risks on large scales.

Introduction

Leaf area index (LAI) is an excellent proxy for biomass estimation because it directly quantifies the amount of leaf surface area relative to the ground area, providing critical insights into the vegetation's photosynthetic capacity and overall health (Parker 2020). Since biomass is closely linked to the amount of photosynthetically active tissue, LAI serves as a reliable indicator of the total biomass present in an ecosystem (Dąbrowska-Zielińska et al. 2024). Additionally, LAI captures variations in canopy structure, density, and leaf area, which are essential factors influencing biomass accumulation. Its non-destructive measurement and correlation with other biophysical parameters make LAI a valuable tool for accurately estimating biomass across diverse vegetation types e.g. of grassland and rangeland (Reddersen et al. 2014). LAI can be measured using ground-based methods, but these approaches are time-consuming, labor-intensive, and difficult to apply at a regional scale. In the last few decades, remote sensing-based approaches which are endowed with high temporal resolution and the capacity for large-scale observation are increasingly used to estimate LAI. As reported by Reinermann et al. (2020), LAI is one of the most widely used index within the studies investigating grassland management with remote sensing data, just like NDVI and band reflectance values. Therefore, research towards practical applications of remote sensing-based LAI is needed to support grassland and rangeland growth modelling and appropriate management decisions.

The aim of our study was to evaluate the suitability of using optical remote sensing LAI for semi-natural grassland yields prediction in Noteć river valley.

Methods

The research was carried out in the years 2020-2023 within the project GrasSAT (www.grassat.eu). Reference data were collected on six semi-natural grasslands located in Noteć river valley (Wielkopolskie region in central-western Poland, one 52º89' N, 16º45' E, two close to each other 53º07' N, 16º92' E and three also located very close to each other 53º05' N, 17º10' E). Investigated area ca. 150 ha of semi-natural grass vegetations was located on organic soils used extensively for cutting raw material two times per year for conserved fodder (hay or haylage). As suggested by Crabbe et al. (2019), on each site, a 30 m × 30 m plot was randomly selected for in-situ ground measurements to encapsulate the resampled 10 m × 10 m spatial resolution of the Sentinel-2 imagery, allowing for a 10 m radius buffer around the 'central pixel' location for uncertainty in spatial registration of the image pixels. Field measurements were carried out every 2 to 3 weeks throughout the growing season. In this paper we investigated the hypothesis that the correlation between semi-natural grassland yield and different LAI obtained in-situ and from satellite is similar. The yield was represented by two indicators: aboveground fresh biomass (FM) and dry biomass (DM). On each site, the FM and DM yields were determined using quadrat frame method from the area of 0.5 × 0.5 m with four replications. LAI at the ground level (LAI-cept) was determined with AccuPAR LP-80 ceptometer (using effective plant area index $L_e = \Omega L$ where Ω refers to a clumping index resulting from the non-random distribution of canopy elements). The remote sensing-based LAI (LAI-sat) was obtained from platform Weekeo based on a neural network that utilizes the surface reflectance of Sentinel-2A bands. The relationships between the in situ LAI-cept and biomass and the LAI-sat data were determined. The correlations were tested using the Pearson's *r* coefficient in the R statistical environment and modelled using simple linear regression with confidence interval displayed around the regression line (Wickham, 2016).

Results

The analysis has shown that there is a high correlation between all the in-situ grassland yields and the optical indicators of LAI. The correlation between LAI and FM is similarly for LAI-cept and for LAI-sat (r = 0.904 and r = 0.905, respectively). In the case of correlation between LAI and DM the LAI-cept is slightly better than LAI-sat (r = 0.936 and r = 0.904, respectively). In general our results indicate that linear relationships between LAI-sat or LAI-cept and the studied semi-natural grassland yield indicators are high. However, the scatter plots illustrating these relationships suggest that yield estimation using optical LAI indicators is most precise before the accumulation of semi-natural grassland biomass reaches ca. 1000 g m^{-2} of FM or 200 g m^{-2} of DM (Figure 1). All these threshold values are consistent with one another. Above these thresholds, the studied LAI indicators seem to be less responsive to the accumulation of semi-natural grassland biomass increase, which is indicated by the wider points dispersion and the weaker trend of increase in the plots. This is related to the change in the structure of aboveground biomass due to the transition from the vegetative to the generative growth stage in grasses and other plants. Another reason is foliage overlapping that makes some leaves invisible to the optical sensors. In such situation a combination of both, cover to mass can be used, like is commonly used in Australia at high and/or stoloniferous spreading pastures (Barnetson et al. 2021).

Discussion

Our study has shown that LAI-sat can be used to predict yield of semi-natural grassland yields in river valleys in decision support systems for its management, but the precision of this prediction can be further improved in future research. However, as reported by Reddersen et al. (2014), models for predicting biomass of extensively managed grassland using exclusive LAI were barely suited to predict biomass accurately, but can be improved significantly when combined with waveband selected common vegetation indices. We further propose that for tall and dense swards, the relationship between the yield and LAI-sat is modelled using a two-segment regression line (Muggeo, 2008), with the first segment steeper than the second one, and the breakpoint (yield indicator value where the two segments are connected) located near the above-mentioned threshold values. Interesting findings regarding pasture yield estimation were presented by Barnetson et al. (2021), suggesting the need to measure the biomass structure, i.e. height or density. In the case of coastal grassland and inland woodland pasture, they developed deep learning predictive models of pasture yield from field measurements and both remotely piloted aircraft systems and satellite imagery.

The accuracy between LAI and FM or DM was slightly higher for LAI-cept than for LAI-sat, but the correlation between the in-situ grassland yield and the optical indicators of LAI was very high ($r > 0.90$). This result confirms the findings of other authors, e.g. Klingler et al. (2020) or Dąbrowska-Zielińska et al. (2024), who generally observed a significant influence of the seasonal changes of the canopy structure and morphology on the estimation accuracy. The optical remote sensing LAI applied for semi-natural grassland yields prediction is an efficient method that can be used to monitor the productivity of grass communities located in riparian areas of river valleys. This can help in planning for agricultural practices, can be an efficient tool in decision support system of semi-natural grassland management, and offsetting financial risks on large scales. The remote sensing-base LAI estimated by using Sentinel-2 is also of major importance for optimal semi-natural grassland growth modelling.

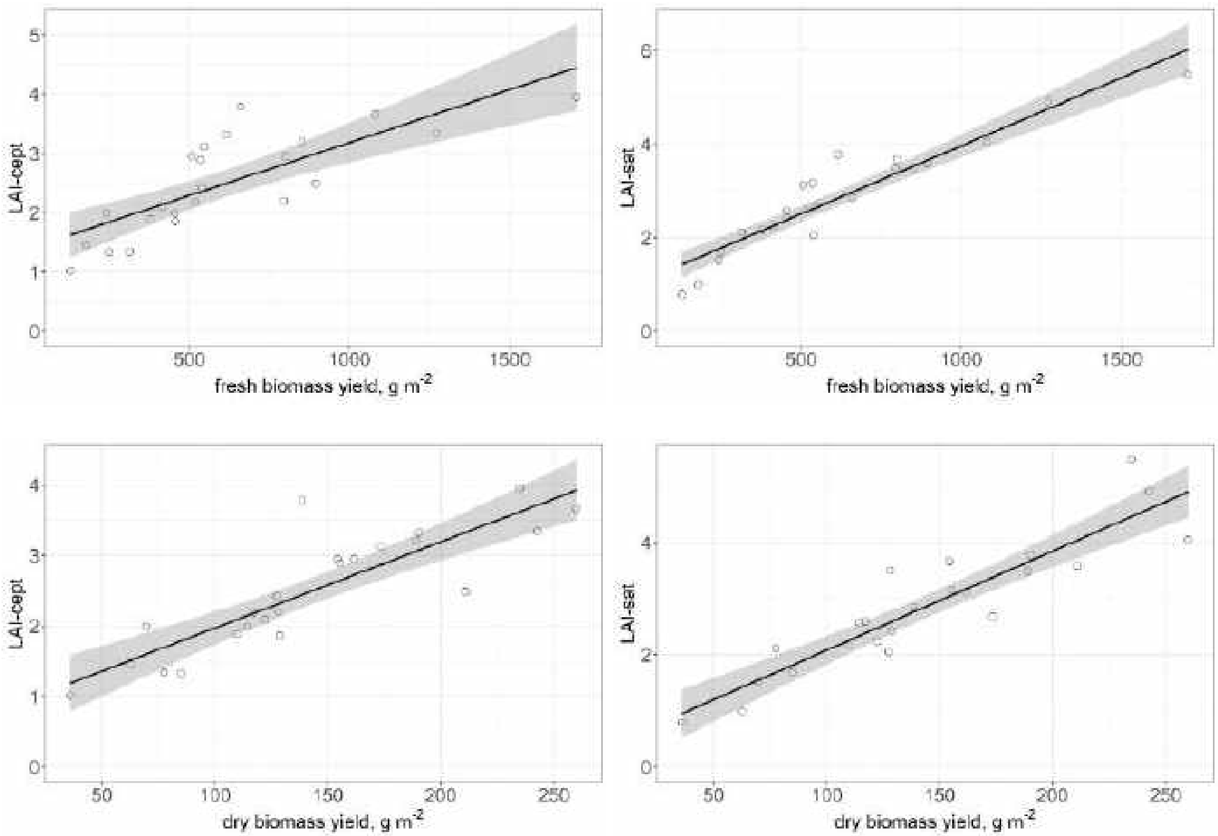

Figure 1. Correlation between in-situ measured LAI (left) and sensing-based LAI (right) and fresh biomass yield and dry biomass yield on semi-natural grassland in Noteć river valley

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Cumulative ground cover maintenance: what does it tell us about the grazing landscape and its management?

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Key words: Ground cover; grazing; land condition

Abstract

Two key challenges in rangeland management are determining the sustainability of management practices and the cumulative impact of those practices on the condition / health / productivity of the managed landscape. To this end remotely sensed cover products have been widely used in recent decades as there are no alternative products with a comparable spatiotemporal coverage and resolution.

We trialled a new approach to remotely assess land condition and management sustainability using ground cover data. The method first benchmarks Spring ground cover per pixel against local ground cover values within the land type (regional comparison (RC)). RC is a useful ground cover benchmark because it accounts for impact of land type and rainfall history on ground cover at any site. We then model Spring RC values based on the RC value of the previous Spring and recency of fire (a driver of ground cover not well accounted for by RC). We interpret the predicted quantile of any model prediction (GCM) as an index of how well the RC value has been maintained over that year at the site.

If annual GCM values do indicate how well ground cover has been maintained within the year, it is possible that long term consistency in GCM values (high or low) may highlight the broader sustainability of the management system (e.g. management that maintains ground cover probably also limits erosion and promotes desirable pasture species). Furthermore, more sustainable management systems might indicate places of high and/or improving land condition. This poster explains how the GCM layers were developed and tests the idea that they could be a useful tool to map both the historical sustainability of management systems as well as their impacts on land condition.

Introduction

Two key challenges in rangeland management are determining the sustainability of management practices and understanding their cumulative impact on the condition / health / productivity of the managed landscape. In the Australian rangelands, the sustainability of grazing management practices impacts the landscape through changes in the composition and amount of ground cover present in the landscape. Consequently, remotely sensed ground cover (GC) data – green and non-green cover such as described by the Queensland Government & Joint Remote Sensing Research Program (2022) – has been used widely in recent decades to track landscape change. Management practice impacts other landscape outcomes as well (e.g. erosion, weed infestation) but there are no analogous remotely sensed datasets with a comparable spatiotemporal coverage and resolution as the existing GC archives to track these outcomes remotely.

One potential geographic identifier of sustainable management practices in grazing land is the consistent maintenance of GC at or above expected (taking into account recent climate and land type) (Beutel & Graz, 2022). If this was the case, and it was possible to quantify and map how well GC was maintained per year, then the cumulative quantum of maintenance could also be mapped and might well indicate the longer-term sustainability of management at any location, at least as far as GC levels are concerned.

Beutel and Graz (2022) trialled this approach by modelling annual change in GC across a section of the Queensland rangelands. That study modelled annual change in ground cover using a large multivariate model and then used the quantile of observed change for any pixel (hereafter GCM: ground cover maintenance score) within its modelled prediction interval to benchmark the observed change for that year. They concluded that cumulative GCM (CGCM) values had some correlation with grazing land condition (Chilcott et al., 2003), but that the GCM model needed to incorporate the impact of fire history and better predict change in GC to fully test the relationship between land condition and CGCM.

Objective

In this study, we developed and tested an alternative approach to generating GCM map layers. The new method models annual change pixel regional comparison (RC) values rather than change in raw ground cover values. Regional comparison values (Beutel et al., 2021) take into account rainfall and land type so were seen as a potentially better target to model than raw GC. The new layer development also incorporates fire recency into GCM calculations. We describe the development of these new GCM layers and their relationship with land condition at a set of sites in Queensland.

Methods and results

Study area

The study area encompasses the Burdekin, Fitzroy and Burnett-Mary catchments, covering around 350,700km^2 in Queensland, Australia (Figure 1). Rainfall in the area is highly variable - between 500 and 1,300 mm annually across the region. Around 175 different land types have been identified in the study area (Department of Agriculture and Fisheries, 2022), many of which are subject to intermittent burning.

Data processing

Our method generated two raster data sets to align with the 30x30m Landsat imagery. We first built seasonal regional comparison (RC) rasters for the study area for each Spring (2014-2023). These images map ground cover quantiles (0 to 100) by comparing cover in each pixel to other pixels in the same land type (Department of Agriculture and Fisheries (2022)) within a 20 km radius. Higher RC pixel values indicate relatively higher levels of ground cover within the land type and local area. Each RC image is thus a point-in-time evaluation of ground cover given the land type, as well as recent local climate and management histories.

We generated a corresponding second set of GCM images to rank annual change in RC values. A quantile random forest model was used to predict RC per pixel for each Spring from two variables: the previous Spring's RC value and the number of months since the most recently mapped fire (fire recency). Fire recency data were based on Collett (2021) and van den Berg (2021), and were included because Beutel and Graz (2022) showed the dramatic impact of fire recency on their GCM images. The model accounted for 51% of the variance in annual RC change, of which $<2\%$ was contributed by inclusion of the fire recency data. The resulting GCM image values range from 0 to 100 and we interpret them as indicative of how well ground cover was maintained after fire recency and starting RC values were accounted for.

Analysis

Assuming that each annual GCM image reflects how well ground cover was maintained in that year, we tested whether cumulative GCM values might correspond to longer term management outcomes. We built cumulative GCM images (CGCM) by averaging annual values per pixel for the period 2015-2023. We then extracted mean CGCM pixel values at 2,220 sites where land condition had been assessed in 90x90m plots between 2021 and 2023, and compared the mean CGCM values allocated to different land condition classes. The boxplot of CGCM scores for each land condition class is shown below (Figure 2). It shows that CGCM differentiates the D (very poor) condition class quite well from others, but better condition classes, particularly A and B, are very similar in terms of CGCM scores.

Discussion

This paper outlines the development of a new version of GCM mapping. This version was built using a different approach to Beutel and Graz (2022); GCM values were based here on the regional comparison methodology rather than modelling GC in a complex multivariate modelling process. This new work also considered fire recency, which was absent from the original analysis.

Our test of whether CGCM values might predict land condition showed CGCM has some potential for mapping D condition but does not discriminate other condition classes very well. D condition sites are typically the easiest to identify remotely because they most often have very low GC levels. As such, it is not surprising that D condition sites were easiest to discriminate using CGCM. The approach may have worked better on other condition classes had we used a longer cumulative period than 2015-2023 or had our model accounted for more of the variance in annual RC change. It is possible too though that CGCM can't discriminate higher land condition classes. Higher classes of condition result more often from change in vegetation composition than GC, and since CGCM is derived from GC imagery, it may lack sufficient capacity to indicate changes in composition.

In this work we were interested in the idea that CGCM might be a tool to map the longer-term sustainability of management practices. We used land condition as a surrogate for management outcomes because these data were available to us. In doing this though we implicitly assumed that more sustainable management systems should have better land condition. This is not always true though. For example, where the management system has recently changed (e.g. through succession or sale) current land condition is likely more due to previous than current management practices, and very poor condition (D) is resistant to most management changes (Chilcott et al. 2003) so may persist through multiple managers and management systems. In summary, land condition may have some relationship to CGCM at the poorer end of the land condition spectrum, but it may not be the best surrogate to test the connection between CGCM and the sustainability of recent management.

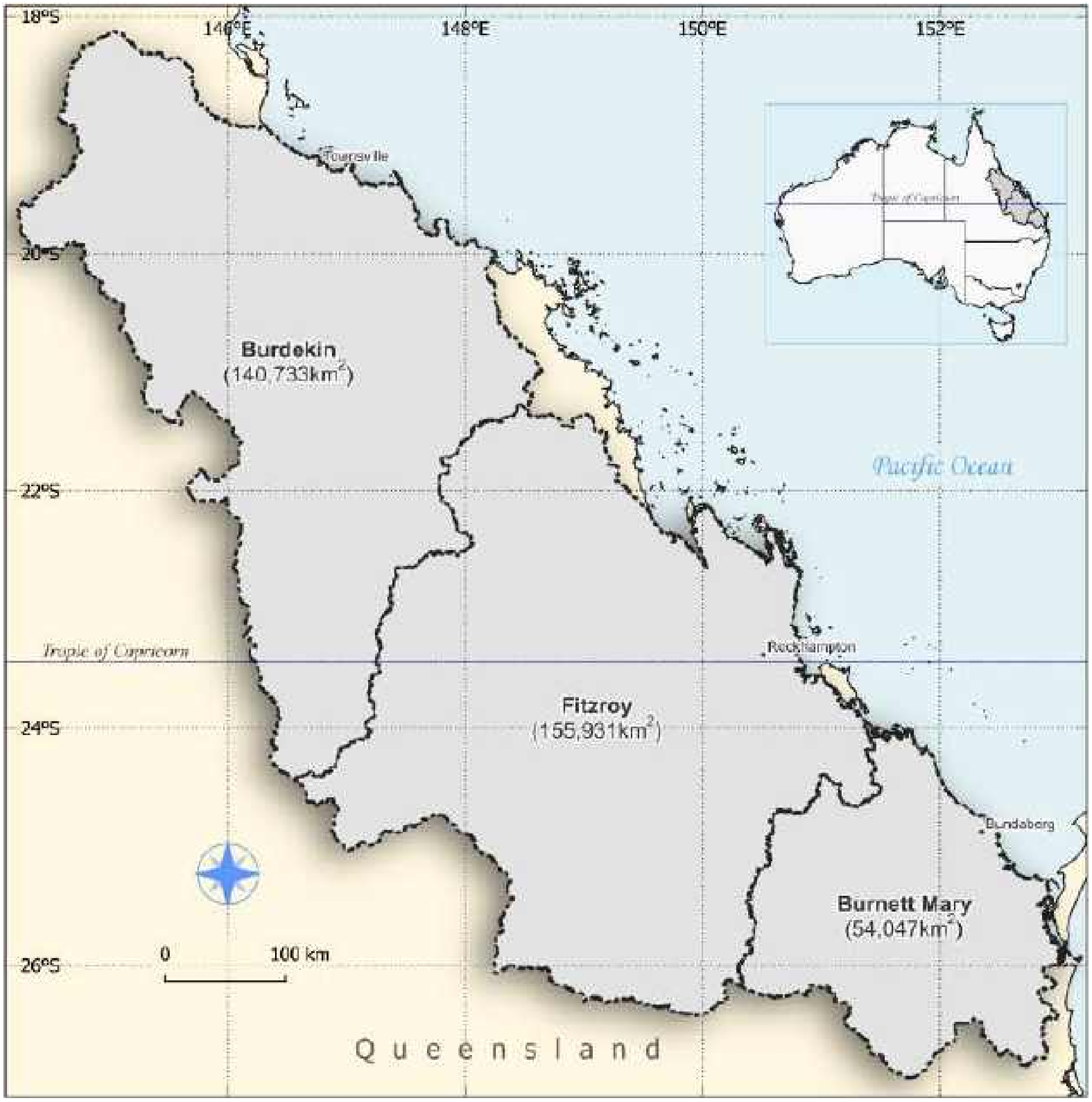

Figure 1. Location of the study area.

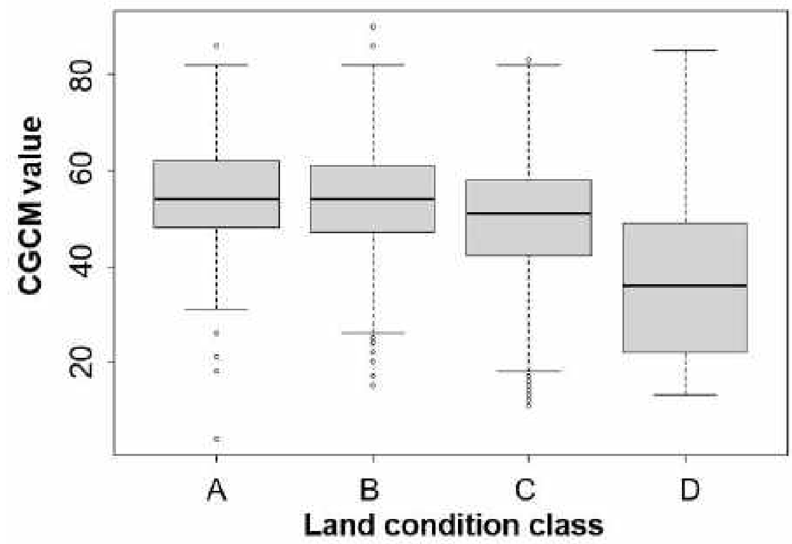

Figure 2. Cumulative (mean) GCM values for different land condition classes on 2220 land condition assessment sites in the study area.

Conclusion

This work is part of a larger project investigating different ways to model Queensland's rangeland health and productivity. This test of the GCM approach suggests that the method may not predict land condition reliably, but we plan several other uses and evaluations of the GCM methodology and products.

Acknowledgements

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There's an app for that: development of a decision support tool for the management of Twolined Spittlebug on Hawaii rangelands

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Key words: Rangelands; Pest Management; Decision Support Tools

Abstract

Twolined spittlebug (TLSB), *Prosapia bicincta*, was detected in Hawaii in 2016 where it had damaged over 2,000 acres of rangeland. Research revealed that TLSB expanded its range to over 178,000 acres in approximately six generations. In highly infested areas, TLSB resulted in nearly 100% die back of key range grasses including Kikuyu (*Pennisetum clandestinum*) and pangola (*Digitaria eriantha*) grasses when nymph densities exceeded 50/m^2. The loss of these important forages provided entry for the establishment of invasive plants including Pamakani (*Eupatorium adenophorum*), wild blackberry (*Rubus* spp.), and fireweed (*Senecio madagascariensis*) among others. These losses forced livestock producers to reduce stocking rates resulting in significant economic losses. Work on a smartphone application to identify, report, and facilitate management of the TLSB started in 2020. The app has four main features. First, an information guide provides an overview of TLSB biology and ecology. Next, the app provides a tool to help users identify TLSB in the field and distinguish it from other, non-pest species. A third tool allows users to report sightings of TLSB. Reports include a geo-referenced picture and basic details about the habitat and geographical location of the pest. The reported data is then captured in a database and displayed on a web-based mapping tool. Users have the option to enter data on TLSB population density and provide estimates on spatial extent and observed damage in their report. Data on TLSB populations is determined by following sampling protocols provided in the fourth tool. This tool allows users to determine the size of the TLSB population, and then, based on the potential damage threshold calculated, select from a series of integrated pest management decisions. It is anticipated that this app will facilitate tracking and documenting the spread of the pest and lead to better pest management decisions for rangeland managers.

Introduction

Twolined spittlebug (TLSB), *Prosapia bicincta* (Say), a pasture and turfgrass pest native to southeastern United States (Shortman et al. 2002, Thompson and Carvalho 2016), was detected in the South Kona district of Hawai´i Island in 2016 (Wilson et al. 2023). The pest negatively impacts rangelands by feeding on important forage grasses (Byers and Wells 1966, Shortman et al. 2002, Wilson et al. 2024). Our research found that between 2017 and 2020 the pest rapidly expanded its range at rate of over 14,000 ha per year and by the end of 2021 occupied over 72,183 ha across the South Kona district in just six generations (Wilson et al. 2023).

The Hawai´i beef industry is economically, culturally, and ecologically important to the state. Over 142,000 head of beef animals are managed across nearly 300,000 acres of rangelands (20% of Hawai´i's land mass) that are managed by over 1,300 ranches. The value of Hawai´i-raised beef cattle is estimated to be more than $48 million annually (USDA-NASS 2022). Over 60% of the beef cattle in the state are raised on the island of Hawai´i where the TLSB currently poses the most significant threat.

In highly infested areas, TLSB resulted in nearly 100% die back of key range grasses including Kikuyu (*Pennisetum clandestinum*) and pangola (*Digitaria eriantha*) grasses when nymph densities exceeded $50/m^2$ (Wilson et al. 2023). The loss of these important forages provided entry for the establishment of invasive plants including Pamakani (*Eupatorium adenophorum*), wild blackberry (*Rubus* spp.), and fireweed (*Senecio madagascariensis*) among others. Twolined Spittlebug's rapid rate of spread and devastating impact on important forage grasses in the South Kona district forced livestock producers to reduce stocking rates resulting in significant economic losses.

In 2020 we started development of a smartphone application to provide livestock producers struggling to manage rangelands in the wake of TLSB infestations a decision support tool. The app was designed with four main user portals. The first portal was an information guide that provided an overview of TLSB biology and ecology. Next, the app provided portal to help users identify TLSB in the field and distinguish it from other, non-pest species. A third portal allowed users to report sightings of TLSB. The fourth portal allowed users to determine the size of the TLSB population, and then, based on the potential damage threshold calculated, select from a series of integrated pest management decisions.

The user reporting portal was designed to facilitate tracking TLSB infestations and distribution. User reports included a geo-referenced image of TLSB nymph or adult, and basic details about the habitat and geographical location of the pest. Users also had the option to enter data on TLSB population density and provide estimates on spatial extent and observed damage in their report. The reported data was then captured in a database and displayed on a web-based mapping tool that was managed by the TLSB research team and yielded important information on the distribution and intensity of infestations, as well as early detection of incipient TLSB populations.

Methods

The purpose of the Twoline Spittlebug (TLSB) smartphone (mobile) application was twofold. First the app would provide a mechanism for users to report positively identified sightings of the pest to the TLSB research team (reporting tool). This information would assist researchers in understanding and mapping the distribution and density of TLSB populations, intensity of infestations, and early detection of incipient infestations. The second intent of the TLSB mobile app was to provide the user, and specifically, affected land managers, information on TLSB habitat, biology, and ecology (information tool), a means of proper identification (identification tool), and a decision support tool for the management of TLSB infestations.

We desired the TLSB mobile application to be available to users on both Android and Apple smartphones. When considering options for programming of the mobile application software we evaluated the advantages and disadvantages of three options: 1) University of Hawaii-Manoa computer science student led development; 2) in-house University of Hawaii-Manoa Informational Technology led development; and 3) professional smartphone application company development. Although the more expensive option ($33,024 mobile app programming, $8,192 administrative website development), the complexity of the mobile application functions we envisioned led us to select working with a professional mobile application software company (Zco Corporation, 58 Technology Way, Suite 2W10, Nashua NH 03060). Static and dynamic data content for the four mobile application portals (information, identification, reporting, and management decision support) were developed from our research on the ecology, biology, and impact of the TLSB on Hawai´i rangelands (Wilson et al. 2023, Wilson et al. 2024). Development of the mobile application began in August of 2020 and was completed in September of 2022.

Information Portal

The purpose of the TLSB mobile application information portal was to provide users with basic information on the habitat, biology and ecology of the pest. This information was static within the mobile application. The information in this portal included background information on the three species of spittlebugs found in Hawai´i including the Twolined Spittlebug, Meadow Spittlebug, and Sunflower Spittlebug. Only the TLSB causes significant damage to Hawai´i rangeland grasses thus recognition of the differences between the spittlebug species are critical to proper management decisions for the control of TLSB. Additionally, the information portal provided users with a general description and development of the three life stages of TLSB (egg, nymph, and adult). The biology and ecology of these three life stages are critical to successful management of the pest in Hawai´i rangelands. Pictures of the three spittlebug species, TLSB life stages, and damage from the pest were provided for visual reference for the user. Finally, links to the other portals (identification, reporting, and management decision support) were provided to guide the user on the use of the mobile application.

Identification Portal

The purpose of the pest identification portal was to provide a process through which the user could positively distinguish TLSB from the other two species of spittlebug found in Hawai´i, and through a positive identification of TLSB, provide an accurate report through the mobile application reporting portal. The identification portal was designed using static information organized as a dichotomous key to guide the user in evaluating spittlebug specimens in the field following Thorne et al. 2022.

Reporting Portal

The purpose of the reporting tool was to provide users a mechanism to report sightings of TLSB that could be verified and mapped providing researchers with critical data on the pest distribution, infestation intensity, and early detection of incipient populations, and provide feedback to users of the mobile app on the distribution and spread of the pest on lands they manage.

The reporting portal was designed to provide a geo-referenced data and picture cache of sightings of adult and/or nymphs by application users. Data collected included a geo-referenced photograph and descriptive information, date, time, and location description of reported sightings. Reported data were cached in an administrative website database and used to verify and map sightings. The map generated was viewable on the administrative website public facing map minus personal/landowner identification information.

Management Decision Support Portal

The purpose management decision support portal was to provide information to the mobile app user, and particularly those landowners affected by TLSB, a decision supported process to assess the level of damage and take economically feasible management actions. Static and dynamic information and data were used in the development of the portal functions with most being created specifically for the functionality of the management decision support portal or modified from existing information. Static information included descriptions of sampling protocols to guide users in determining nymph population densities and/or adult abundance, integrated pest management protocols, and monitoring guidelines for TSLB free areas, known areas of TLSB activity, and areas recovering from TLSB damage. Dynamic data included a scale for determining nymph age class, calculators for quantifying average nymph density by age class or adult abundance, a selection tool to estimate the percentage of area affected (0-25%, 26-50%, 51-75%, or 76-100%), and a cell to enter the total acreage of land affected. Sampling and monitoring protocols, based primarily on quantifying TLSB nymph densities and adult abundance were modified for the mobile application from field sampling protocols described by Wilson et al 2023.

Results and Discussion

Nymph Density by Age Class and Damage Threshold Rating

Assessment of the five TLSB instar stages indicated that the stage one and two, and three and four, could be combined into two age classes based on sharp distinctions in width and length (Table 1). Instar five, comprised a single and final age class for nymph development toward adulthood. Approximate days to adulthood, by age class was derived based on a 50-day egg to adult development of the nymphal stage and divided across the three age classes (Table 1). A tool within the mobile application assists the user in determining age class. The count of nymphs per age class are then input into an in mobile application calculator that yields an average nymph density by age class.

Field data relating nymph densities to observed pasture damage following adult emergence (Wilson et al. 2023, Wilson et al. 2024) were classified as light (< 10 nymph/m^2), medium (11-59 nymph/m^2), and critical (> 60 nymph/m^2) based on expected forage loss. These data were combined with the nymph density by age class and expected days to adult hood to derive a Damage Threshold Rating Scale (Table 2). Damage ratings (1-3) were linked to specific IPM recommendations.

Table 1. Twolined Spittlebug Age Classes (1, 2, or 3) with dimensions and expected days to adulthood.

Age Class	Age class dimensions (mm)		Approximate Days Expected to Adult
	Width	Length	
1	< 0.6 mm	< 2.1 mm	More than 35 days
2	1.0 -1.4 mm	2.1-5.2 mm	Between 15 and 35 days
3	>1.5 mm	> 5.3 mm	Within 15 days

Note: Approximate Days Expected to Adult assumes an average 50 days from egg hatch to adult and an even development rate of 10 days between instar stage and selected to be the half-way point between classes in days.

Table 2. Age Class distribution and Expected Days to Adult by Nymph Density estimates in relation to Potential Future Damage. Yellow (damage level 1) light to moderate forage loss; Orange (damage level 2) moderate to heavy forage loss; Red (damage level 3) heavy to catastrophic forage loss.

Age Class	Nymph Density/Potential Future Damage			Expected Days to Adult
	< 10/ m2	11-59/m2	> 60/m2	
1	1	2	3	More than 35
2	1	2	3	15-35
3	2	3	3	Within 15

Integrated Pest Management Strategies

Integrated Pest Management practices for the control of TLSB in Hawaii rangelands includes intensive grazing management and strategic applications of recommended pesticides. With increasing damage from adult TLSB feeding, additional measures include using herbicides to control emerging weeds, and reseeding with TLSB resistant forages. Recommendations on specific IPM measures to employ depend on the expected level of impact and progress from intensive grazing management (applied for damage ratings 1-3), strategic pesticide applications (applied for damage ratings 2-3), to weed management and seeding TLSB resistant grasses (applied at damage rating 3). Within the mobile application, the user is directed to a specific IPM recommendations depending on the calculated damage rating from their input data.

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Rapid assessments of herbage biomass and quality using field hyperspectral (HS) measurements with 1D-CNN

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Key words: Deep learning; forage quality; grassland management; remote sensing

Abstract

Assessments of herbage biomass and forage quality using field hyperspectral (HS) sensing provide valuable support to farmers in making precise forage management decisions. The field HS data, which includes measurements of canopy reflectance in the visible and near-infrared wavelength range (400-2350 nm), has been extensively studied in grassland assessment research. Partial least squares (PLS) regression has been widely adopted as a standard calibration method for estimating herbage biomass (BM) and determining forage quality parameters, such as crude protein (CP) and neutral detergent fiber (NDF) concentrations. In this study, a one-dimensional convolutional neural network (1D-CNN) model was developed as a non-destructive and rapid method for evaluating forage composition. The relationships between HS measurements taken on the ground and forage components obtained through harvest and chemical analysis at ground level were analyzed. The dataset in the orchard grass-dominated meadow field consisted of 200 samples from seven fields in three regions of Hokkaido, Japan, surveyed prior to the first grass harvest in May/June 2023. Overall, the 1D-CNN models showed better predictive accuracies for most parameters (BM, CP, and NDF) than standard PLS regressions. The 1D-CNN model demonstrated a good predictive accuracy ($R^2 = 0.950$) for BM, but less accurate predictions for concentrations of CP ($R^2 = 0.650$) and NDF ($R^2 = 0.506$). However, when the content in percentage was converted to standing mass (g/m²), high predictive accuracies in CP mass ($R^2 = 0.814$) and NDF mass ($R^2 = 0.837$) were achieved. These results are expected to contribute to the advancement of forage management by enabling rapid and accurate evaluation of forage components.

Introduction

In Hokkaido, Japan's largest feed-producing region, the environmental impact of excessive fertilizer application on grassland ecosystems has become a significant concern (Takeda 2001). In the meadow fields, issues such as weed invasion and soil degradation diminish the nutritional value of forage grasses, adversely affecting livestock health and productivity (Nishida 2002; Otsuka 1995). These factors also contribute to spatial variation in grass yield and forage composition. Grass forages, including orchardgrass (OG; *Dactylis glomerata* L.) and timothy (TY; *Phleum pratense* L.), along with legume forages such as white clover (WC; *Trifolium repens* L.), red clover (RC; *T. pratense* L.), and alfalfa (AL; *Medicago sativa* L.) are widely utilized in Hokkaido (Yamada 2009). Consequently, the rapid and accurate evaluation of the nutrient composition of these forages is essential for maintaining livestock health and productivity (Coleman and Moore 2003).

To address these challenges, remote sensing technology, using satellites and drones, has been increasingly employed as a diagnostic tool to evaluate grass resources and vegetation conditions across extensive areas quantitatively (Kawamura et al. 2012). Among these technologies, hyperspectral (HS) remote sensing technology, which measures continuous wavelengths in the visible to near-infrared (NIR) spectrum, has proven to be a powerful method for estimating the nutritional value of forages in the field (Zarco-Tejada 2000). Specifically, field HS measurements at canopy scale employs spectral analysis that is sensitive to the unique structural and chemical characteristics of these plant communities, allowing for the successful estimation of herbage biomass (BM), crude protein (CP), neutral detergent fiber (NDF), and other quality-related parameters (Lim 2016; Pullanagari et al. 2012).

In HS data processing and laboratory NIR spectroscopy, partial least squares (PLS) regression has been widely employed to estimate herbage BM and forage quality status (Marten et al. 1983). However, existing models are dataset-dependent and cannot be universally applied to different pastures. Therefore, it is necessary to develop a new model for each grassland (Fernández-Habas et al. 2022). In contrast, deep learning enables highly accurate estimation independent of data, allowing a single model to be applied to different meadow fields. Consequently, the objective of this study was to develop a nondestructive and rapid estimation model of herbage BM and forage nutritive status (CP and NDF) through deep learning by examining the relationship between field HS data and herbage BM or forage quality conducted prior to the first grass cutting in seven OG-dominated meadow fields in Hokkaido, Japan. In the present study, a one-dimensional convolutional neural network (1D-CNN) (Kawamura et al. 2021) was utilized for deep learning and compared with PLS.

Methods

Field surveys were conducted across seven meadow fields of OG-legume mixtures at three research institutions: (1) Obihiro University of Agriculture and Veterinary Medicine (OBH), (2) NARO Hokkaido Agricultural Research Center (HRC), and (3) Rakuno Gakuen University (RGU) in Hokkaido, Japan (Figure 1). Both RGU, located in Ebetsu City, and HRC, located in Sapporo City, are in a region characterized by a harsh, cold, and snowy climate. The Obihiro City area in Tokachi, while experiencing less snowfall than Sapporo and Ebetsu during winter, encounters lower temperatures. According to data from the Japan Meteorological Agency's Automated Meteorological Data Acquisition System (AMeDAS), the mean annual temperatures in 2023 were recorded as 10.95°C in Sapporo, 8.89°C in Ebetsu, and 7.16°C in Obihiro. Additionally, annual precipitation in these cities was recorded as 966, 965, and 919 mm, respectively.

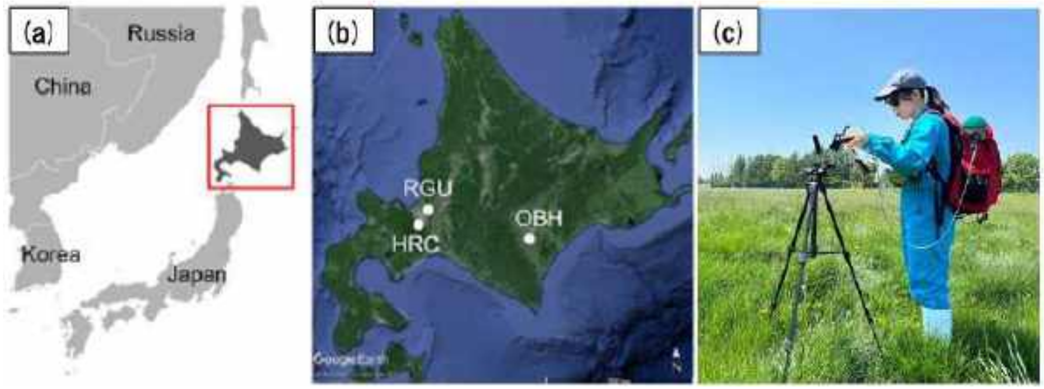

Fig 1 Location of Hokkaido, Japan (a) and three research institutions (b) with a photograph depicting the field HS measurement at HRC (c).

Field surveys were conducted between May 16 and May 29, 2023, during wich 200 samples were obtained. An ASD Fieldspec 4 Hi-Res spectroradiometer (Malvern Panalytical Ltd., UK) was employed to acquire field HS data (350–2500 nm). The sensor head was held approximately 50 cm above the canopy at the nadir position. The spectroradiometer had a 25° field of view (FOV), producing a view area with a 22 cm diameter at the canopy level.

Following the field HS measurements, grass height (5 points) was recorded and averaged as a surface sward height (SSH) within randomly placed quadrats (50 cm × 50 cm) in the field, and aboveground biomass was harvested at 0 cm above the ground surface. Grass samples were classified into five groups: OG, kentucky bluegrass (KB; *Poa pratensis* L.), legumes (WC + RC + AL), weeds, and dead materials, then dried in a dryer at 65°C for 72 hours and weighed for dry matter weight (g DM/m^2). Herbage BM was computed as the sum of the values for OG, KB, legumes, and weeds. Chemical analyses were then performed at the Federation of the Tokachi Agricultural Cooperative Association, Agricultural Product Chemical Research Laboratory.

Data preprocessing and PLS regression analyses were performed using Matlab software ver. 8.10 (MathWorks, Sherborn, MA, USA). In the development of the deep learning model, a one-dimensional convolutional neural network (1D-CNN) architecture was employed, which is suitable for one-dimensional spectral information. data set (n = 200) was sprit into training (80%, n = 160) and test (20%; n = 40) subsets. Then, the models were developed using training dataset, and the model accuracy was assessed using leave-one-out cross-validated R^2 and root mean squared error (RMSE). The predictive ability was evaluated using the test dataset.

Results

In PLS analyses, the cross-validated R^2 values indicated very low predictive accuracies (R^2= 0.095–0.266) andsubstantial errors, as denoted by the RMSE for herbage BM (111.343 g DM/m^2), CP (3.665%), NDF (7.351%), CPmass (21.167 g DM/m^2), and NDFmass (72.439 g DM/m^2), respectively.

The 1D-CNN models exhibited superior predictive accuracies for most parameters compared to standard PLS regressions. Specifically, the 1D-CNN model demonstrated commendable predictive accuracy (R^2 = 0.950) for BM, although it yielded less accurate predictions for the concentrations of CP (R^2 = 0.650) and NDF (R^2 = 0.506). In contrast, when the percentage content was converted to standing mass (g/m^2), high predictive accuracies were achieved for CP mass (R^2 = 0.814) and NDF mass (R^2 = 0.837).

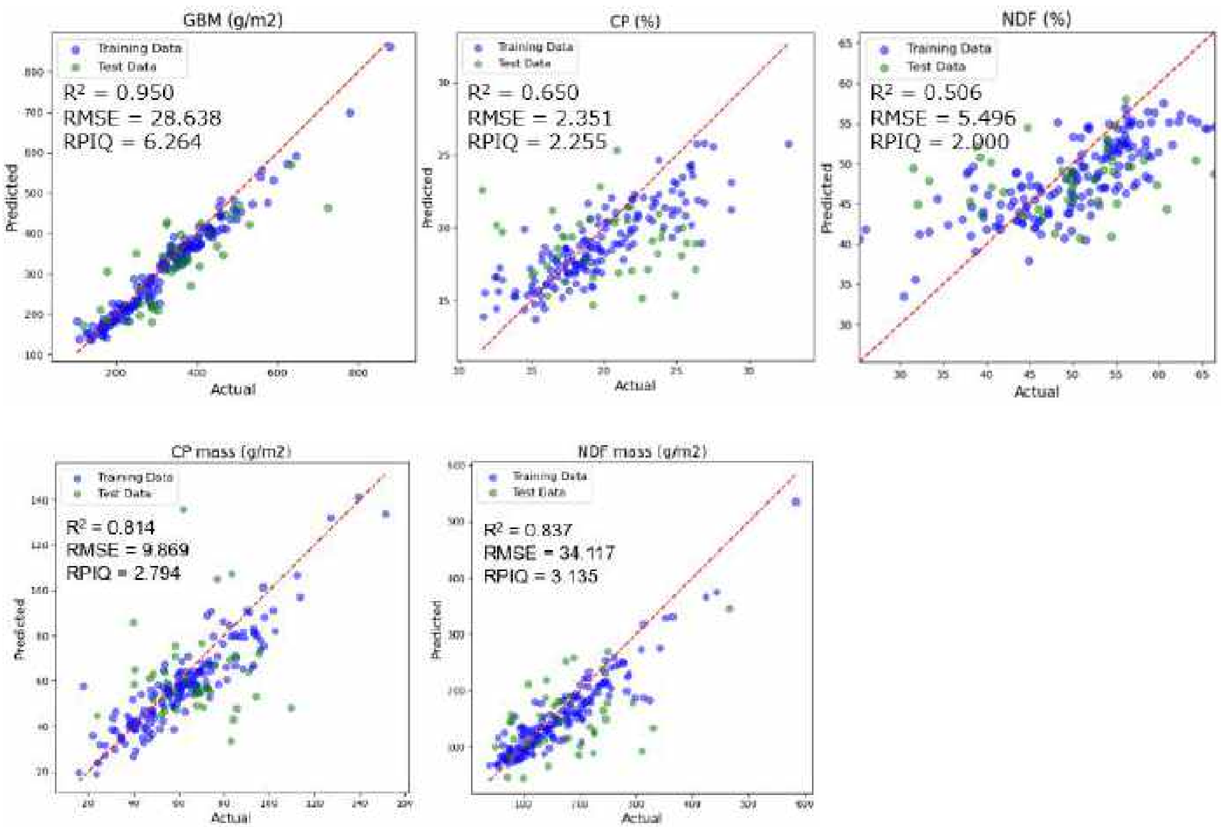

Fig 2 Relationships between observed- and predicted-values of herbage BM (a), CP content (b), NDF content (c), CP mass (d), and NDF mass (e).

Discussion

The PLS regression analysis conducted using the dataset collected from the seven fields did not exhibit the same level of estimation accuracy as observed in prior studies (Fernández-Habas et al. 2022). Conversely, the application of the 1D-CNN method from deep learning revealed a significant enhancement in predictive accuracy. Additionally, it has been suggested that the estimation accuracy for CP and NDF, which displayed low estimation performance, could be improved by converting these parameters into standing mass information.

These findings imply that the estimation accuracy can be enhanced through deep learning applied to the spectral data gathered from hyperspectral measurements utilizing 1D-CNN. Furthermore, the versatility of the model indicates its potential applicability across various fields. Moreover, given that the sensing data captures the surface reflectance of the plant community, it may be more advantageous to utilize standing mass over concentrations of CP or NDF.

In this investigation, we developed an estimation model to assess herbage BM and forage quality via deep learning from ground-based hyperspectral data. However, the dataset (n = 200) utilized in this study is relatively small in terms of data size for deep learning applications. Future efforts should focus on expanding the dataset to further enhance accuracy and versatility.

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AI modeling to predict vegetation diversity of protected rangelands in national parks

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Key words: AI; biodiversity; Lar National Park; MLP

Abstract

The impact of livestock and tourism on vegetation includes a reduction in biodiversity and in some instances, species extinction. To assess these stressor-effect relationships and provide a management tool for protected rangelands of Iran's Lar National Park, we created a multilayer perceptron (MLP) artificial neural network model to forecast vegetation diversity in relation to human activities. Recreation and restricted zones, representing areas with the highest and lowest human impact, were chosen as sampling sites. Vegetation diversity, indicated by the number of species, was recorded in 210 sample plots. Additionally, twelve landform and soil variables were documented and utilized in developing the model. Sensitivity analyses revealed that the intensity of human activity (in four classes of livestock and tourism population) and soil moisture were the most critical inputs affecting the MLP. The MLP demonstrated strong performance, with R2 values of 0.91 for training, 0.83 for validation, and 0.88 for test datasets. A graphical user interface was created to integrate the MLP model into an environmental decision support system for protected rangelands managers, allowing them to predict impacts and formulate proactive plans to manage human activities affecting vegetation diversity.

Introduction

In Iran, the primary objective of national park management is to mitigate the adverse effects of human activities, particularly tourism and livestock husbandry. These activities have been linked to a range of negative impacts on vegetation, including biodiversity loss, degradation of plant communities, diminished plant regeneration, and, in some cases, species extinction. Numerous studies have documented a decline in species richness with increasing human activity in grasslands. Moreover, livestock grazing and tourism have been shown to negatively impact plant regeneration and elevate the risk of extinction for certain species (Newsome et al. 2013). To address these challenges, mathematical and quantitative methods are essential for analyzing the conditions of national parks where human activities are causing vegetation degradation. Recent advancements have led to the development of mathematical models for environmental impact assessment (Jahani 2016), which consider both human activities and ecosystem characteristics. This study aims to apply a Multi-Layer Perceptron (MLP) neural network model to predict the effects of human activities, such as livestock grazing and tourism, on vegetation diversity in Lar National Park, Iran.

Methods

To evaluate the effect of human activities on vegetation diversity, sampling areas were strategically chosen to represent sites with maximum (recreation zone) and minimum (restricted zone) human impact. Two sampling grids were employed, resulting in the selection of 105 sampling locations across the study areas. Given that the restricted zone covered a larger area compared to the recreation zone, the sampling sites were more widely spaced in the restricted zone. The grid dimensions were 200 × 500 meters in the recreation zone and 600 × 500 meters in the restricted zone. Plant species were identified and counted within 2 × 2-meter sample plots at each sampling location, and the number of species recorded served as a measure of vegetation diversity.

Species identification in each plot was conducted using local plant identification resources (Lar National Park Group, 2012). Additionally, 12 landform and soil variables were recorded at each 2 × 2-meter sample plot, including altitude (m), plot slope (%), hill direction exposure (north, east, south, and west), soil depth (cm), percentages of clay, silt, and sand in the soil texture, soil organic matter content (%), soil electrical conductivity (dS/m), soil porosity (%), and soil moisture (%). Four qualitative classes of human activity intensity were estimated by local park rangers: 1) no presence of livestock and tourists, 2) sporadic presence of tourists, 3) intensive presence of livestock and tourists, and 4) intensive presence of livestock and tourists with overnight stays. These predictor variables were used to develop a model to estimate the expected vegetation diversity (species count) in the sample plots, which served as the model output.

The dataset was randomly divided into three subsets: a training dataset comprising 60% of all samples (126 samples), a validation dataset comprising 20% of all samples (42 samples), and a test dataset comprising the remaining 20% of samples (42 samples). The ANN function in MATLAB (2018) was employed to design the MLP model structure and test the outcomes.

Results

In this study, a total of 210 sample plots were analyzed to assess vegetation diversity in both the recreation zone (characterized by maximum human activities) and the restricted zone (characterized by minimal human activities). Various combinations of layers and neurons, along with different activation functions for both hidden and output layers, were tested to optimize the ANN. Initially, the optimization process involved experimenting with a hidden layer containing between 5 and 30 neurons, selected randomly. Subsequently, the performance of the MLP was evaluated in configurations with 2 and 3 hidden layers, each containing the same number of neurons.

During neural network training, different numbers of hidden layers and neurons per layer were explored. The coefficients of determination (R^2) indicate the accuracy of these networks in predicting vegetation diversity based on the input variables. According to the results, Model with a structure of 12-6-6-1 (12 input variables, 6 neurons in each of the hidden layers, and 1 output variable), achieved the highest R^2 values across the training, validation, and test datasets (0.95, 0.87, and 0.93, respectively). This model demonstrated the best performance in structure optimization.

The MLP model demonstrated exceptional accuracy in predicting vegetation diversity in national parks, with the optimal network achieving a coefficient of determination (R^2) of 0.88 during the test phase. This indicates that the MLP is highly effective for assessing human impact in areas where vegetation cover is most affected by human activities. Consequently, a sensitivity analysis was conducted on the predicted outputs of the optimal MLP. Figure 1 highlights the sensitivities of the MLP to various input variables, revealing that the intensity of human activities and soil moisture were the most influential factors affecting the MLP's outputs.

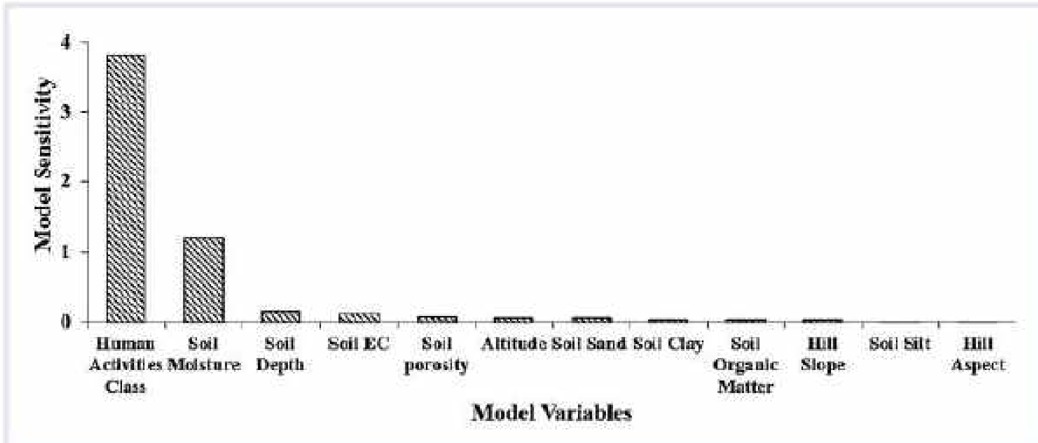

Figure 1: Sensitivity analysis of MLP model for prediction plant diversity

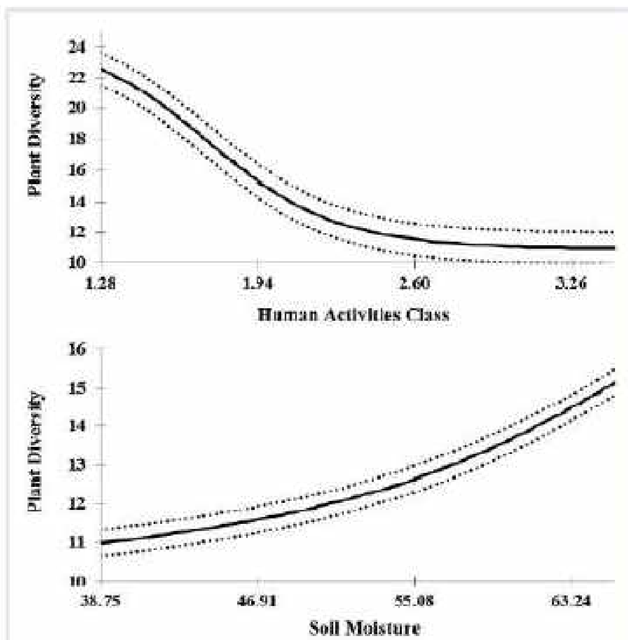

Figure 2: The trend of plant diversity changes in respond to human activity class and soil moisture.

The sensitivity analysis results show that the intensity of human activities and soil moisture had the greatest impact on vegetation diversity. Figure 2 illustrates that as the intensity of human activities increases, vegetation diversity declines; specifically, a 2-unit increase in activity intensity leads to a 10-unit decrease in vegetation diversity. This means that higher levels of human activity result in a significant reduction in the number of plant species observed in the sample plots. Additionally, an increase in soil moisture correlates with a rise in vegetation diversity—specifically, a 25% increase in soil moisture leads to an approximately 5-unit increase in vegetation diversity. Thus, higher soil moisture levels contribute to an increase in the number of plant species in the area.

Discussion [Conclusions/Implications]

In this study, an MLP model was developed to predict how human activities affect natural vegetation diversity. The goal is to aid managers in estimating the potential impact of human activities while balancing ecological conservation goals in national parks. Using MATLAB (2018) and appropriate validation techniques, the model described here is applicable to areas with ecological conditions similar to our study area in Iran. For regions with different ecological conditions, the model can be adapted by incorporating new data sets. From a planning perspective, areas with higher soil moisture are better able to withstand human activities and are more likely to recover quickly. This should be considered in national park management planning. The data used in this study are robust, consisting of 210 sample plots that provide reliable information on the impact of human activities and land properties, which were used to develop the quantitative model for predicting vegetation diversity.

Human activities have been used as variables in predicting environmental impacts to inform management decisions. Jahani et al. (2016) previously assessed the accuracy of neural network models in evaluating forestry impacts using the optimized forest degradation model (OFDM) with MLP, applied to predict forest degradation from human activities like livestock grazing and tourism.

Our study highlights the influence of both human activities and habitat conditions on vegetation diversity. De Vries et al. (2010) argue that expert-based models estimate plant diversity responses to environmental variables. Models developed for specific regions like the Netherlands (Wamelink et al. 2005) have shown promise, emphasizing the importance of measuring variables such as landform, soil acidity, and nutrient and water availability. Our research, alongside Jahani et al. (2020), found that soil organic matter and moisture are crucial factors influencing plant diversity after human activities.

In Lar National Park, tourist activities tend to compress soil and vegetation, making shrubs more sensitive to human activities than herbaceous plants (Whinam and Chilcott 2003). Soil conditions, such as moisture and nutrient availability, affect vegetation damage and ecosystem regeneration potential. Soils with higher moisture support greater plant diversity (Whinam and Chilcott 2003), which aligns with the MLP model's sensitivity analysis results. For example, a 25% increase in soil moisture (from 38% to 63%) could lead to an additional 4 plant species (11 to 15) in the habitat. Given that soil moisture in Lar National Park ranges from 25% to 80%, our model effectively assessed the impact of soil moisture on plant diversity.

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Evaluating the spatial distribution of cattle dung pats from UAV images in grazing ecosystems

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Key words: Deep learning; drone; grazing management; smart farming

Abstract

Livestock excretions play a crucial role in nutrient cycling within pasture ecosystems. However, traditional field observation methods require significant human effort and time. In this study, we developed the Dung Detector (DD) model, which utilizes unmanned aerial vehicle (UAV) images and the You Only Look Once (YOLO) v5 object detection approach, to identify cattle dung in pastures. We have also evaluated the spatial distribution of cattle dung pats in these pastures. The DD model consists of five paddocks, namely Obihiro (OBH), Shintoku (STK), Minokamo (MNO), Miyota (MYT), and Yatsugatake (YGK). A custom dataset containing 1,504 images segmented from UAV orthomosaic images was used for training. The accuracy of the DD model was assessed by comparing it with ground truth data obtained from 2-3 quadrats (10 m × 10 m) in each paddock. Accuracy (F-score) of the DD model in each plot ranged from 0.432 to 0.861, with better results observed in paddocks characterized by simpler grass species and lower surface grass height (SSH). The spatial distribution of cattle dung pats detected by the DD model showed a heterogeneous distribution pattern within the plots due to differences in where grazing livestock stayed due to fences, shaded forests, and water troughs.

Introduction

Cattle dung in pastures constitutes a critical source of soil nutrients; however, it also significantly contributes to greenhouse gas (GHG) emissions, particularly methane (CH_4) and nitrous oxide (N_2O) (Cai and Akiyama, 2017; Lombardi et al. 2022). The application of nitrification inhibitors, such as dicyandiamide (DCD), has been proposed as a mitigation strategy for these emissions; nonetheless, the application process can be costly and labor-intensive when employed across extensive agricultural fields (Betteridge et al. 2010). Additionally, cattle foraging behavior results in an uneven distribution of dung, particularly in hilly grassland environments (Yoshitake et al. 2014). The real-time mapping of dung distribution could enable targeted application of DCD, thereby contributing to the reduction of GHG emissions.

Current methodologies for monitoring cattle defecation, including global navigation satellite system (GNSS)-based technologies, are encumbered by limitations in battery life and overall usability (Watanabe et al. 2019). Drones have emerged as a promising alternative for the detection of cattle dung, with investigations demonstrating their ability to identify fresh dung based on color and shape. However, challenges remain in detecting older dung, especially within heterogeneous pasture ecosystems where soil coloration may closely resemble that of dung (Yoshitoshi et al. 2015). Geographic object-based image analysis (OBIA) presents potential avenues for improvement; nonetheless, it is also constrained by factors such as site-specific dependency and limited versatility (Blaschke, 2010).

In response to these challenges, the present study employs a deep learning-based object detection methodology to enhance accuracy and adaptability. Among the various algorithms available, YOLO (You Only Look Once) is particularly notable for its efficiency and widespread application in agricultural contexts, including weed and cattle detection (Ahmad et al., 2021; Gallo et al., 2023). The "Dung Detector (DD)" model was developed utilizing YOLOv5, which was selected for its robust performance and adaptability. This model was trained on a custom dataset specifically tailored to drone imagery of cattle dung, thereby addressing the existing gap in available datasets.

Methods

The study was conducted in June-July, 2022 across five pastures in Japan: Obihiro (OBH), Shintoku (STK), Minokamo (MNO), Miyota (MYT), and Yatsugatake (YGK) (Figure 1; Kawamura et al. 2024). These locations include two permanent grazing paddocks (OBH, MNO) and three rotational grazing paddocks (STK, MYT, YGK), with sizes ranging from 0.59 ha (OBH) to 3.72 ha (STK). Terrain varied from flat (OBH, slope = 1.0°) to hilly (MYT, slope = 8.7°), with slopes calculated using 5-m mesh digital elevation models (DEM5A and DEM5B) published by the Geospatial Information Authority of Japan (https://fgd.gsi.go.jp/download/ref_dem.html).

Fig 1 Location of five target paddocks: (a) Obihiro (OBH), (b) Shintoku (c) Minokamo (MNO), (d) Miyota (MYT), and (e) Yatsugatake (YGK) (Kawamura et al. 2024). White letters at the bottom of the pictures are

the dominant grass species of the paddock and the survey dates. KB, Kentucky bluegrass (*Poa pratensis* L.); DC, *Digitaria cilaris* (Retz.) Koeler; OG, Orchard grass (*Dactylis glomerata* L.); PR, Perennial ryegrass (*Lolium perenne* L.); RC, Red clover (*Trifolium pretense* L.); TY, Timothy (*Phleum pretense* L.); WC, White clover (*Trifolim repens* L.); ZJ, Zoysia japonica Steud.

A Parrot Anafi drone was utilized for image capture. The flights were conducted in accordance with the mission parameters established by Pix4Dcapture, which specified an 85% forward overlap and a 75% side overlap at an altitude of 28 meters, resulting in a ground sampling distance of 0.95 cm. Ground control points (GCPs) and ground-truth data were collected using Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS) technology. Two 10 × 10 meter quadrats within five paddocks (OBH, STK, MKB, MNO, MYT) were surveyed to validate the locations of dung.

Orthomosaic RGB images with a resolution of 1 cm were generated using Metashape Pro and subsequently partitioned into 640 × 640 pixel tiles for compatibility with the YOLO model. The images were saved in JPG format for the purpose of annotation and in GeoTIFF format for the extraction of dung location data.

A custom dataset consisting of 1,504 images was developed, allocating 80% of the data for training and 20% for validation. Image labelling was conducted using MakeSense, with two classes designated: dung and stones. The YOLOv5x model underwent training for 500 epochs employing an Nvidia RTX A4000 GPU. The model exhibiting the highest mean Average Precision (mAP) on the validation dataset was selected for subsequent testing.

Dung detection was conducted across four paddocks, with the exclusion of YGK due to the absence of ground-truth data. The assessment of detection accuracy was executed utilizing Precision, Recall, Overall Accuracy (OA), and F-score metrics, which were calculated based on the counts of true positives (TP), false positives (FP), and false negatives (FN). The F-score provided a comprehensive evaluation of model performance, with values approaching 1 indicative of superior accuracy.

Results

Using the DD model, cattle dung detection was conducted in five paddocks across Hokkaido (OBH, STK), Gifu (MNO), Nagano (MYT), and Yamanashi (YGK) prefectures (Figure 1). The detected dung counts were 666 (OBH), 2,429 (STK), 688 (MNO), 165 (MYT), and 3,716 (YGK), respectively. The model achieved high accuracy in OBH (F-score = 0.861) and STK (0.835), where the grass was short and simple in species composition. Dung color variations, from dark brown to white, were also detected effectively (Figure 2a). In contrast, in MNO and MYT, dense vegetation and taller grass (MYT: mean height 38.9 cm) resulted in lower recall (0.500, 0.276), as many dung pats were concealed under the grass despite precision exceeding 0.9.

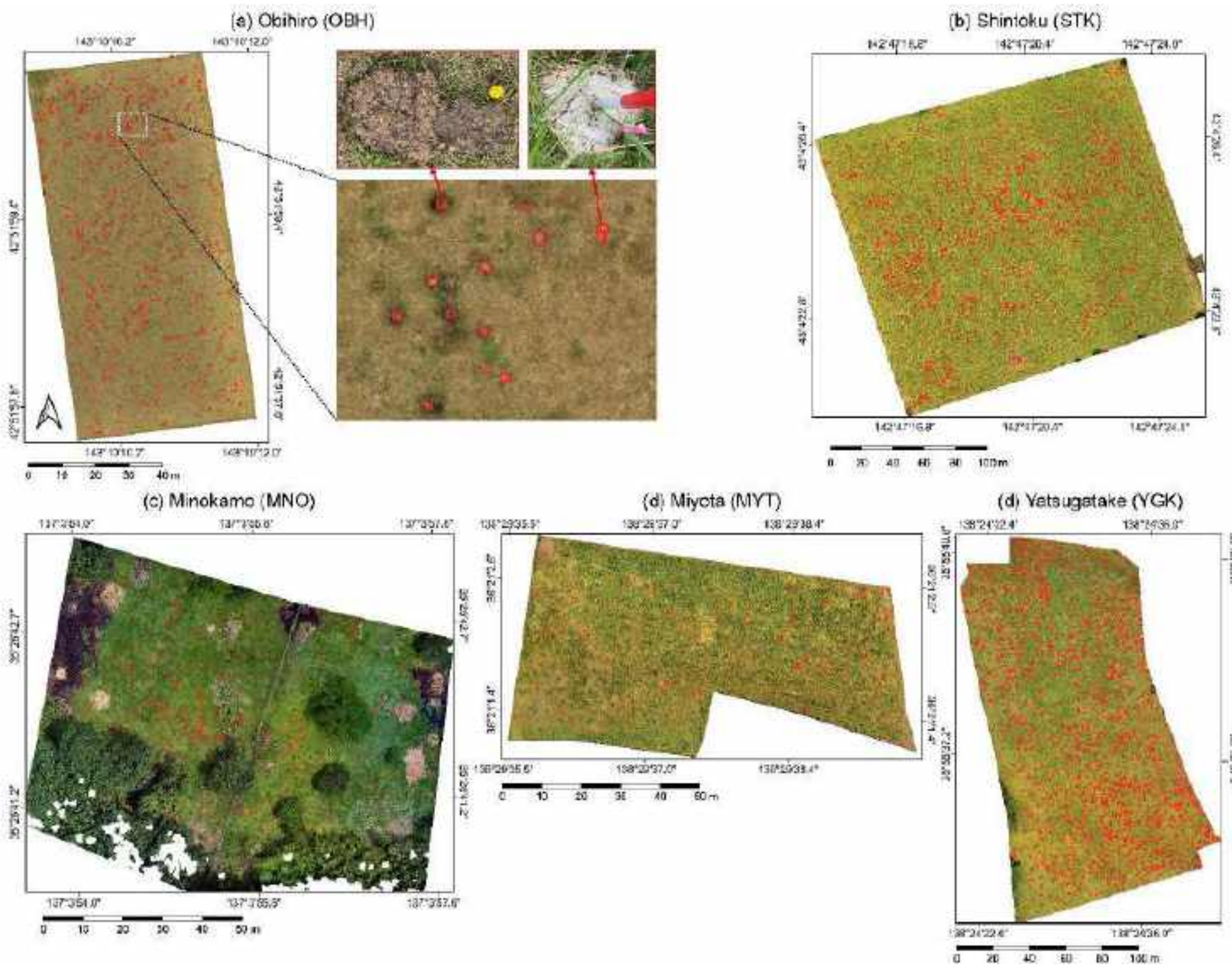

Fig 2 Spatial distribution of cattle dung pats detected from drone images using YOLOv5 in five paddocks (Kawamura et al. 2024).

Discussion

The application of deep learning (DL) for remotely sensed image data is expanding in grassland and livestock management (Muro et al., 2022); however, cattle dung datasets for grassland ecosystems remain underrepresented. This study developed the DD model using YOLOv5 and a custom dataset (1,504 images) to detect dung pats in drone images. The model identified between 666 and 3,716 dung pats per field, consistent with estimates of dung production (8–13 pats per day per cow). These results suggest that the detected dung pats were approximately 10 days old or less.

Dung detection accuracy was highest in short-grass pastures (OBH, STK; F-score = 0.861, 0.835) but exhibited lower performance in tall grass pastures (MYT; Recall = 0.281), where vegetation and terrain obscured dung in the drone images. The camera angle (80°) and the presence of invasive tall grasses, such as *Phalaris arundinacea*, likely contributed to the challenges in detection, indicating a need for methodological adjustments in future studies. Furthermore, updates to the detection models are necessary to enhance performance in complex environments.

In comparison to machine learning and Object-Based Image Analysis (OBIA) methods (Yoshitoshi et al. 2015), YOLOv5 demonstrated versatility across multiple paddocks, albeit with slightly lower accuracy. Enhancements can be achieved by updating the model with newer YOLO versions and incorporating expanded datasets, which could improve performance and applicability to a range of pasture types.

This pilot study highlights the potential of DL and drone technology for identifying the distribution of cattle dung, which can be beneficial for grazing management. However, several challenges persist: the model currently provides only the location and approximate size of dung (bounding boxes) without information regarding dung age or mass. Given that dung mass and age significantly influence nutrient cycling, grass recovery, and GHG emissions, future research should focus on evaluating dung decomposition processes while integrating seasonal and geographic variations (Cai et al., 2017; Saggar et al., 2015).

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Readily available: rangelands information and learning tools from the rangelands partnership

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Key words: open access; information systems; land management tools; information resources and videos; knowledge sharing

Abstract
Actively collaborating with institutions and organizations in the U.S. and around the world, the Rangelands Partnership is committed to providing reliable science-based information resources through the Rangelands Gateway web portal (https://rangelandsgateway.org/). The Gateway brings together rangeland ecology content from the United States, Australia, Canada, Mexico, South Africa, and other countries in addition to organizations such as the United Nations Food and Agriculture Organization (FAO). The Partnership's vision is to support the information needs of multiple audiences including range managers, natural resource professionals, Extension specialists, educators, decision-makers, and students as well as to contribute to improving the health and sustainability of rangelands and the communities of people who depend on them by providing credible and useful information.

Introduction
The Rangelands Partnership (RP) is a unique collaboration, spanning several decades between range scientists, information technicians, and librarians. This interdisciplinary team of experts has created the Rangelands Gateway (RG) website which provides a wide variety of freely available information resources and tools, including articles, technical reports, videos, global resources, and more. The website brings together information on key topics such as large landscape conservation, human and economic dimensions of rangelands and maintaining and improving rangelands. The poster that accompanies this paper focuses particularly on foundational educational tools and resources such as glossaries and videos for anyone including those new to the concepts of rangeland ecology and management. There are quality materials available on RG for students, researchers, public and private land managers, and educators.

Methods
The multi-disciplinary group of range scientists, librarians and IT specialists in the RP accomplishes the work through regularly scheduled Zoom meetings, a RP listserv (an email group), the RP Newsletter and

an annual RP conference that rotates between RP member states with both in-person and Zoom attendance options.

Individual members are encouraged to provide troubleshooting input on the RG website. For example, in August 2023 a librarian noticed the search interface wasn't providing consistent and complete results. That started a journey of working with the technological specialist team at the University of Arizona, followed by testing done by librarians and range scientists, further modifications by the technical specialists, resulting in an improved search experience on the RG.

A particularly valuable and impactful method for accomplishing our goal of providing reliable science-based information resources through the RG has been the establishment of a Memorandum of Agreement (MOA) between the Society for Range Management (SRM), Elsevier, the University of Arizona (UA) Libraries, the UA College of Agriculture, Life & Environmental Sciences. The MOA allows the RP to provide open access to articles published in the Society of Range Management's (SRM) major publications, *Rangeland Ecology and Management* (REM) and *Rangelands* magazine. Full issues of *REM* and its predecessor *Journal of Range Management* are available from volume 1 (1948) up to five years from the present year. SRM's *Rangelands* issues are available from volume 1 (1979) up to two years from the present year. These two publications bring a wealth of peer-reviewed articles available through the RG.

In addition, throughout the existence of the Rangelands Partnership, RP members have actively pursued and received grant funding. This has allowed the Partnership to create and deliver much needed educational resources for multiple audiences through diverse platforms including videos, digital apps and decision-making tools, providing access to a complete reference website.

Results

The Rangelands Gateway (https://rangelandsgateway.org/) contains a Library of more than 23,612 records of articles, conference proceedings, reports, along with videos, maps and educational and decision support tools. It also includes backfiles (archived articles) of the Society for Range Management (SRM) journals, publications from the Australian Rangeland Society and the Grasslands Society of Southern Africa, and content from other organizations and about other countries.

More than 70 videos on various rangeland topics can be found on the YouTube channel (https://www.youtube.com/user/GlobalRangelands) highlighted on the Tools page in addition to distance education courses, career information and other resources. Visit the Topics section to view content such as Rangelands in the World, Large Landscape Conservation and others.

The Global section on the Gateway highlights organizations and initiatives around the world that the Partnership is engaged with, including the 2026 International Year of Rangelands and Pastoralists (IYRP) and regional IYRP groups share plans and resources for outreach and education in advance of 2026. Visit the Rangelands Gateway web portal to learn more about how the Rangelands Partnership is "working together for our global rangelands future" by increasing access to valuable information resources through technology, information systems and communication. These materials are open access and freely available to the world.

Conclusions

There are challenges faced by RP members. For example, finding time to do volunteer/service Partnership work such as taking leadership positions in the RP Executive Committee, keeping up with fixing errors in

RG records, keeping website pages refreshed and up-to-date and other important RP work when responsibilities of paying jobs take priority, is a significant and ongoing challenge.

In spite of these challenges, the RP remains committed to the vision statement: "A multi-disciplinary collaboration that creates and furnishes authoritative, reliable, and vetted rangeland ecology content for range managers, natural resource professionals, Extension educators, decision-makers, and students to support the health and sustainability of rangelands and the communities of people who depend on them."

The ongoing success of the Rangelands Partnership can be attributed to the powerful synergy of the collaboration of range scientists, librarians, and technological specialists. The combination of these professionals diligently working together has resulted in continued efforts towards web-based sharing of quality and scientifically valid rangelands information and learning tools.

Acknowledgements
The Western Education/Extension and Research Activity (WERA) under the auspices of The Western Association of Agricultural Experiment Station Directors started supporting the Rangelands Partnership in 2008 and has done so annually. Many members in the partnership have received various grants from the United State Department of Agriculture agencies. On the RG website there is a long list of Partners and Collaborators that have contributed time, expertise, information materials, and funds towards this effort.

Using historical photos to monitor long -term changes in South Australian rangelands

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Key words: Historical vegetation changes repeat photography.

Abstract

Using repeat photography, or retaking photos at a later date from the same or similar locality, is a technique often used to illustrate changes particularly inbuilt environments. In rangelands and other natural environments, the technique in a general sense is often used to illustrate changes in rangelands measured or monitored by other means. The concept of a photographic monitoring point, or photopoint, is derived from this simple concept, and is commonly used to describe photo-sites taken from a fixed point, either using posts, pegs or other markers, or by means of an accurately geo-positioned location.

The project seeks to find out what ecological changes in the South Australian Rangeland area can be revealed simply by accurately re-locating sites where the original photo was taken 50-100 years ago. The original photos were sourced mainly from the records of early pastoral inspectors and Pastoral Board members. A few were sourced from pastoralists, as well as other government officials.

An appraisal of changes evident from 103 photo-pairs this year reveal almost ubiquitous improvement in site condition, and vegetation cover. However some areas, particularly with sandy soils show significant increases in less palatable shrubs and bushes.

Introduction

The poster provides a summary of changes in vegetation, soils, and other aspects of pastoral landscapes revealed from the relocation and repeat photography taken of the 103 sites where historical photos were taken, dating back to early last century. A book entitled "Land, Lease and Lens" has been produced which includes all the changing photo-pairs relocated in 2024.

The project, completed by Bren and Elizabeth Lay in 2024, was originally developed in 1995 as a research project funded by the then Australian Natural Heritage Trust. At that time, the Pastoral Board was overseeing the first round of pastoral lease assessments under the *Pastoral Land Management and Conservation Act 1989*. That program involved the establishment of fixed ground-based photopoints set up in each paddock or land type on all properties held under pastoral lease tenure. These new sites generally had quantitative data including belt transects and plant species lists collected at the time of establishment or re-visit.

At the time of the first round of pastoral lease assessments, there was an expectation that these new photopoints would be regularly re-visited. The Board in the 1990's emphasised its desire to obtain the "Second point on the graph" as a general expression for its role in capturing any significant land condition trends at the site (and surrounding area) during this process.

The simple objective of this work was, therefore, to determine what information, at both a site, and regional level, can be gained from analysis of retakes of a suite of historical photos. This recognised that in most cases no data was gathered at the time the photos were first taken. However, for many sites, site data was gathered during retakes at the time the project was begun, in the 1995-2000 period. These sites will be shown as a series of three photos in the book, as in the series included here (fig 1-3).

Methods

Most of the photos gathered for this project and re-visited in 2024 were taken from published or unpublished historical texts, or from reports submitted to the Board by early pastoral inspectors or Board members.

Of particular note here is the photos taken by one of the Board's earliest Inspectors appointed in 1924; Mr Cecil Goode, who was the first person attached to the Board, who accurately recorded the location from where he took many of the photos in his inspection reports. These photos date from the early 1940's, and provided some of the more interesting photo-comparisons to come out of this study.

The methods used for this repeat photography project was similar to that of books or monographs published overseas, particularly in the United States of America, such as Hastings and Turner (1965).

The challenge: finding the sites.

We recognised that because there was generally minimal or no data attached to the original photos, then they would only be worth the effort to re-visit if there was a reasonable prospect that the location could be found, or that the scene in the photo could be matched with a reasonably degree of certainty.

Achieving this part of the project sounded straightforward, but turned out to be quite challenging for us. because:

- Paddock or property configurations had changed, with fencing not maintained or removed
- Tracks were no longer visible, or had overgrown or washed out.
- The original track alignment had sometimes been obliterated by bulldozed replacement tracks or roads
- Even where the site location was known or evident, it was sometimes physically impossible to drive to it, necessitating a walk or swim to the exact location.
- The location was found, but deemed unsuitable due to the original scene being occluded by tree or shrub growth in the foreground of the photo.
- Site data was not available to us, or to the lessee concerned.

Despite these challenges, some sites were found purely by perceptive observations of the station managers or the authors.

Results

Altogether 103 sites were re-photographed and a selection included in the book if they fitted this criterion *and* showed or contributed to an interesting story from an ecological or land condition perspective. The re-takes were completed in calendar year 2024. At least another 50 sites were searched for without success, or were abandoned/not included for the reasons listed above.

For each site, these successful or abortive attempts involved vehicle traverses of up to100km or more, and the large amount of off-track traverse resulted in the destruction of more than a dozen AT rated tyres.

Analysis of changes

For the purpose of comparing and analysing the changes evident in the photo-pairs or triples, the rangeland region was divided into six districts recognised by the S.A. Arid Lands Landscape Board. as these districts were defined, at least in part, by land type, it made sense to investigate whether or not there were any generalisations which could be made about changes evident in each district. In addition, if any vegetation type occurred more widely, the question was asked as to what significant trends were evident over these long time periods.

For this paper and to illustrate the process, trends evident from a typical three-photo series in the Northern Flinders Ranges are summarised as Figures1-3.

The generally barren landscapes in overgrazed areas and distinctive topographic features fortunately enabled accurate re-location of many sites, although tree and shrub growth in some cases precluded views of the mid and background areas.

Discussion [Conclusions/Implications]

When undertaking this project, we were guided in our approach by the many publications using this technique. A good discussion and bibliographic summary of work using repeat photography from an Australian rangelands perspective is Pickard (2002). He points out that there are relatively few comprehensive studies using this approach in this country. In South Australia, studies of changes over long time periods at Koonamore (Hall et. Al. (1964) provide some of the best insights as to the value of long-term repeat photography from fixed points.

It is from the USA that a number of studies such as this one provide the material on historical or ecological changes in a particular region or land type. Some of them have been produced as a book, often best described as a generalised account of landscape changes in a particular area or region. Progulske (1974,), and Gruell (2001) have provided insightful accounts over long time periods in coffee-table book format.

Conclusions

The question most often asked of this work is "Were there any consistent trends evident across the rangelands of South Australia over these long time periods?". Based on a careful comparison of changes evident in the 100 or so photo-pairs, it was clear that:

- More than 75% of sites had clearly improved in condition, based on commonly accepted criteria
- Many sites distant from stock watering points had dramatically improved due presumably to the reduction of rabbit populations since the release of the Calicivirus.
- A number of native trees have changed little over the 50-100 year time interval. Red mallee (*Eucalyptus socialis)*, coolabah (*E. microtheca*) and Flinders Ranges corkbark (*Hakea edniana*) are foremost among these.

- By contrast, common wattle species, such as mulga (*Acacia aneura*), western myall (*A. papyrocarpa*) and sandhill wattle (*A. ligulata*) have often not survived over these time periods, or have regenerated spectacularly where seasonal conditions have enabled this to occur.
- In the northern cattle country, changes in abundance and composition of short-lived herbaceous plants and grasses are far more evident than was the case at sites further south. This may have been due, at least in part, to the heavy summer rains received in some areas in early 2024.

Acknowledgements
We are indebted to the Pastoral Board of South Australia for its encouragement and financial support for this project. Many of the sites where an intermediate photo was taken in the 1990's were found and documented by rangeland officers John McDonald and Tonia Brown. Senior rangeland officer John (Max) Maconochie and Pastoral Unit manager Saravan Peacock provided the support needed for off-site operation as a contractor. The provision of GIS support enabled real-time navigation, - critically important in enabling many sites to be found and re-taken. Even so, we could not have completed the re-visits to so many sites, often in parts of properties where no road access remains, without the assistance of many property owners and/or managers.


1966

Figure 1: Dunbar Hut Warraweena Station, Flinders Ranges. A stock watering point about 1km west of here explains the degradation and gullying evident, compounded by uncontrolled goat and rabbit grazing pressure. The only vegetation on the range at rear are some remnant native cypress-pines.


1999

Figure 2 Dunbar Hut, Warraweena Station (now formalised as PP 6682). Dramatic improvement in land condition 33 years later, in part explained by the purchase of the lease by a conservation company, which also encourages the control of feral goats. Extensive regeneration of the pines is now evident, at rear, complemented by the recent growth of Lemon-scented grass following a good summer rainfall event that year.


2024

Figure 3 Dunbar Hut, Warraweena Station. (PP 6682)

The fence has now been removed for firewood, while the regeneration of pines continues on the range behind, together with various Wattle species. In the foreground dry seasonal conditions prevail with no annual growth

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Development and implementation of a forage management platform in Uruguay ('iPasto').

Abstract

Introduction

Methods

iPasto is a digital platform for data management (Lombardo 2021). It is a web application that allows recording, calculating and visualizing information for improving pasture management at the paddock and farm scale. It links management and productivity data of grassland and paddocks (lots or grazing areas) of a farm. The data recorded in the farm (paddock or field monitoring) and data from remote sensing generate real-time rangeland performance information, which is stored in a database for further analysis. The platform is divided into 3 modules. The first module is basic information, where the user configures his farm with his grazing areas; the second module is pasture monitoring; and the third is grazing areas monitoring. The forage monitoring allows, through the use of remote sensing and an ecophysiological model adapted from Monteith (1972), to estimate and visualize information on the Net Aerial Primary Production (NAPP) at the paddock and farm scale for the various forage resources from 2000 to the present day. The main outputs of this module are: 1-NAPP (kg DM). The 'Paddock Monitoring' module allows updating the status of the paddocks, as well as displaying the following outputs or global forage performance indicators on the farm: 2-Grass Availability (GA) at a point in time (kg DM/ ha); 3-Meal Plate Index (MPI), an index which compares the forage or grass available with that required for optimal livestock performance (Duarte 2020), . The result is expressed in decimal,; an MPI value of 1 means that the available grazing area equals that needed, while lower or higher values show shortages or surpluses respectively. 4-Proportion of area available for grazing at different forage height (*i.e.* generated from the proportion of area at three height ranges); this variable has three indicators: proportion of area with forage height < 2.5 cm'(PGR-2.5), 2.5 to 5 cm(PGR2.5To5) and > 5 cm(PGR5).

iPasto is developed following a basic Client-Server architecture. The website is developed using the ReactJS framework, also in JavaScript. This unifies the use of a single language for both components of the application. The database is SQL and MySQL is used to implement it. Pipelines were developed to implement CI/CD to streamline the deployment/testing/put into production process. This software gives the possibility to capture information with the desired frequency and generate a database in real time. The implementation of iPasto accumulates more than 2 years of use from June 2021 to March 2023. After the work of dissemination and training in the use of the platform, its implementation begins with 25 farms which are members of the Grassland Management Project FPTA No. 356 (Pereira Machin 2020) executed by the Instituto Plan Agropecuario (IPA). This program is extended now to more than 400 producers associated with the institution. For the descriptive analysis of its main outputs, we used the 2021-2022 and 2022-2023 seasons for the group of initial establishments of the monitoring proposal.

Results
The iPasto platform is available for users registered in Instituto Plan Agropecuario. The results in Table 1. show that the grasslands aboveground net primary productivity (NAPP) was 4534 kg DM/ha. Grass Availability (GA) was 950 KgDM /ha. The Meal Plate Index (MPI) was 0.75 and the proportion of the ranch with forage height > 5 cm (PRG5) was 27%. Meat productivity (MP) was 109 kg/ha, NAPP required to produce one kg of meat (GMP) was 46 and Meat production efficiency by stock (MPES) was 165 Kg MP for US.

PRG5 (in Figure 1) indicted there are 3 groups (High, Medium and Low Systems). High systems (PRG5=60%): GA=1440, MPI=0.85 MP=153, GMP=30, Meat production by stock unit (MPES)=175, SU=1, mainly integrated by rotational grazing management and continuous grazing with resting. Medium systems (PRG5=22%): GA=886, MPI=0.72, MP=99, GMP=51, MPES=128, SU=0.84, mainly integrated by continuous grazing with breaks (grazing with rest periods, no grazing). Low systems (PRG5=5%): GA=642, MPI=0.71, MP=87, GMP=50, MPES=154, SU=0.6, correspond mainly to continuous grazing. Therefore, high systems have the best values for grass use efficiency (GMP and MPES), linked to improved values of GA, MPI, PRG5, MP and SU. In low and medium systems, MP and MPES are improved when MPI, GA and SU are improved and when a rotational grazing module is included in the continuous grazing. There is a positive trend in the MPES as MPI gets higher in March and June for all the ranches.

Table 1. Index averages 2021/2022 and 2022-2023

	2021-2022	2022-2023	AVERAGE
NAPP (KgMS/ha/year)	4901 [3290-6558]	4167 [2163-5226]	4534
GA (KgDM/ha)	1015 [336-3415]	885 [208-1951]	950
MPI [0 To 1.2]	0.79	0.70	0.75
SU (KgLive Weigh)	307	323	315
MP (Kg/ha/year)	113	105	109
GMP (KgDM/Kg of MP)	46	47	46.5
MPES (Kg/Stock Unit)	149	141	145

(NAPP: aboveground net primary productivity, GA: Grass Availability, MPI: Meal Plate Index, SU:Stock Animal Unit, MP: Meat productivity, GMP: ANPP required to produce one kg of meat MPES: Meat production efficiency by stock)

Discussion
iPasto is a tool that allows data capture and generates simple indicators that assist in the management of forage resources. The database is enriched daily, which offers the possibility of including artificial intelligence (AI) to develop automatic processes that improve accuracy in the estimation of existing and future indicators. It has the potential, through scaling up to the national level, to become a free platform with institutional backing and support to improve decision-making in adaptation processes and contribute to efficiency in the use of forage. High systems have the best values for grass use efficiency (GMP and MPES), linked to improved values of GA, MPI, PRG5, MP and SU. In low and medium systems, MP and MPES are improved when MPI, GA and SU are improved and when a rotational grazing module is included in the continuous grazing. There is a positive trend in the MPES as MPI gets higher in March and June for all the ranches.

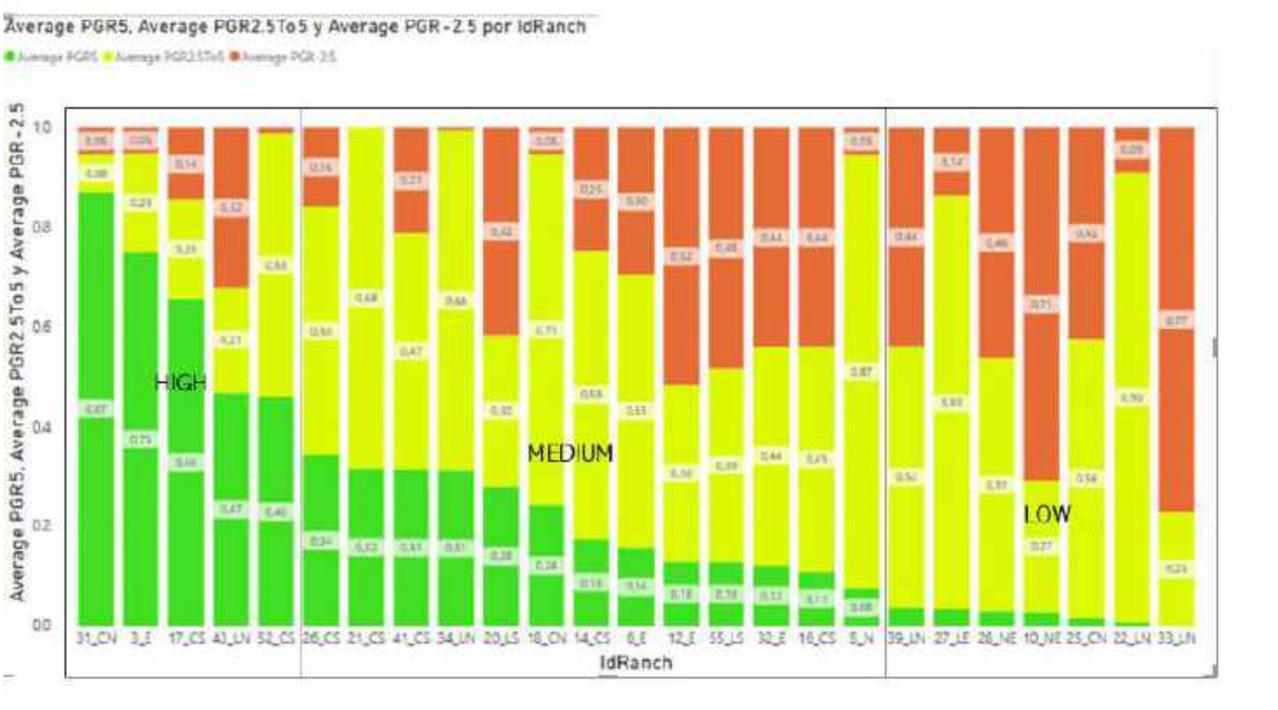

Figure 1. PGR5 evolution 2021/2022 and 2022/2023 by 25 ranches.

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Using crowd sourcing and geopositioned images to document near real time rangeland condition

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Key words: Image processing; digital photography; rangeland assessment; geotagged photographs; community engagement.

Abstract

Monitoring rangeland vegetation is essential for sustainable land management, biodiversity conservation, and climate change mitigation. Traditional vegetation monitoring methods often require extensive fieldwork, which can be time-consuming and costly. Crowdsourcing, which leverages the collective power of a large number of volunteers, offers a promising alternative. This study examines the effectiveness of using crowdsourcing to collect geopositioned images for monitoring rangeland vegetation. By engaging herders and pastoralists with smartphones featuring built-in GPS capabilities, a substantial dataset of geotagged photographs from diverse rangelands was amassed. These images were transferred to a central repository when an internet connection was available, ensuring continuous data flow from even the most remote areas. Subsequently, the images were analysed using advanced image processing and machine learning techniques to assess vegetation and ground cover in near real time. Preliminary results indicate that our protocol can provide high spatial and temporal resolution imagery, which complements traditional monitoring methods by offering more immediate and detailed insights. These images also serve as ground truth for supervised classification of large-scale remote sensing satellite scenes. Additionally, this approach enables sampling of inaccessible remote areas while promoting community engagement and environmental awareness among pastoral communities. The necessary steps for implementation are discussed, along with examples from various locations. The findings highlight the potential of crowdsourcing as a cost-effective and scalable tool for rangeland monitoring and management, showcasing its ability to enhance both data quality and stakeholder participation.

Introduction

Vegetation canopy cover is a critical biophysical indicator for assessing rangeland condition. It protects the soil surface and influences key ecological processes such as rainfall infiltration, soil erosion reduction, soil respiration, sunlight interception, and wind erosion, thus supporting overall ecosystem functionality (Spaeth Jr, 2020; Park et al, 2024). Additionally, vegetation cover is a vital measure of rangeland health, closely correlated with climate conditions (Almalki et al, 2023). Its composition and structure, which directly impact rangeland productivity, are influenced by grazing practices and other human activities (Sanaei et al, 2018).

Assessing changes in vegetation cover is fundamental for understanding the interaction between environmental and climatic conditions, human activities, land-use practices, and natural ecosystems (D'adamo et al, 2021). Monitoring these changes over time provides valuable information that informs effective management planning and promotes sustainable resource utilization (Azarm et al, 2021). Data on vegetation cover changes are crucial for predicting future trends and establishing a long-term framework to enhance decision-making and resource management (Shi et al, 2022). Therefore, the availability of accurate, up-to-date information is essential for supporting effective monitoring, planning, and management efforts in rangeland ecosystems.

However, quantifying ecosystem parameters to track conditions and trends remains challenging, time-intensive, and costly, resulting in limited detailed records for many areas worldwide. To address these challenges, this paper presents a procedure for local scale monitoring that documents rangeland conditions in near real-time. By integrating crowdsourcing, geopositioned digital images, and advanced image processing software, we enable the rapid sampling and recording of vegetation, litter, and soil parameters. VegMeasure®, an image analysis tool developed to monitor vegetation cover over time (Louhaichi et al, 2001; Louhaichi and Hassan, 2018), serves as a component of this process. This approach offers a practical, efficient, and scalable solution for enhancing rangeland monitoring and management.

Methods

The VegMeasure® software offers an efficient and cost-effective solution for estimating rangeland vegetation parameters and conducting non-destructive monitoring. To facilitate data collection, three pastoralists were equipped with smartphones featuring GPS-enabled 16-megapixel digital cameras. Participants received training on proper image acquisition techniques before starting data collection.

Images were captured using a pole-mounted camera to maintain a consistent height, as recommended by Booth et al. (2004) (Fig. 1a). When a pole was unavailable, handheld images were taken at a comfortable height (Fig. 1b). The pastoralists were trained to hold the smartphones vertically to ensure accurate GPS georeferencing during image acquisition. Each pastoralist captured images across their respective rangeland locations, ensuring diverse coverage of vegetation and bare ground conditions. Captured images were uploaded to a designated repository once a Wi-Fi connection was available and were subsequently processed using VegMeasure® software. The software employed a supervised classification method, assigning each pixel in an image to a specific class type based on predefined categories, enabling the classification of different land cover types. While VegMeasure® can classify ground cover into multiple categories, including vegetation, bare ground, rocks, and litter (Louhaichi et al, 2018), this study utilized a simplified two-class system, focusing on vegetation cover and bare ground. Classification accuracy was assessed using the accuracy assessment tool in VegMeasure®, which computes an error matrix and derives the Kappa Index of Agreement to quantify classification reliability. Stratified random sampling was applied, selecting 180 points per class from 50% of the images to validate the accuracy of the classified outputs.

Fig. 1a: Technical staff from Sughd Province - Tajikistan using a pole for taking straight down images.

Fig. 1b: Pastoralist from Rasht valley in Northeastern Tajikistan, taking images using a smartphone.

Results

A total of 180 images, with 60 captured by each pastoralist (which accounted for approximately 70-75% of their total images) in the Rasht Valley, were analyzed after excluding those that were not vertically oriented or were affected by shadows to ensure the quality and consistency of the dataset. The analysis revealed notable differences in vegetation and bare ground cover across the areas managed by the three pastoralists. The first pastoralist's images showed an average vegetation cover of 60%, with values ranging from 50% to 65%, while bare ground accounted for the remaining 40%, ranging from 35% to 50%. The second pastoralist's images exhibited a significantly higher average vegetation cover of 70%, with a range of 59% to 81%, and a correspondingly lower bare ground cover of 30%, ranging from 19% to 40%. In comparison, the third pastoralist's images indicated an average vegetation cover of 53%, with bare ground making up 47%. The classification accuracy of the analysis was consistently high, ranging from 95-99% (Fig. 2 a, b).

Fig. 2a: Straight down image of Tajikistan grassland (before).

Fig. 2b: Processed image using VegMeasure software (after): plant cover 78.5%, bare ground 21.5%, classification accuracy: 98%

Discussion

The results demonstrate the potential of using readily available smartphone technology, paired with VegMeasure software, for efficient and cost-effective assessment of rangeland vegetation cover in the Rasht Valley of Tajikistan. The variation in vegetation cover across rangelands, where pastoralists graze their animals, highlights the spatial heterogeneity typical of rangelands, particularly in terms of plant cover. This variation emphasizes the need for localized monitoring and tailored management strategies (Bestelmeyer et al, 2019).

This approach offers a significant advantage over traditional methods, as it reduces the labour-intensive and time-consuming aspects of rangeland assessment (Yu and Guo 2021). Additionally, it allows for continuous monitoring over time, enabling the study of both current and past conditions (Hu et al, 2024). Each image captured includes GPS location data, providing a valuable tool for tracking changes in vegetation cover and informing management strategies However, changing weather conditions like snow and rain, uneven rangeland geography, maintaining the phone's level and angle, and issues with shadows and lighting were challenging for pastoralists taking photos.

Despite these challenges, the simplicity of image acquisition—requiring only basic training in proper image capture techniques—makes this approach easily accessible to local communities, empowering them to actively participate in monitoring their rangelands. Furthermore, this participatory approach fosters knowledge sharing and facilitates communication of rangeland conditions to local authorities, which is essential for effective decision-making and sustainable rangeland management.

Conclusions/Implications

Integrating geo-referenced images collected through community networks can play a pivotal role in the sustainable management and restoration of Tajikistan's rangelands and ecosystems. This approach not only has the potential to significantly reduce monitoring costs but also facilitates the generation of detailed datasets critical for tracking site changes and trends over time. It enables seasonal or annual revisits to monitored sites, providing insights into the spatial and temporal impacts of natural and human interventions. Moreover, it standardizes ground cover estimates across sites, overcoming the limitations of traditional visual assessments. Ultimately, this method supports both ecological restoration efforts and the empowerment of local communities.

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Pastoralist piloted drone monitoring – drones as a tool not a toy

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Keywords: Drones; Livestock; Rangelands; Precision

Abstract

Landscape management is at the heart of what pastoralists do. Ultimately the viability and sustainability of pastoral businesses is based on how their landscape functions and responds to rainfall. Core to the concept of improving landscape function in a rainfall limited climate – Rainfall Use Efficiency. Management strategies that improve Rainfall Use Efficiency such as regenerative grazing and erosion control techniques can be implemented on any property but need to be done so in a targeted and informed way. The challenge in achieving good landscape management comes not only in knowing what to do but more importantly when to do it. This is particularly challenging given the variable climatic conditions and diverse landscape types experienced in the Pilbara.

Emerging Ag Technologies are providing tools and data that make managing the variability easier. Drone technology is a rapidly growing industry and is becoming increasingly accessible. Drones present an opportunity to gather information about your landscape in a repeatable, reliable and efficient way, and to use that information to make informed decisions about your landscape management.

With funding from the Southwest WA Drought Resilience and Innovation Adoption Hub, Contour Consulting has developed a new tool that is pastoralist-friendly and allows for more informed pasture assessment and calibration of your stocking decisions. The process is end-to-end, from establishing monitoring sites through to follow-up support, and is tailored to your property.

The tool provides quantitative pasture and landscape condition data through repeatable assessments that will give land managers direction and confidence to make proactive grazing management decisions. It also creates a database of evidence that could be used in documenting improved management as part of a carbon or natural capital project.

Introduction

Australian Rangelands span an impressive area of 6,300,000 km^2 area and represent a diverse array of vegetation types. Despite this diversification, they function as a cohesive natural ecosystem which is primarily utilised for grazing livestock (Wilson, 1988). Australian Rangelands are incredibly vast, requiring modern solutions for precision agriculture to monitor these areas effectively. Tracking the large-scale ecosystem changes is mandatory for the better landscape and livestock management. To monitor these areas, tools like drones play a crucial in the livestock production and management.

Drones have been proven to offer numerous advantages from the last 10 years as a part of precision agriculture (Zuo, 2021). The information gathered can assist the pastoralist to make quick decisions about whether to intervene to guarantee the best possible output at the end of the season. Digital, thermal, and multispectral cameras are the most often utilized types of cameras, and they are crucial in giving the necessary information on vegetation and livestock conditions (Aquilani, 2022).

Unmanned Aerial Vehicle (UAV) technology was used along with in person site assessments to develop a digital library of different sites on the Yerilla Station in the Goldfields region of Western Australia, to accelerate the process of decision-making regarding stocking numbers and pasture utilisation. On-ground photos, cattle condition assessments and remote sensing technology were integrated for better pasture management across different seasons. This Project was joint venture between Contour Consulting and the Southwest Drought Hub WA.

Methodology

Eight monitoring sites, each with 3 to 4 subsites (Figure 1), were selected for drone monitoring at Yerilla Station, 150 km northwest of Kalgoorlie Boulder in the goldfields region of Western Australia. Sites were selected using a combination of geospatial desktop analysis and in consultation with the station manager. Detailed information about the land system, pasture type, current pasture condition, occurrence of erosion and its extent/type, and important indicator species i.e. increaser and decreaser species were recorded during an initial on-ground visit to each of the sites. Rainfall data is being recorded by installing rain gauges on each of the sites. Subsites were selected in areas that had a higher probability of responsiveness to the changing seasonal conditions and management. Observations were made about the grazing extent, palatable species, micro-habitat areas and recruitment rate of desirable species. This data forms the basis for the land manager to be able to interpret and identify pasture condition changes through reassessment.

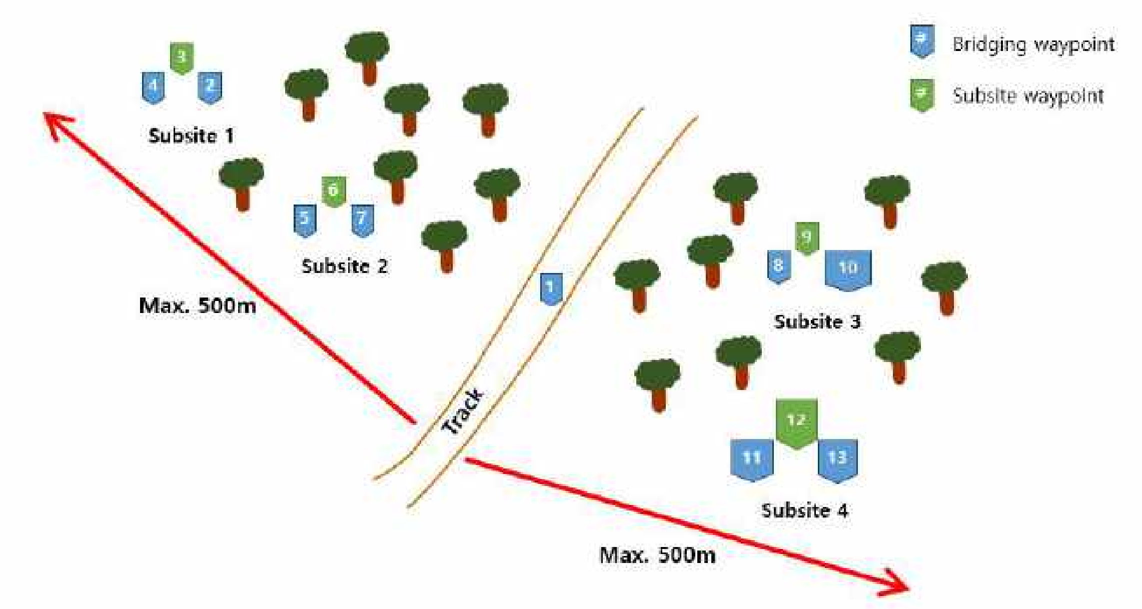

Figure 1: Setting up the monitoring site along with 4 different subsites

Autonomous flight waypoints were setup to capture an RGB photo of each subsite using the off-shelf drone technology and a drone programming app 'Litchi for DJI Drones' (Figure 2). Photos are taken at or above the canopy height to allow for monitoring of understorey species. Birdseye photos can be used to assess ground cover in grassland sites.

At Yerilla, photos of each subsite were captured monthly in a repeatable manner to build up a library for monitoring the growth of the palatable species, changes in the pasture and indicator species for grazing management decisions. A 'rolling rainfall to stocking rate' spreadsheet was developed to assist the station manager in monitoring rainfall and current stocking rates. Using the station's median rainfall data, this tool compares the current stocking rate to the suggested rate (Figure 3). This tracker offers useful information for making well-informed stocking decisions, such as whether to move stock into or out of an area based on pasture conditions and recent rainfall when paired with monthly photos. An assessment sheet is used as go-to-go record keeper for all the observations and action during assessment or re-assessment of a monitoring site. Information about desirable/undesirable species, rain gauge reading, temperature and any adjustment made to the stocking numbers are recorded to keep all the crucial details in check for better site evaluation process.

Figure 2: Flight path simulation of a monitoring site in the Litchi app for DJI drones.

Results

Using drones as a part of modern precision agriculture has made the process of decision-making more efficient and faster. Reassessment of sites takes approximately 8-10 minutes. The data collected through the monitoring system supports land managers to proactively manage grazing across their property. During dry seasons, feed requirements for stock can be budgeted with the assistance of drones as a part of pre-planning. To prevent overgrazing, the Yerilla station manager now employs this technology with confidence for prompt livestock movement. This economical approach has the potential to be widely used. In addition to helping the cattle industry achieve high welfare outcomes and production targets, it offers to improve rangeland conditions over the long term and manage rangelands for drought resistance. Pastoralists from all around WA, including those from the Pilbara, Kimberley, and Goldfields-Nullarbor regions, have expressed their interest in learning more about the package.

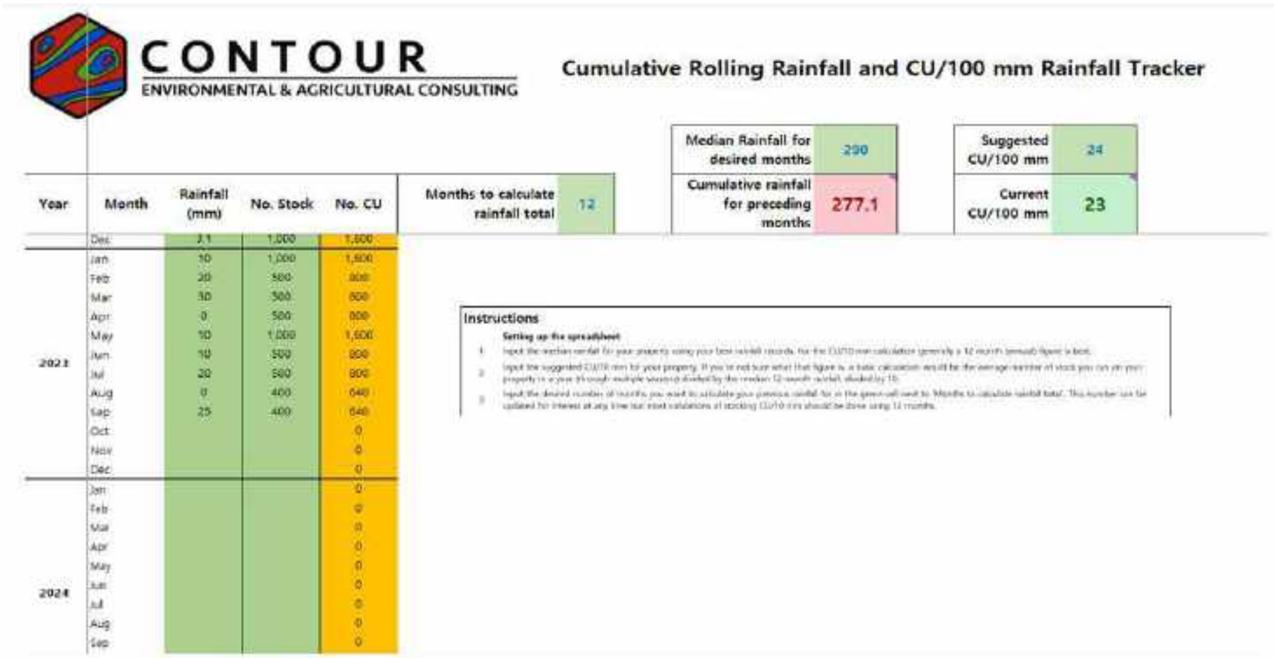

Figure 3: Cumulative Rolling Rainfall and Cattle Units/100 mm rainfall tracker

Conclusion

In conclusion, drones have revolutionized the precision agriculture methods and the way pastoralists manage their stock. UAVs assist pastoralists by keeping track of their livestock, monitoring the land's condition and identifying potential threats with a bird's eye view. The use of aerial imagery technology may help managers to not only increase productivity, but also enhance sustainability in the pastoral industry. The data-driven decisions have improved time management, which is a crucial factor for pastoralists. This modern precision agriculture tool can help to mitigate the risk associated with droughts or harsh weather conditions, ensuring the longevity of the rangeland operations and better management of the livestock. Ultimately, the adoption of UAVs represent an analytical thinking approach that aligns with the future of Australian Rangelands, making the way for a more productive pastoral sector.

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High-performance forage classification models for smart agriculture: a study on Keras, SVM, and BPNN

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Key words: Back Propagation Neural Network; Support Vector Machines; Keras image classification model; radial basis function

Abstract

A robust and accurate image classification model is essential for the development of a smartphone application to help farmers identify forages from weeds. This study focused on developing and comparing three models: Keras-based deep learning, Support Vector Machine (SVM), and Back Propagation Neural Network (BPNN). A total of 1500 images of alfalfa (*Medicago sativa*), sericea lespedeza (*Lespedeza cuneata*), and weeds were used. The Keras model was tested with varying image sizes, batch sizes, and epochs. The highest performance was achieved with an image size of 128, a batch size of 8, and 100 epochs, yielding accuracy, precision, recall, and F1 scores of 99.01%, but with the highest training time of 44.25 seconds. Alternatively, using a smaller image size of 32 and a batch size of 32 with 50 epochs resulted in a lower accuracy of 98.38%, but significantly reduced training time to 9.61 seconds. The SVM model, with a Radial Basis Function (RBF) kernel, had excellent performance metrics, achieving an accuracy, precision, recall, and F1 score of 99.02%, with an exceptionally low training time of 0.059 seconds and a testing time of 0.01 seconds. This indicates the SVM's efficiency and suitability for rapid classification tasks. The BPNN model, tested with an image size of 128 and a neuron structure of over 200 iterations, achieved an accuracy of 98.36%, with a training time of 2.17 seconds and a minimal testing time of 0.0017 seconds, also showing efficient computational performance. The SVM model is recommended for the smartphone application due to its high accuracy, precision, recall, and F1 score, with its minimal computational requirements, making

it both robust and efficient. This model's attributes align well with the practical needs of farmers for quick and reliable forage identification under field conditions.

Introduction

An effective and precise image classification model is essential for assisting farmers in differentiating forages from field weeds (Islam et al., 2021). In agricultural systems, precise identification of forages is crucial for optimizing livestock feed quality, enhancing farm output, and reducing losses due to poor resource mismanagement (Monteiro et al., 2021). Conventional identification methods are frequently laborious, subjective, and reliant on specialist knowledge, underscoring the necessity for automated solutions capable of operating effectively in practical environments, such as agricultural fields and pastures (Boruah et al., 2024).

Smartphone applications with sophisticated picture classification features can provide an effective solution for farmers by facilitating the swift and accurate identification of forages and weeds (Siddique et al., 2024). The effectiveness of these applications depends on the creation of classification models that achieve a compromise between high accuracy and computational efficiency, especially considering the processing limitations of mobile devices (Zhang et al., 2019). Recent breakthroughs in machine learning, encompassing deep learning, and traditional techniques, like Support Vector Machines (SVM) and neural networks, offer intriguing opportunities for developing such tools (Zhang et al., 2019; Siddique et al., 2024).

This research highlights the urgent necessity for novel and accessible solutions for forage identification through the examination of advanced machine learning techniques. It seeks to address shortcomings in existing agricultural methods by offering a solid technology framework for precision farming instruments customized to the practical needs of farmers through utilization of machine learning approaches to determine the ideal model configuration achieving both high performance and computational efficiency. The study aim was to evaluate these models on their possible incorporation into a smartphone application for agricultural purposes, focusing on their capacity to process field data reliably and efficiently.

Methods

This study utilized a systematic approach to develop and evaluate image classification models for differentiating alfalfa and sericea lespedeza forage plants among field weeds. The dataset comprised images organized into three distinct classes. Images were preprocessed by resizing them to uniform dimensions, normalizing pixel values to a range of 0-1, and calculating fractal dimensions for enhanced feature extraction. Additional preprocessing included data augmentation techniques, such as rotation, translation, and zooming, implemented using the TensorFlow ImageDataGenerator.

Three primary modeling approaches were investigated: traditional machine learning models, a custom Keras-based deep learning model, and pre-trained deep learning architectures. Traditional models, including Support Vector Machines (SVM) and Back Propagation Neural Networks (BPNN), were trained on features extracted from the preprocessed images. Dimensionality reduction for these models was performed using Principal Component Analysis (PCA) to reduce computational complexity. The SVM models were tuned for different kernels (linear, RBF, and polynomial) and penalty parameters (C), while BPNN models were optimized for hidden layer configurations and maximum iterations. A custom Keras-based deep learning model was implemented with multiple dense layers, batch normalization, and dropout for regularization. The model was trained using the Adam optimizer and sparse categorical cross-entropy loss function. Hyperparameter tuning involved experimenting with batch sizes (8, 16), epochs (25, 50), and input image sizes (75x75, 512x512). Early stopping and learning rate reduction callbacks were employed to avoid overfitting and enhance convergence. The image data set was split into a 70:20:10 ratio as training, testing, and validation sets, respectively, for each model tested.

Performance metrics, including accuracy, precision, recall, F1-score, training time, and testing time, were recorded for all models. Hyperparameter tuning was conducted using grid search and cross-validation for SVM and other traditional models. An ensemble model combining SVM and BPNN was developed to leverage the strengths of individual classifiers. Comparative analyses were conducted to identify the best-performing configurations, and results were visualized through confusion matrices and performance plots.

Results

The results highlight the performance evaluation of three classification models—Keras-based deep learning, SVM, and BPNN—for forage identification among field plant weeds. A total of 1500 images were used to develop and test these models, with detailed performance metrics and computational requirements assessed.

The Keras model demonstrated high flexibility in parameter tuning, with image size, batch size, and epochs significantly impacting performance. The optimal configuration, using an image size of 128, a batch size of 8, and 100 epochs, yielded an accuracy of 99.01%, precision of 99.01%, recall of 99.01%, and an F1 score of 99.01%. However, this configuration incurred the highest computational cost, with a training time of 44.25 seconds. In contrast, a smaller image size of 32, batch size of 32, and 50 epochs achieved slightly reduced accuracy (98.38%), but considerably decreased the training time to 9.61 seconds. These results underline the trade-off between model accuracy and computational efficiency.

The SVM model, employing a Radial Basis Function (RBF) kernel, emerged as the most computationally efficient among the three models. It achieved accuracy, precision, recall, and F1 scores of 99.02%, with a remarkably low training time of 0.059 seconds and a testing time of just 0.01 seconds. These metrics demonstrate the SVM model's capability for rapid and accurate classification, making it highly suitable for applications requiring minimal computational resources.

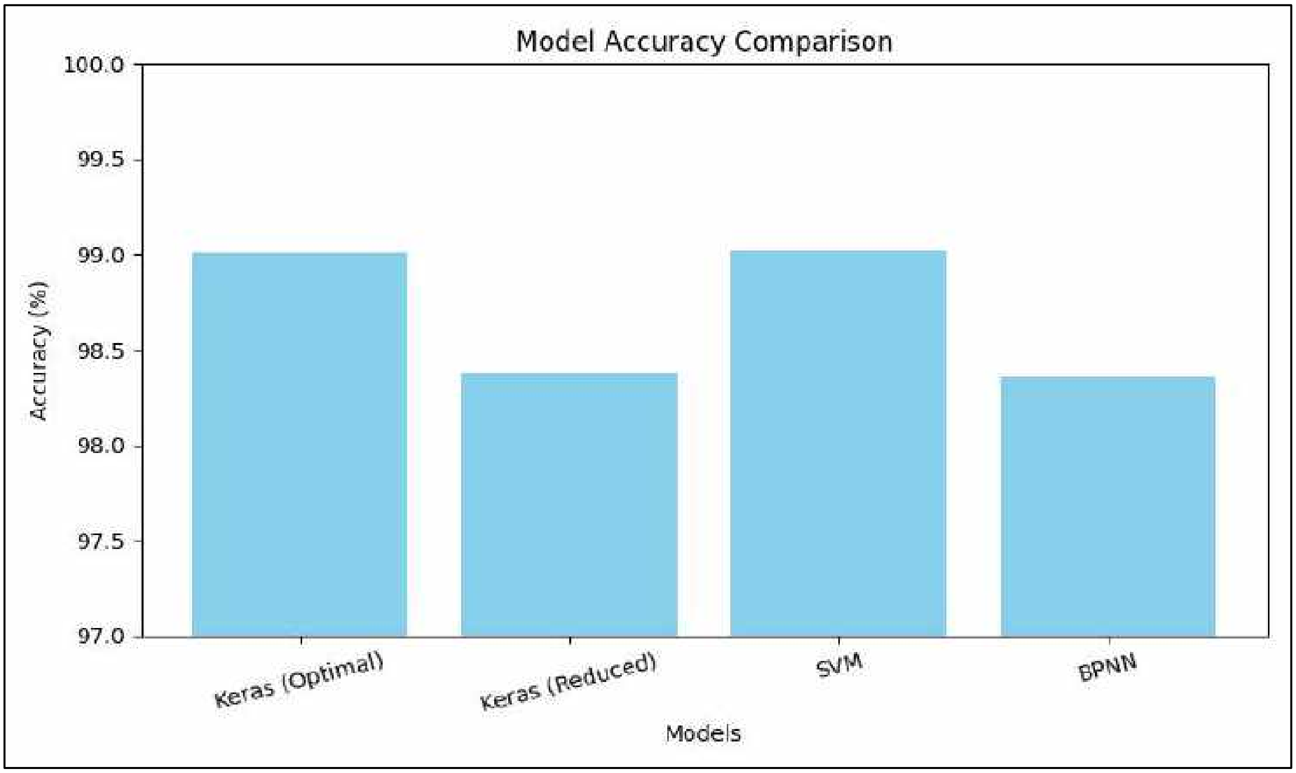

Figure 1. Graphical representation of different models for the accuracy in identification of different forage species.

The BPNN model, tested with an image size of 128 and a neuron structure across 200 iterations, achieved an accuracy of 98.36%. While its performance was slightly lower than the Keras and SVM models, it demonstrated excellent computational efficiency, with a training time of 2.17 seconds and a testing time of only 0.0017 seconds. This makes it a viable option when computational constraints are a priority.

Discussion

This study demonstrates the use of image classification in agriculture by building and assessing three machine learning models specifically designed for forage identification among field weeds. The results underscore the advantages and compromises of each model, offering an in-depth examination to inform their practical use.

The Keras-based deep learning model exhibited an accuracy of 99.01% and resilience under optimum conditions. Nonetheless, its substantial processing requirements, evidenced by a training duration of 44.25 seconds, may restrict its applicability in resource-limited settings, such as smartphones. Modifications to image and batch sizes demonstrated the model's flexibility, resulting in a small decrease in accuracy to 98.38% alongside a considerably reduced training duration of 9.61 seconds. This scalability emphasizes the adaptability of deep learning, while also revealing its reliance on accessible computer resources.

The SVM model, utilizing a RBF kernel, proved to be the most effective and feasible choice, attaining the highest accuracy (99.02%) and precision metrics, alongside extremely low computing demands. The training duration of 0.059 seconds and testing duration of 0.01 seconds render it very appropriate for real-time applications. These results corroborate previous studies highlighting the SVM's resilience and computational efficacy in managing smaller datasets and non-linear classification challenges (Khawaja et al., 2024; Siddique et al., 2024). The efficiency of the SVM model renders it an exemplary choice for the proposed smartphone application, providing farmers with a swift and dependable diagnostic instrument.

The Back Propagation Neural Network (BPNN) demonstrated exceptional performance, with an accuracy of 98.36% with low training and testing durations of 2.17 seconds and 0.0017 seconds, respectively. Its computational economy renders it suitable for situations necessitating swift processing; nonetheless, its somewhat diminished accuracy indicates it is suboptimal for high-precision jobs in comparison to SVM and Keras models. These findings validate earlier research that recognized BPNN as an efficient lightweight alternative for limited contexts (Siddique et al., 2024).

This study's main contribution is the construction and comparative analysis of machine learning models for a smartphone application designed for forage identification. The SVM model excels as the most pragmatic option because of its excellent accuracy and computational economy. This approach corresponds with the practical limitations faced by farmers, who necessitate swift, dependable, and resource-efficient solutions for agricultural production challenges. This research's ramifications also transcend forage detection, demonstrating the potential of incorporating machine learning into agricultural tools to improve production and decision-making.

Subsequent research should investigate the scalability of these models for larger and more heterogeneous datasets, along with their applicability to multi-class classification problems. Moreover, incorporating the SVM model into user-friendly smartphone interfaces could augment its practical utility, facilitating the adoption of smart farming technology. This study establishes the foundation for resource-efficient, AI-driven agricultural solutions, connecting advanced technology with practical field application.

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The relationship between canopy volume and leaf dry matter of a shrub species on the west coast of South Africa

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Key words: browse; Succulent Karoo; regression analysis

Abstract

In the winter rainfall region of South Africa, browse, such as shrubs and dwarf shrubs, is vital fodder for animals during the dry season. However, understanding how much fodder these shrubs can provide sustainably is limited. Existing methods for measuring browse production are insufficient for shrubs in this region. This study focused on *Roepera morgsana*, a common but less palatable shrub in the Succulent Karoo biome. The objectives were to find the minimum measurements needed to estimate canopy volume (CVol) and its correlation with leaf dry matter (LDM). The study was conducted at Nortier Research Farm near Lambert's Bay, selecting 25 healthy, non-browsed plants. Seven measurements, including total height and canopy diameter were taken before harvesting. After harvesting, plant material was divided into edible and non-edible parts, dried, and weighed. CVol was determined using various methods, and Pearson's correlation was used to find the best formula to describe LDM. Results showed that CVol based on three measurements (total height and canopy diameter) using Penderis' formula provided the best estimation of LDM ($p < 0.0001$). An exponential regression model best predicted LDM from CVol ($p < 0.0001$), offering a reliable non-destructive method for estimating browse availability from *R. morgsana*. This research contributes to better understanding the browse production of shrubs in winter rainfall regions, providing land managers with a valuable tool for veld management. Moreover, it lays the groundwork for developing similar models for other shrub species, enhancing the sustainability of fodder resources for browsing animals in these regions.

Introduction

The Succulent Karoo and Fynbos Biomes along the west coast of South Africa, with its mediterranean climate with warm dry summers and cool wet winters, are both recognized as biodiversity hotspots with more than 6000 recorded plant species of which many are endemic (Mittermeier et al. 2011; Mucina and Rutherford 2006). The main land use along the west coast is extensive farming, with livestock and to a smaller degree game species. The sustainable utilisation of this natural resource is thus very important. Browse, such as shrubs and dwarf shrubs, is vital fodder for animals during the dry season, as it is the main perennial growth form utilised as fodder in this area (Nenzhelele et al. 2020). However, understanding how much fodder these shrubs can provide sustainably is limited. Non-destructive methods have previously been developed to determine the browse production of savanna trees and some shrubs (Penderis 2012; Smit 2014) and dwarf shrubs in the Nama Karoo (Malan 2015; Smit and Janse van Rensburg 2021), but no techniques exist for shrubs in the winter rainfall region. Smit (1989, 2014) and Penderis (2012) found a relation between canopy volume of the trees and shrubs and their leaf dry mass, while Smit and Janse van Rensburg (2021) found that canopy diameter and the leaf dry mass of a dwarf shrub was highly correlated.

This study focused on *Roepera morgsana,* a less palatable shrub species that is common along the West Coast and other parts of the Succulent Karoo. This species sheds most of its leaves early in the dry season but is among the first to produce new, palatable growth. It grows up to 1.5 m high, is multi-branched and has mesophyllous, slightly fleshy leaves (Le Roux 2015).

The objectives of this research were to determine the least number of measurements necessary to calculate canopy volume (CVol) with the best fit to leaf dry matter (LDM), and to determine the relationship between CVol and LDM and develop a regression model that best predicts LDM.

Methods

Study site

The study was conducted at Nortier Research Farm (32.0345° S; 18.3324° E) situated in the West Strandveld bioregion and Lambert's Bay Strandveld (FS1) vegetation type with many elements of both the Succulent Karoo and Fynbos biome (Mucina and Rutherford 2006). The long-term average annual rainfall is 200 mm with 64% received during late autumn and winter.

Data collection

Twenty-five healthy, non-browsed *R. morgsana* plants were randomly selected at the end of the peak growing season in early October. Seven measurements of each plant were taken before harvesting, namely total height (HT), height at maximum canopy diameter (HM), height of first leaves or potential leaf-bearing stems (HL), maximum canopy diameter (D; average of two perpendicular measurements) and base diameter of foliage at height of first foliage or potential leaf-bearing branches (B; average of two perpendicular measurements). After the measurements were taken the plants were cut down at ground level, and plant material was divided between edible (leaves, and twigs < 2 mm in diameter) and non-edible (stems > 2 mm diameter) parts per individual, dried to a constant mass at 70 °C and weighed. Canopy volume (CVol) was determined according to the BECVOL method (Smit 2014), Penderis' method (Penderis 2012) and basic ellipsoid and cylinder volume formulae.

Data analysis

Pearson's correlation was used to determine the volume formulae that best describe leaf dry matter (LDM). Three regression models, namely linear ($Y = a + bX$), exponential ($Y = a*e^{b(\ln X)}$) and multiplicative ($\ln Y = \ln a + b(\ln X)$), where Y = LDM (kg) and X = CVol (m^3), were tested to determine which volume formulae predict the LDM the best. The linear regressions were performed with XLSTAT (Addinsoft 2023), while the non-linear regression procedure (PROC NLIN) of SAS software (version 9.4; SAS Institute Inc, Cary, USA) was used to fit exponential functions to the data. The natural logarithmic values of CVol were used in the exponential and multiplicative regression models to change the line from convex to concave to get a better fit of the model (Smit 2014).

Results

Pearson's correlation matrix showed that CVol with three measurements (HT and D) using Penderis' formula was the best explanatory variable to describe leaf dry matter ($r = 0.933$; $p < 0.0001$) compared to the other measured shrub dimensions.

All the data points for each model of the three regression models fall within the 95% confidence intervals of the observed data and has very high coefficients of determination values ($r^2 > 0.87$) (Fig. 1). The exponential regression model ($Y = 0.678*\exp^{0.663(\ln X)}$) gave the best prediction of LDM ($r = 0.957$; $p <$ 0.0001; RMSE = 0.163; AIC = -86.688) compared to the linear and multiplicative regression models (Table 1). The square root of variance of residuals (RMSE) is a good measure of how accurately the model predicts the response, while Akaike information criterion (AIC) is used to compare different possible models and determine which one is the best fit for the data. The lower these values are the better the fit of the model (Archontoulis and Miguez 2015).

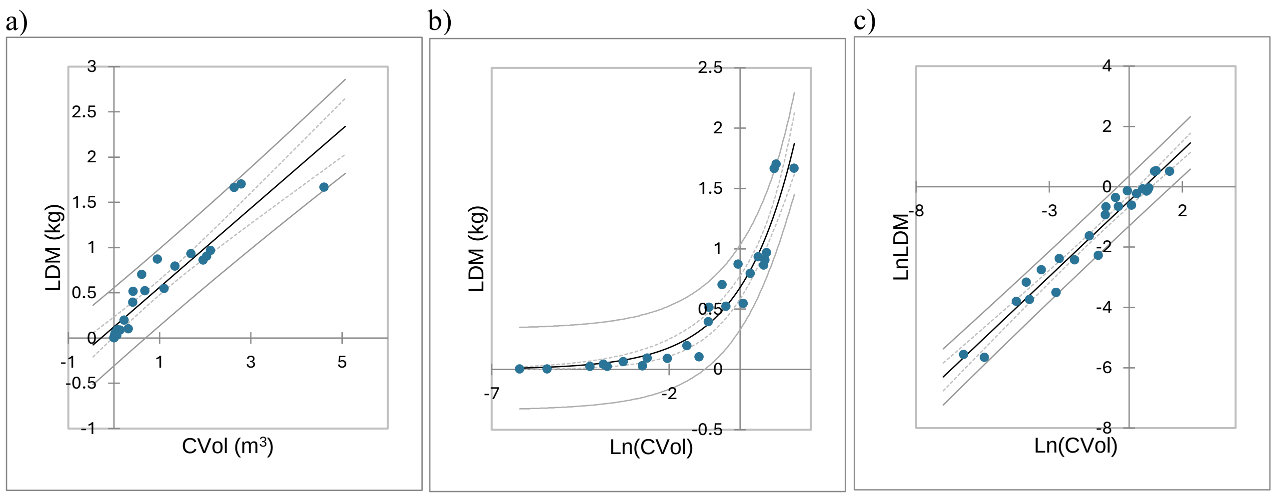

Figure 1: Three different regression analyses (a = linear; b = exponential; c = multiplicative) of the relationship between CVol (m^3) and the LDM (kg) for *Roepera morgsana* following Penderis' formula. The natural logarithm conversion of CVol were used for the Exponential and Multiplicative regression analyses. (Model; --- Confidence interval (mean 95%); Confidence interval (observed 95%))

Table 1 Results of the regression analyses of the relationship between CVol (m^3) and LDM (kg) of *Roepera morgsana* following Penderis' formula.

Regression model	***n***	***r***	***R²***	***p***	**a**	**b**	**RMSE**	**AIC**
Linear	25	0.933	0.870	< 0.0001	0.125	0.437	0.202	-78.051
Exponential	25	0.957	0.915	< 0.0001	0.6799	0.6633	0.163	-86.688
Multiplicative	25	0.977	0.955	< 0.0001	-0.470	0.836	0.391	-45.081

Discussion

Smit (2014) used seven measurements to determine the canopy volume of trees, Penderis (2012) found similar results with only six measurements. Smit and van Rensburg (2021) used only three measurements (HT and D) to find highly significant correlations between CVol and LDM of dwarf shrubs in the Nama

Karoo. *Roepera morgsana* has a similar shape to dwarf shrubs, although it is a much larger plant, and therefore a highly significant correlation between CVol and LDM was found with the same three measurements. Fewer measurements will result in less field work and make the model more attractive for use by land managers, and at the same time ensure that the predictive quality of the model is not sacrificed (Penderis 2012).

The exponential regression model provides a reliable non-destructive method for estimating the browse availability from *R. morgsana*. Available browse is that plant material of a shrub that is potentially edible for browsers based on the height above ground level to which the browsing animals can reach (Penderis 2012). Smit (1989) and Penderis (2012) developed different models, using their measurements for canopy volume, to determine the available browse at the different feeding levels. At 1.5 m high parts of *R. morgsana* is out of reach for sheep, the most common livestock along the west coast, that only browse up to 1.0 m high (Du Plessis et al. 2004). Using Penderis' formula for canopy volume in the regression model allows one to determine the available browse of *R. morgsana* at a specific height above ground level. Knowing the production potential of the vegetation can contribute to the success of sustainable extensive farming with livestock and wildlife (Penderis 2012; Smit 2014).

Conclusion and Implications

This research contributes to better understanding the browse production of shrubs in winter rainfall regions, providing land managers with a valuable tool for range management. Moreover, it lays the groundwork for developing similar models for other shrub species, enhancing the sustainability of fodder resources for browsing animals in these regions.

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Sustainable management to reduce grasslands grazing pressure and improve household income in northern China

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Key words: Farm optimized model; household production; lambing time; pen feeding; seasonal grazing.

ABSTRACT:
Analyses of the status of current livestock production and alternative management practices for livestock production can help farmers improve their farming systems based on their particular local resources and markets. The farm surveys and parameterization of the models were developed by scientists and farmers working together to evaluate the effects of finances, grassland management, animal management and changes in farm infrastructure. Our study aimed to utilize bioeconomic models to optimize farm and livestock production systems in the agro-pastoral area in northern China. These analyses will hopefully lead to improved incomes, provide workable options for farmers and policy makers to restore grasslands and result in sustainable utilization of China's grassland resources.

To examine possible ways to sustainably manage grassland in the agro-pastoral areas, a formal survey of sheep farmers was conducted, and data from experimental trials were obtained in Hebei Province of northern China. The model of farm management analyzed annual feed supply and demand and showed that the gap in the annual feed supply and demand could be reduced by using improved sheep breeds for meat production instead of current breeds. Economic analysis showed that maximal profits could be achieved by using a combination of seasonal grazing at a grazing intensity of 5.4–6 sheep ha^{-1} and pen feeding. In addition, changing lambing time to November would reduce grazing pressure during the summer, which will be beneficial for grassland restoration and enhanced ecosystem services.

By obtaining accurate on-farm information from pastoralists and using these data to parameterize two models, realistic changes in management strategies were identified that could increase farm income and reduce grassland grazing pressure. This activity increased public awareness of optimized farm management tools and provided a sound basis for identifying management alternatives for the sustainable management of grassland resources.

Introduction

Traditional livestock management practices in northern China are often based on survival through the year rather than producing goods for a market and running the farm as a business. What happens on these grasslands has important implications for millions of people in this region of China, and also safeguards the northern and the southeast cropland region of China. Analyses of the status of current livestock production and alternative management practices for livestock production can help farmers improve their farming systems based on their particular local resources and markets (Takahashi et al. 2011; Komarek et al. 2012; Zheng et al. 2013). Model analysis of farm production provides a valuable tool for both government officials and farmers to optimize natural resource use for livestock production. Model solutions have been used to try and guide farmers to increase market access and develop quality standards, thereby making livestock production more profitable Parsons et al. 2011; Komarek et al. 2012; Zheng et al. 2013). The objective of our study was to utilize bioeconomic models to optimize farm and livestock production systems in the agro-pastoral area of Fengning County, Hebei Province in northern China. The farming analysis model was developed by scientists and farmers working together in the northern grassland area of China to evaluate the effects of finance, grassland and animal management and farm infrastructural changes (Kemp et al. 2011). The objective of our study was to utilize bioeconomic models to optimize farm and livestock production systems in the agro-pastoral area of Fengning County, Hebei Province in northern China. These analyses will hopefully lead to improved incomes, provide workable options for farmers and policy makers to restore grasslands and result in sustainable utilization of China's grassland resources.

Methods

Data to parameterize the models were obtained from various sources, including farm surveys, published information, expert opinions and field trials (Ma et al. 2014). Several functional relationships between various biological parameters and either grassland condition or livestock condition were derived using experimental trials in the local area (Figure 1).

Data collected from the farm surveys and field trials were used to parameterize two models: StageONE Feed-Balance Analyser Model and StageTWO Optimising Model (Takahashi et al. 2011). The model uses metabolisable energy to link feed supply, demand and utilization. Both models derive net farm livestock financial returns for the starting conditions using biophysical and financial data.

Results

Current sheep production system in Fengning County

In the southeast portion of the Mongolian Plateau, Hebei fine-wool sheep and small-tail sheep crossed with Mongolian sheep are the dominant livestock. The typical farm averages 5 to 8 ha of land for fodder (typically maize silage, oats, wheat and potatoes), and about 700 ha of grassland is communally used by the village. Lambs are born from January to March and sold at about 8 to 12 months of age, according to the herder's need and market price. Grassland is continuously grazed at a stocking rate of 4.0 sheep ha^{-1} throughout the year, resulting in very high grazing pressures. Though a few small household farmers feed sheep during winter, energy and nutrient deficiency are typical from late-September to May because of poor forage nutrition and animal management (Figure 2a).

Figure 1 Study location of Fengning County, Hebei Province in northern China.

Options for farm improvement using different sheep breeds

In recent years, most farmers switched their focus to meat production due to the favorable mutton market. Farmers prefer small-tail sheep to other varieties because of the high birth rate, though this variety is not good for meat production. Given the poor nutrition of animals during winter and the high cost of purchased fodder, one alternative strategy is to use sheep varieties with good meat production. Some local farmers have crossed local ewes such as small-tail sheep with German Merino rams or Dubo rams for improved meat production. These crosses can increase live-weight gain with grazing during the summer and pen feeding in winter. Data from these new sheep breeds and the pen feeding trial were used to re-run the StageONE Model. The model results showed that the energy gap between maintenance and actual feed intake was narrowed (Figure 2b).

Options for farm improvement by changing lambing time

Results from the StageONE Model showed that lambing in January through March resulted in a sub-maintenance level of energy intake for ewes during most of the year (Figure 3a). Lambing in Jan. would be predicted to result in a major feed deficit from January through April (60% of maintenance). April lambing (Figure 3b) was closer to the maintenance level during November to February, but resulted in a large feed deficit during March to June (50% of maintenance). Lambing in June (Figure 3c) enabled an improved feed equivalent during winter and spring; however, intake did not meet maintenance levels during summer grazing in June and July. Lambing in November (Figure 3d) allowed intake to reach maintenance levels for nearly the entire year. This strategy might be further improved by possibly selling lambs and cull animals earlier (3 to 4 months of age) and by providing good nutrition in feeding pens. By lambing in November, pregnant ewes would have a greater probability of accessing higher quality forage during the summer, resulting in a higher lamb birth weight.

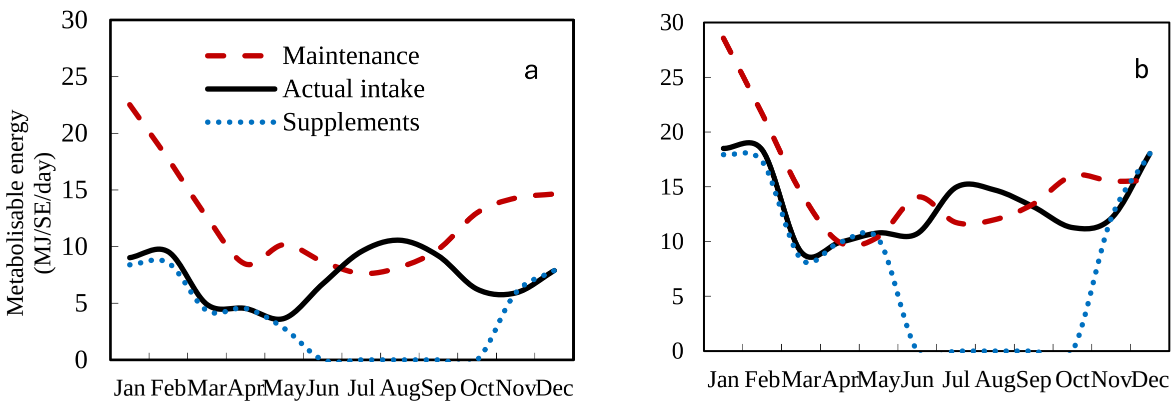

Figure 2 Metabolisable energy (ME) requirement, total ME intake and ME from supplements at the same live-weight per sheep equivalent for a typical farm in Fengning County, Hebei Province: a) current farm production and b) farm production using an improved sheep breed. (Note: Total ME intake is the intake of forage plus supplements. Ewes lambing in January).

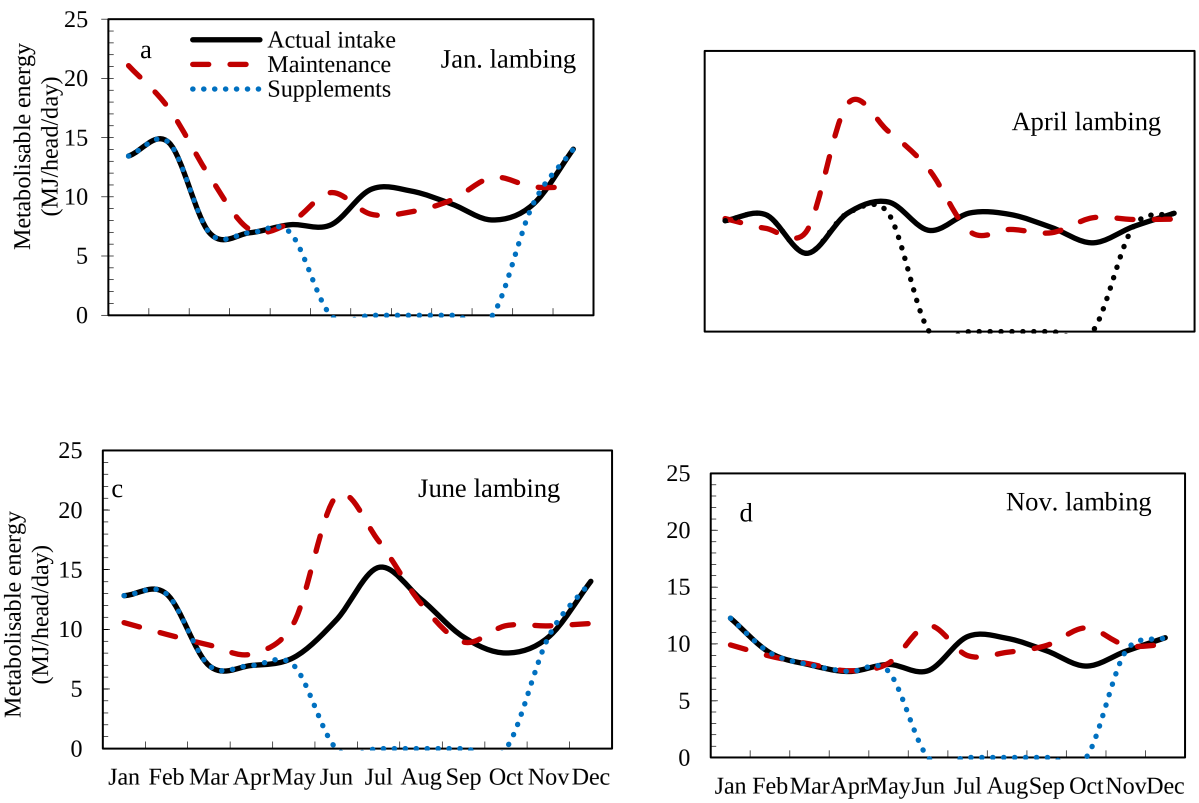

Figure 3 The effect of lambing time on feed energy balance for ewes in Fengning County, Hebei Province for: a) lambing in January (typical practice), b) lambing in April, c) lambing in June and d) lambing in November. With pen feeding from 15 Oct. to 15 June, feeding oat hay at 0.2 kg/day/head, alfalfa hay at 0.5 kg/day/head, maize grain at 0.1 kg/day/head, and other protein sources at 0.1 kg/day/head (ME = metabolisable energy).

Discussion

A key issue for managing livestock is maintaining a balance between livestock feed requirement and livestock feed availability (Darnhofer et al. 2010; Ma et al. 2014). Efforts to achieve this balance typically focus on increasing the forage and feed available to livestock and improved livestock performance through breeding (Herrero et al. 2009). Based on our local farm survey and the application of *StageONE* and *StageTWO* Models, we identified several strategies that may be beneficial for improving sheep management in northern China.

Analyses of the current livestock production status and alternative production management strategies through on-farm surveys and the application of model analysis showed the following changes should be made to the current farming system: 1) grasslands should only be grazed during the growing season, 2) pen feeding should be done during the non-growing season and 3) lambing time should be changed. These changes would better match local resources and lamb markets. The farm surveys and parameterization of the models were developed by scientists and farmers working together to evaluate the effects of finances, grassland management, animal management and changes in farm infrastructure. By obtaining accurate on-farm information from pastoralists and using these data to parameterize two models, realistic changes in management strategies were identified to increase farm income and reduce grassland grazing pressure. This activity increased public awareness of optimized farm management tools and provided a sound basis for identifying management alternatives for the sustainable management of grassland resources. Hopefully this process can be applied in other regions of China to more sustainably manage China's vital grassland ecosystems and improve the livelihood of pastoralists.

Acknowledgements

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THEME 4. INTEGRATING RANGELAND ECOLOGY INTO MANAGEMENT

Ameliorating rangeland soil health

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XII INTERNATIONAL RANGELAND CONGRESS AUSTRALIA 2025

Soil microbial community and functionality in response to degradation in alpine grassland: a meta-analysis

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Key words: grassland degradation; microbial diversity; microbial adaptation; nitrogen cycling

Abstract

Alpine grasslands have undergone severe degradation over the past half century. Investigating the changes in soil microbial communities is crucial for developing effective restoration strategies in degraded grassland. In this study, we synthesize data from 36 studies worldwide and show that soil microbial alpha and beta diversity did not show significant response to grassland degradation. However, we found increases in the relative abundance of bacteria related to adaptation to extreme environments, e.g., *Gemmatimonadetes*, but decreases in the relative abundance of sensitive fungi taxa (e.g., *Basidiomycota*) following degradation. Additionally, we observed a decline in soil functions related to nitrogen decomposition and fixation under heavy degradation. Overall, these findings advance our understanding of the impact of grassland degradation on soil microbial communities and their functions across a large scale. This study highlights the importance of restoring soil microbial communities in degraded grasslands to sustain soil function. Future research should develop suitable practices associated with microbial inoculation or regulation to facilitate grassland restoration.

Introduction

Alpine grasslands are experiencing serious degradation due to the dual impacts of climate change and human activities. Soil microbial communities are of great importance for ecosystem functions, for instance, nutrient cycling. Usually, significant changes in soil microbial diversity and community structure will occur following degradation in temperate grassland. However, previous studies did not observe directional changes in soil microbial community composition in alpine grassland. For example, a previous study suggest that there was a decrease in bacterial richness after degradation (Wang *et al.*, 2021), while another study found bacterial richness did not show significant response to degradation, and the response of fungal richness varied by site (Che *et al.*, 2019). Given that the variance in microbial diversity and community composition induced by grassland degradation can dramatically suppress ecosystem functions (Breidenbach *et al.*, 2022), there is an urgent need to uncover the general response of soil microbes to degradation at a global scale when restoring degraded grasslands. We aimed to systematically assess the response of microbial communities to degradation in alpine grassland through Meta-analysis. This study will provide a scientific basis for formulating ecological protection and restoration strategies.

Methods

Data collection

We searched Web of Science (WoS, http://apps.webof knowledge.com/) in January 2024, with the following topic search ((grassland OR alpine) AND (micro* OR bacteria OR fungi OR AMF OR arbuscular mycorrhiza* fung* OR AM fung* OR AM symbiosis) AND (degrad* OR degenerat* OR deteriorat* OR deplet* OR restor* OR recover* OR reestablish* OR rehabilitat* OR renew*)). This search yielded more than 14,000 records. To avoid bias, the following criteria were used to screen studies: (1) The study was conducted on alpine grasslands and clearly described whether the studied grasslands were degraded or not. (2) Microbial community structure was determined using high-throughput sequencing, and at least calculated one soil microbial community metric, including alpha diversity (e.g., Chao1 or Simpson), beta diversity, and community structure was reported. (3) The study site was old-growth grassland rather than artificial grassland. (4) Sampling was conducted during the peak growing season. (5) Experiments with factors, such as N deposition, warming, drought, etc., were excluded. (6) Only field studies were selected, and laboratory incubation studies were not included. Finally, a total of 36 publications were remained for meta-analysis. For each study, we extracted means, sample size and standard deviation (SD) or standard error (SE) or 95% confidence interval (CI) if reported. If results were presented graphically, the software WebPlotDigitizer 4.6 (https://automeris.io/WebPlotDigitizer/) was used to digitize the data. Given that the levels of degradation likely affect the results, we captured the levels of degradation for each study. The degraded grasslands were considered to be lightly degraded if vegetation cover has decreased by more than 30%, and heavily degraded grasslands were those with a decrease of more than 50% in vegetation cover, compared to undegraded grasslands.

Calculation of the individual response ratios (RRs)

We used the natural logarithm-transformed (ln) RR to calculate the response of variables for each case study:

$$RR = ln\frac{Xt}{Xc} \qquad (1)$$

where $\bar{X}_t$ and $\bar{X}_c$ are the means of the concerned variable in the degraded and undegraded grasslands, respectively.

Its variance (v) were calculated as:

$$v = \frac{SDt^2}{Xt^2} + \frac{SDc^2}{Xc^2} \qquad (2)$$

where SD_t and SD_c are the standard deviations of the variable in the degraded and undegraded grasslands, respectively.

Calculation of the overall RR

All statistical analyses were performed in R (R Devel opment Core Team, 2024) using the R package *metafor* (Wolfgang Viechtbauer, 2010). The mixed-effect model was used to calculate the overall RR and the corresponding 95% confidence intervals of target variables. This model was also used to compare the RRs of variables between the light and heavy degradation by the omnibus test (QM). If the 95% confidence intervals for one RR overlapped with zero, then it was considered as an insignificant response to grassland degradation.

Results

Grassland degradation did not alter microbial diversity but reduced microbial function.

Grassland degradation did not affect alpha diversity (Chao1 and Simpson) and beta diversity of bacteria and fungi, but significantly changed community structure (Fig 1a). For instance, grassland degradation increased *Gemmatimonadetes*, while decreased *Basidiomycota* (Fig 1b). Grassland degradation had no effects on microbe biomass, enzyme activities of carbon (C) and nitrogen (N) decomposition. Grassland degradation did not affect the abundance of denitrification and nitrification genes, but decreased gene abundance related to nitrogen fixation (Fig 1c).

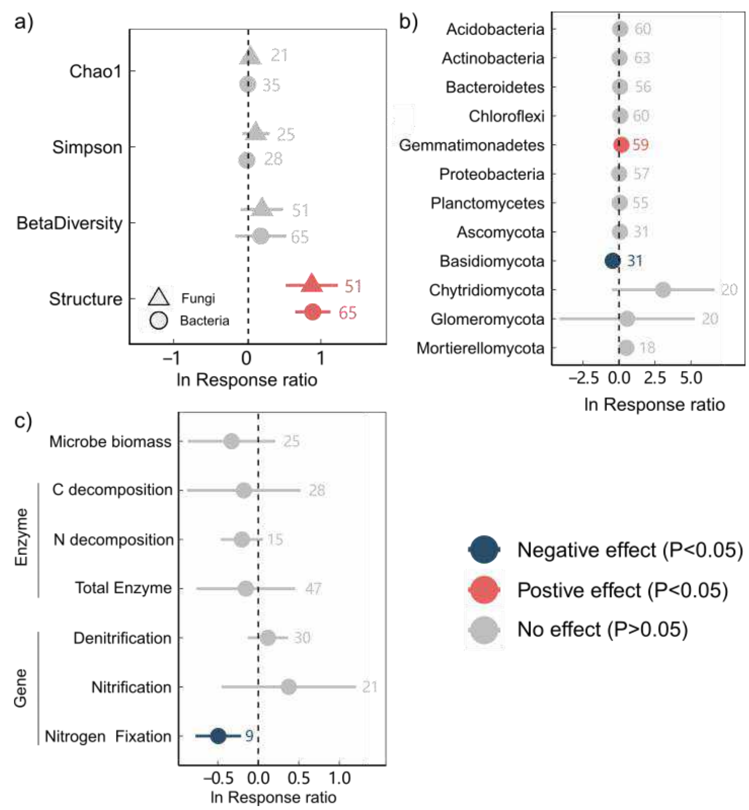

Fig. 1 Response ratios of soil microbial diversity (a), microbial community composition (b) and microbial function (c). Points are weighted means of RRs with 95% confidence intervals. The numbers on the right side of confidence intervals represent sample sizes. Positive mean values indicate increased variables induced by degraded grassland (red dots), while negative mean values indicate decreased variables induced by degraded grassland (blue dots). The intersection of confidence intervals and zero line indicates that there is no significant difference between the degraded and undegraded grassland (grey dots).

The RRs were significantly affected by the levels of degradation (Fig 2). As the levels of grassland degradation increased, we observed stronger RRs of enzyme activities (Fig 2a) and genes related to N cycling (Fig 2b). The overall and light degradation did not significantly affect C decomposition and N decomposition enzyme activities. However, when grasslands experienced heavily degradation, there were dramatic decreases in C and N decomposition enzyme activities (Fig 2a).

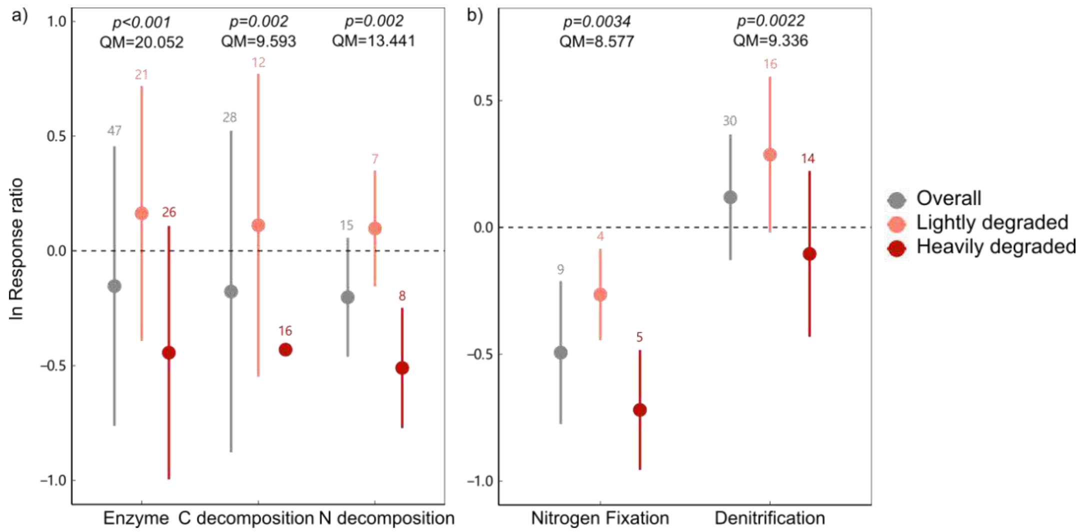

Fig. 2 Response ratios of soil enzyme activities (a) and functional genes (b) across grassland degradation levels. Points are weighted means of RRs with 95% confidence intervals. The numbers on the right side of confidence intervals represent sample sizes. Positive mean values indicate increased variables induced by degraded grassland (red dots), while negative mean values indicate decreased variables induced by degraded grassland (blue dots). The intersection of confidence intervals and zero line indicates that there is no significant difference between the degraded and undegraded grassland (grey dots).

Discussion

Grassland degradation altered soil microbial community structure. Degraded grasslands had lower soil nutrient content and poorer physical soil properties, such as reduced soil organic carbon content and lower aggregate stability, compared to undegraded grasslands (Li *et al.*, 2021; Luo *et al.*, 2023). These changes may explain the increase in the relative abundance of *Gemmatimonadetes*, which can adapt to extreme environments, and the decrease in *Basidiomycota*, which are particularly sensitive to environmental disturbances. Grassland degradation did not significantly affect microbial diversity. Microbial communities can sustain biodiversity through species turnover. For instance, following grassland degradation, certain microbial taxa, such as drought-tolerant bacteria, can replace less resilient species, thus preserving overall species diversity within the community (Liu *et al.*, 2023).

Grassland degradation decreased nitrogen fixation genes. The abundance of efficient nitrogen-fixing bacteria, such as *Rhizobium* spp., decreased, while microorganisms with lower nitrogen-fixing efficiency became more dominant following grassland degradation (Zhang *et al.*, 2022). Heavy degradation suppressed C and N cycling indicated by a decrease in C and N decomposition genes. Key microbial groups, such as efficient N-fixing bacteria and decomposers, diminished and cannot be replaced by other microorganisms, leading to a decline in critical soil ecological functions, such as organic matter decomposition and nitrogen cycling (Breidenbach *et al.*, 2022). This suggest that practices stimulating C and N cycling or increasing nutrient content should be developed in further studies. Light degradation did not significantly affect other functions of soil microbes, suggesting that these functions may be redundant (Louca *et al.*, 2018).

Grassland degradation shifted soil microbial community composition, increasing stress-tolerant taxa while decreasing those that are sensitive. Additionally, heavy degradation weakened soil functions, suggesting the loss of functional redundancy. These findings highlight the importance of managing microbial communities in grassland restoration. Future restoration efforts should prioritize the recovery of microbial community and functional redundancy. Moreover, the severity of grassland degradation influenced the maintenance of soil functions, highlighting the importance of early intervention and effective land management to prevent irreversible loss of microbial functions.

Acknowledgements
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Using gypsum to ameliorate a highly-saline, scalded claypan

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Key words: scald amelioration; gypsum; sodicity

Abstract

Scalds are common on degraded soils in the rangelands of western NSW. Scalds restrict plant growth and biological activity. Scalds form due to dispersive (sodic) sealing surfaces and high salinity. Sodic soils can be stabilised by the addition of gypsum which flocculates the soil in the short term and decreases the propensity to disperse in the medium to longer term while facilitating leaching of problematic chloride salts. This study examined the use of gypsum to remediate a scald that was sodic (exchangeable sodium percentage (ESP) >10%) and had high salinity (electrical conductivity (ECe) ~45 dS/m) to at least 60 cm soil depth. Mechanical disturbance (ripping with a single mouldboard plough) previously trialled resulted in only minimal establishment of halophytes with shallow roots but with no survival. A replicated trial was established to examine the response of soil and pasture to four rates of gypsum: nil (Control), 1 t/ha (Low), 2.5 t/ha (Moderate), and 6.5 t/ha (High). The design allowed remote monitoring via Sentinel imagery.

After 12 months there was greater volunteer plant establishment and decreased surface salinity (to ~5 dS/m) in the High treatment areas. Satellite imagery indicated greater cover of green vegetation (NDVI) during the growing season, but only in the High treatments. While the timing of rainfall and leaching of salts will influence the persistence of the improvements, the results so far show the amelioration of an extreme scald with appropriate techniques.

Introduction

Scalded soils present problematic conditions for water infiltration and for plant establishment and growth. Scalds are areas that have lost their topsoil, leaving a clay subsoil as the new surface layer which is commonly hard, saline or sodic. Scalded country is common on alluvial and residual soils in the rangelands of western NSW and in dry regions globally. Researchers since the 1940s have demonstrated remediation of scalded land in the NSW rangelands by natural regeneration, and intervention by ripping, ponding, and managing grazing pressure. Successful remediation is the restoration of functioning soils and productive systems. Because salinity is a common feature of soils in dry areas and is close to the surface on scalded sites, flushing salts deeper into the profile is key to scald remediation.

Gypsum applied to dispersive soils can act to flocculate the soil surface in the near term while infiltration leaches undesirable salts deeper. In the longer term, calcium in the gypsum can exchange with sodium on clay surfaces to decrease their propensity to disperse. When vegetation establishes, infiltration can be enhanced and wicking of salts to the surface decreased; all these processes reinforce the amelioration of the scald.

The objective of this study was to assess remediation of a scald on an alluvial soil in north-west NSW, using different rates of gypsum, and to compare the soil conditions between the treated site and a nearby area that is recovering naturally.

Methods

The trial was located on 'Gurrawarra', approximately 80 km north-east of Bourke, NSW Australia (29º46'41"S, 146º23'19") on a scald situated on an alluvial meander plain west of the current Culgoa River. The climate is semi-arid, with an average annual rainfall of 370 mm, with a summer dominant rainfall pattern. Preliminary assessment of the scald identified high salinity, a dispersive surface and highly aggregated subsurface. The scald has persisted despite previous mechanical disturbance (ripping with a single mouldboard plough). The site was devoid of vegetation except for some small dead halophytes present in the old rip lines.

The application of gypsum was chosen because the landowners had noted the long-term (>10 years) effect of established vegetation at isolated spots where gypsum tailings had been dumped on the property. Prior to the application of the gypsum, soils were analysed at 0-10 cm, 10-20 cm, 20-30 cm and 30-60 cm for salinity (Shaw, 1999) and sodicity profiles (electrical conductivity, soluble chloride, exchangeable sodium percentage). Exchangeable cations were measured by the Tucker method with pre-wash to minimise any artefact of soluble salts or dissolution of sparingly soluble salts (15C1, Rayment and Lyons, 2011). Satellite data to calculate NDVI (normalised difference vegetation index; no units) for each plot was downloaded from the Sentinel portal (Copernicus; https://sentinel.esa.int/web/sentinel/home) from the first available date (2-11-2016) to November 2024. Laboratory analyses of samples collected in July 2023 from inside and outside the old gypsum dump and a separate self-ameliorating scald were also made for comparison with the trial.

The trial was established in July 2023. Three replicates of four treatments (including a Control) were established in 50 x 50 m plots. Gypsum was spread evenly at rates to reflect the approximate amount of gypsum dissolved through 10 cm at field capacity (1 t/ha, Low), a standard rate to allow for some leaching (2.5 t/ha, Moderate), and a rate to allow additional time for leaching and adequate for replacement of Na with Ca on the clay exchange sites (6.5 t/ha, High; Loveday 1976). The soil surface was tilled to approximately 10 cm after spreading to minimise wind drift. Banks were mounded around the site to minimise run-on.

Soil sampling and assessment of vegetation cover was undertaken in July 2024. 20 soil samples in each plot were composited at depths 0-5, 5-10, 10-20, 20-30cm for the same laboratory analysis as the 2023 samples. Additional samples were collected from the general plot area and the pre-existing rip lines (Control and High plots only), and under patches of newly established vegetation (High plots only) to assess effects of ripping and vegetation. Ground cover (percent cover of plant, litter, cryptogam, coarse woody debris, dung, rock or bare ground) was monitored in twenty 0.5 x 0.5 m quadrats located along four transects in each plot. Standard errors (se) were calculated for each measure.

Results

No differences in soil properties between treatment plots were found in the initial measurements. Drought conditions persisted following establishment of the trial until early 2024 after which 300 mm fell through the winter and spring. A visible response of improved infiltration in the High treatment compared to surface ponding in other plots was borne out with increased vegetation cover in July 2024. Vegetation cover did not differ significantly between the Control, Low and Medium treatments (averaging 4.2-7.2%) but was higher on the High gypsum treatment (average 18.0%, Figure 1). Despite the response of vegetation to the High rate of gypsum, there was no significant difference between the treatments in salinity down the soil profile (Figure 2). However, there was an overall decrease in salinity at the surface, and translocation to below 20 cm, compared to 2023 following good rainfall (Figure 2). The soil under vegetation in the High plots had lower salinity through to 20 cm depth than the bare Control and the bare patches within the High plots (Figure 3). The existing rip lines also affected salinity: within the High plots the salinity in the rip lines was lower than the bare areas in the 0-5 cm and 20-30 cm increments; and in the Control plots the salinity was lower in the Rip lines than away from the rip lines through the to 20 cm. After just one year there was no change in sodicity with any rate of gypsum (data not shown).

The salinity levels of the upper profile in the gypsum dump and under vegetation of the self-ameliorating area were low, while outside the dump the salinity was high and in bare areas of the self-ameliorating area the salinity was half that of the trial site. The sodicity inside the gypsum dump was lower compared to outside (5% and 15%, respectively, data not shown).

The relatively good 2024 season was reflected in the greater NDVI in the Control, Low and Moderate plots compared to the period preceding the trial (Figure 4). The apparent increase in NDVI immediately following installation was likely due to the surface disturbance. The greater plant cover observed in the High treatment compared to the other plots was consistent with the NDVI (up to 0.21), while there was no difference in NDVI between the Control, Low and Moderate plots.

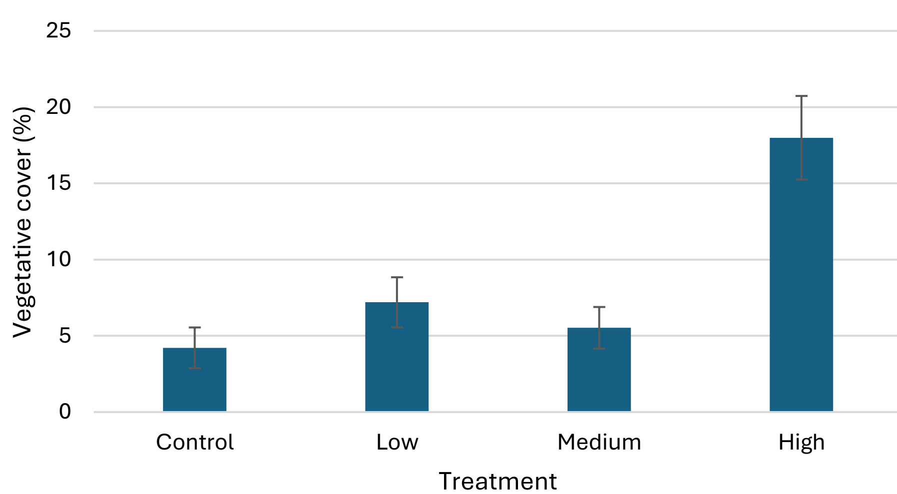

Figure 1. Average vegetative (plant + litter) cover within the different gypsum treatment plots in July 2024 (+/- 1 se).

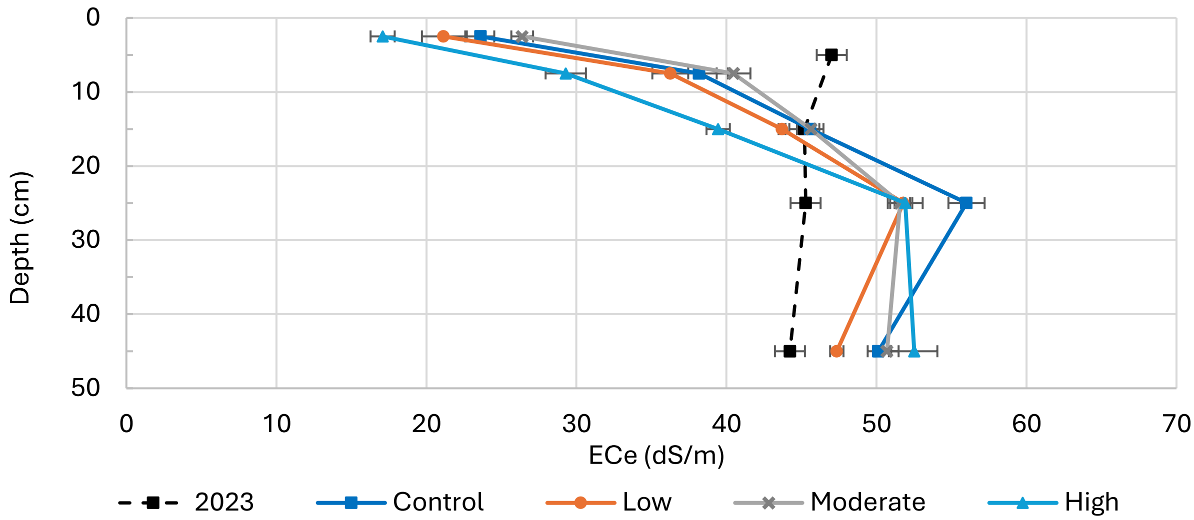

Figure 2. Average salinity (electrical conductivity, ECe) down the soil profile of the Control and Low, Moderate and High gypsum application plots in July 2024 and the site average in July 2023 (+/- 1 se).

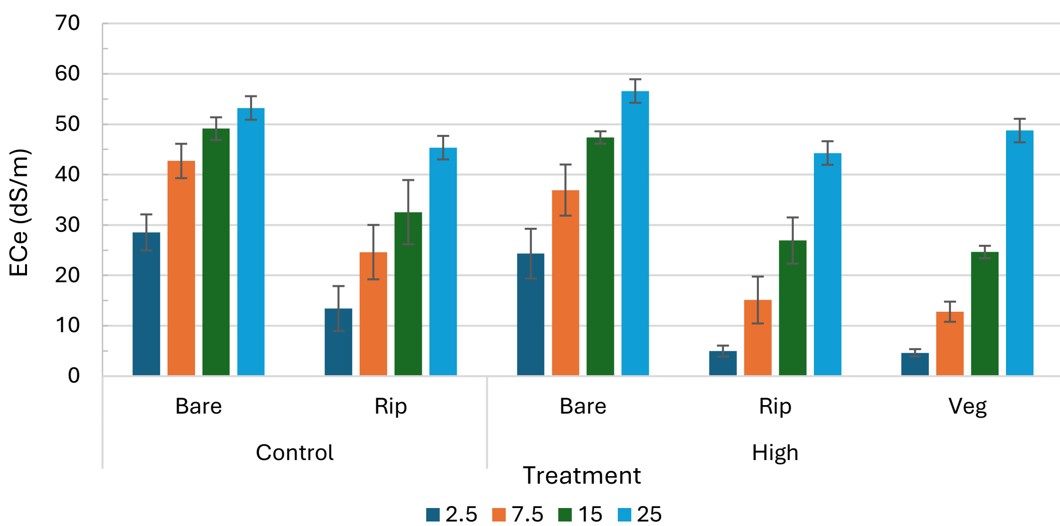

Figure 3. Salinity (electrical conductivity, ECe) within the Control and High treatments in July 2024 (+/- 1 se). Insufficient (~no) vegetation was present for sampling outside of rip lines in control plots.

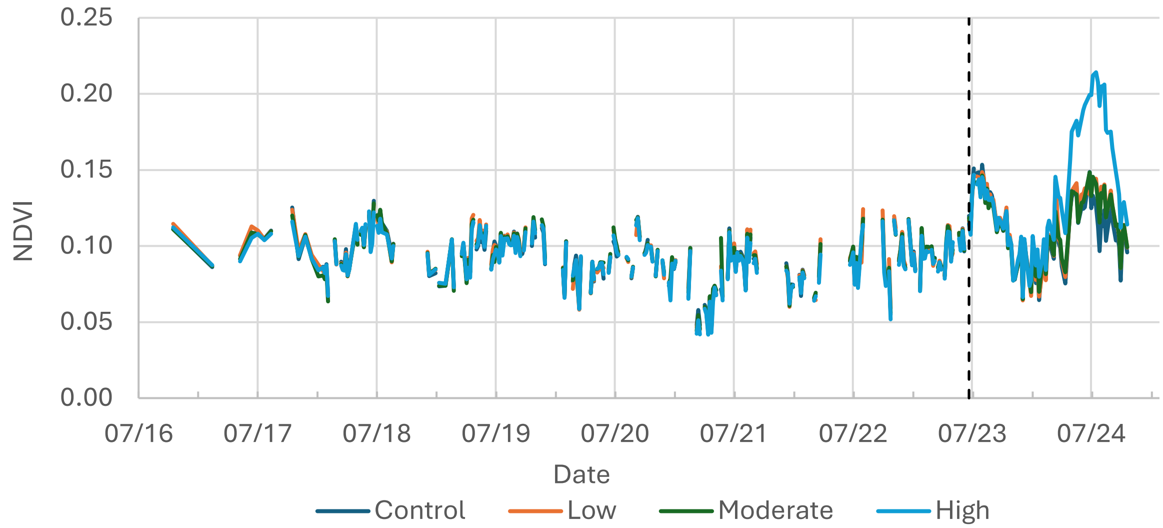

Figure 4. Remotely sensed NDVI over time at the gypsum demonstration site by treatment (vertical dashed line indicated date in installation).

Discussion

The overall response of both soil and vegetation to the gypsum application and earlier ripping on the scald has been an improvement in soil properties and a subsequent increase in plant establishment. The earlier ripping appeared to allow better infiltration and flushing of salts. However, these rip lines are narrow (~30 cm), and particularly in the Control areas the vegetation is still sparse. By comparison, the effect of the gypsum was promising but only at the High rate. While patchy, establishment of substantial patches of vegetation beyond the rip lines in vegetation the High treatment is likely to more effectively leach salts (Jones 1967). While senesced at the time of reporting (late spring 2024), the surface cover remains and serves to enhance infiltration.

The long-term success of the amelioration will depend on the persistence of the changes in the coming season and through drier periods. Persistent vegetation cover (even if senesced) would minimise wicking and re-occurrence of surface salinity, while ongoing exchange of Na for Ca would improve the inherent dispersibility. The marked change in salinity between 2023 and 2024, and between the treatments in 2024 compared to no significant change in sodicity indicates how much more dynamic fluctuations in salinity are compared to exchange processes. By comparison, the decrease in sodicity at the gypsum dump has occurred over 10 years at an unknown rate but likely very high rate of gypsum (Loveday 1976). Rather, landscape characteristics and the extent of the limiting factors guide the appropriate remediation technique and suitable rate of gypsum application. As is well understood (e.g. Jones 1967, Eldridge 1988), it is the leaching of salts that is often key to improving the rootzone for plant establishment and initiating positive feedback, and subsequent management and conditions determine the ongoing success of scald amelioration.

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Soil testing to support decision making in the rangelands

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Key words: acidity; salinity; phosphorus deficiency; organic carbon

Abstract

Soil testing is not typically conducted in extensive and low input rangelands systems. To assess the usefulness of quantifying soil properties, we benchmarked selected soil physicochemical properties with producers from 33 properties in the semi-arid rangelands of NSW, Australia. Producers selected sampling locations of different soil types and landscape positions to compare attributes of the upper rootzone (10 cm increments to 30 cm) for pH, salinity, exchangeable cations, sulphur (S), phosphorus (P), and soil organic carbon (SOC).

Laboratory analyses typically showed an increasing soil pH with depth to alkaline levels on alluvial soils. The pH of non-alluvial soils (aeolian and bedrock-derived soils) was evenly distributed from moderately acidic to moderately alkaline, though some areas were identified with acidity constraints. Soil salinity was generally low, but some targeted sites had soil salinity levels comparable to sea water. Sodic soils were found in many areas. Low SOC was associated with high salinity and sodicity. Soil P was high in some areas, particularly the alkaline alluvial soils, though on some non-alluvial soils P was low enough to limit livestock productivity.

Benchmarking soil properties proved a strategic tool for rangeland producers to identify constraints not previously quantified and assess management options. Some targeted ameliorants or supplements may lead to improved productivity and returns on investment. The results provide a basis for further investigation to address any constraints and variable productivity.

Introduction

Chemical, physical and biological properties influence the inherent productivity of soils, though soil testing is not typically conducted in extensive and low input rangeland systems. Management in rangelands is complicated by a typically variable climate, often compounded by historic degradation which sees producers managing landscapes in various stages of soil stabilisation and recovery. This management requires attention to soil health, identified by farmers in NSW semi-arid rangelands as a priority for their production systems.

The objective of this paper was to identify potential constraints to production in NSW rangelands from targeted soil sampling on 33 properties in the semi-arid rangelands of NSW, Australia.

Methods
Producers were trained in soil sampling for laboratory testing in 2023. Samples were collected from up to four sites each, enabling comparison between sites. Training in the use of the soil kits was undertaken through regional workshops and discussion with the project team. At each site, samples were composited at depths 0-10, 10-20 and 20-30 cm for laboratory testing. Laboratory testing of samples to characterise the upper rootzone increments included pH in water (pHw) and $CaCl_2$ (pHCa), electrical conductivity (EC), exchangeable cations, soil organic carbon (SOC) by dry combustion, P by Colwell and BSES, and S (KCl40). Chloride (Cl) was measured on selected samples for salinity (Shaw 1999) and effective EC was estimated according to Shaw (1999) for samples with EC>0.3 dS/m or by Slavich and Peterson (1993). Exchangeable cations were measured according to pH and EC (15C1 for samples with pHw>7.3 and EC>0.3, or 15E1; all procedures as per Rayment and Lyons 2011). Results were grouped into samples taken from alluvial or non-alluvial sites.

Results
Acidity, salinity, sodicity and organic carbon
Across all sites, the pH of the 0-10 cm samples ranged from slightly acidic to slightly alkaline (Figure 1), generally increasing with depth. The difference between pHw and pHCa varied with EC, from zero (highest EC) to two units (lowest EC). Approximately 5% of samples had pHCa less than 4.8 (minimum 4.1).

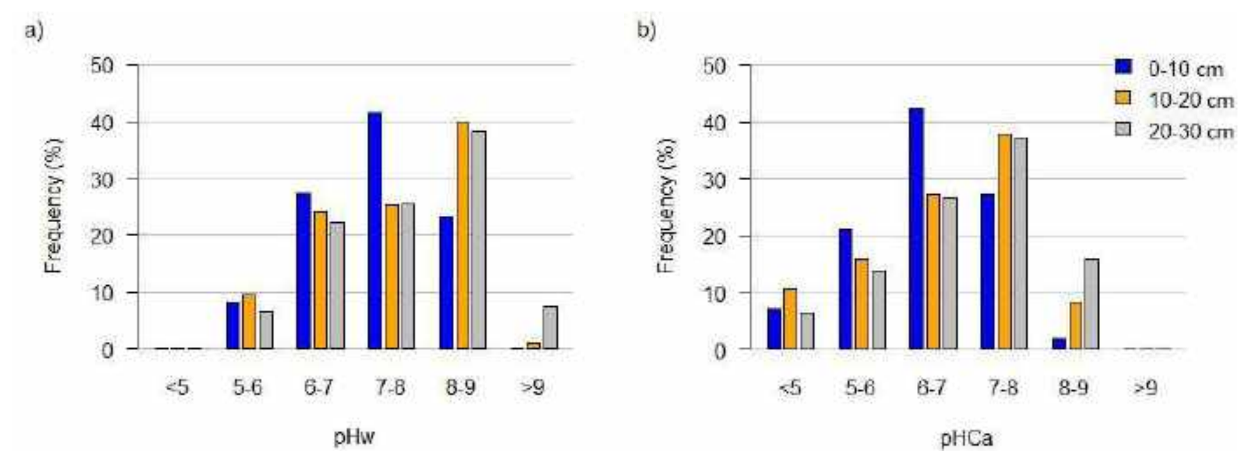

Figure 1. Frequency distribution of soil a) pHw and b) pHCa by depth for all samples.

Salinity was generally low in the samples collected from the upper 30 cm at each site (Figure 2). High salinity was more common in alluvial areas than the non-alluvial areas. 14% of sites sampled were areas of low productivity areas or scalds where the salinity was above 8 dS/m, and as high as the mid-fifties dS/m.

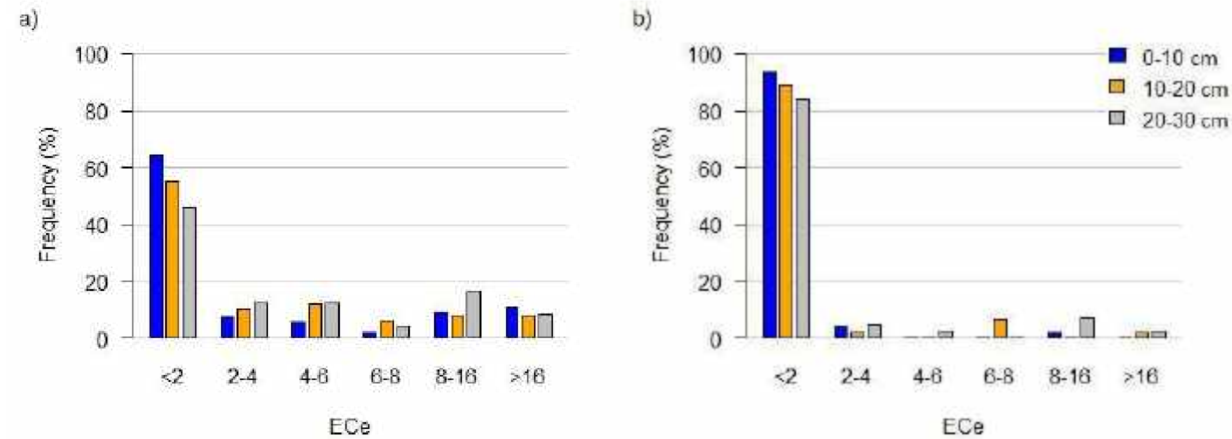

Figure 2. Salinity (electrical conductivity, ECe (dS/m) by depth in a) alluvial and b) non-alluvial areas.

Sodicity (ESP> 6%) was more common on the alluvial soils than the non-alluvial soils. There was a pattern of lower SOC in samples of increasing salinity and sodicity (Figure 3).

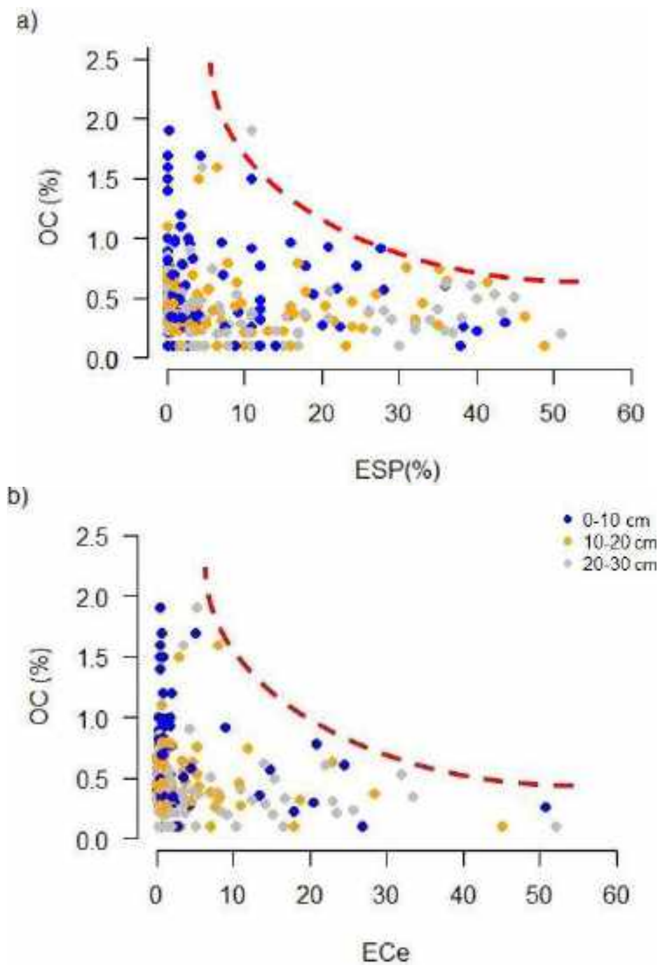

Figure 3. Relationship between soil organic carbon and a) ESP and b) salinity, by depth for all samples.

Fertility

The Colwell-P results ranged from below the laboratory's limit of reporting (LOR; <2 mg/kg) to 160 mg/kg (Figure 4). Colwell-P was higher in the surface than the deeper increments, and the non-alluvial soils had lower Colwell-P than the alluvial sites. In the non-alluvial areas 33% of 0-10 cm samples had Colwell-P <5 mg/kg, and a further 15% <8 mg/kg. At acidic to neutral pH levels the ratio of BSES-P:Colwell-P was between 1:1 and 4:1 (Figure 5), but at pHw >7.5 the ratio increased over 5:1 and up to 24:1 in 34% of 82 samples.

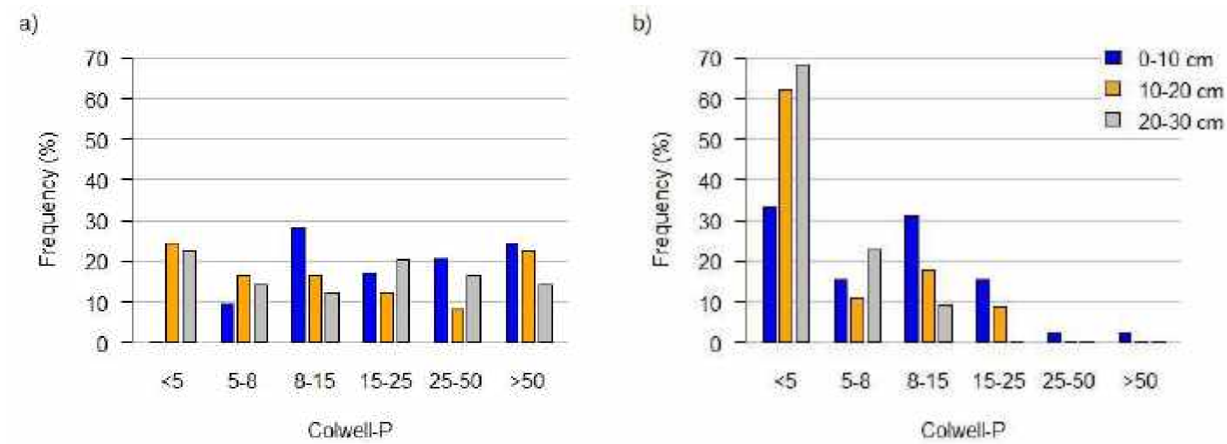

Figure 4. Frequency distribution of Colwell-P (mg/kg) by depth from a) alluvial and b) non-alluvial sites.

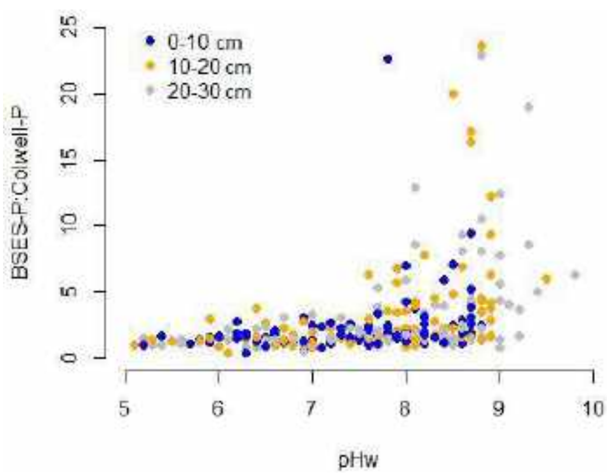

Figure 5. The ratio of BSES-P:Colwell-P v pHw by depth for all samples.

Sulphur levels were low (<5 mg/kg) at 42% of alluvial sites and 82% of non-alluvial sites (Figure 6). At the non-alluvial sites there was generally no substantial store at depth (92% had <10 mg/kg and 72% <5 mg/kg). By comparison, half the alluvial sites with low surface S had >20 mg/kg in the lower depth increments.

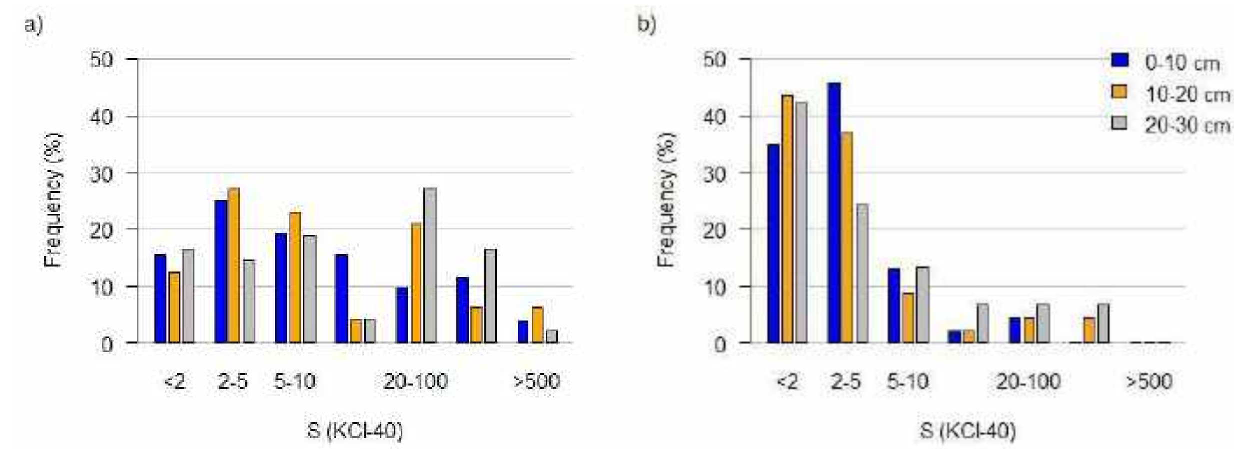

Figure 6. Frequency distribution of sulphur (mg/kg) by depth from a) alluvial and b) non-alluvial sites.

Discussion

Soil testing is rarely undertaken in the low input, extensive nature of livestock production in the semi-arid rangelands of southern Australia despite soil erosion, sodicity, surface sealing and salinity commonly causing constraints to production. Due to low rainfall, the soils are generally less leached and therefore can have higher pH, salinity, and fertility than high rainfall regions. Conversely, organic matter levels are generally low, which accentuates a range of soil structural and nutrient cycling problems.

This survey highlights the influence that attributes such as geomorphology have on soil properties. For example, soil alkalinity can induce nutrient deficiencies, while acidity found in some non-alluvial soils can restrict root growth and seedling establishment through nutrient imbalances and aluminium toxicity. The difference between pHw and pHCa fundamentally reflects the ions in solution (Slattery et al. 1999), and the most saline soils had the closest values. Salinity was a consistent feature of scalded areas, and in marginal areas was observed to vary within metres from high levels on bare ground and low levels under plant cover. Salinity >10 dS/m was common at such sites, and some cases approached double the concentration of seawater.

Low sodicity of the non-alluvial sites was expected as the region (Cobar pediplain, NSW Australia) has little sodicity, while sodium accumulation is common in western alluvial systems (Isbell et al 1997). Sodicity limits infiltration and root growth, and salinity limits moisture availability to plants. The low SOC with high sodicity and salinity may reflect a restriction to plant growth and accumulation of organic matter. Understanding these patterns highlights the importance of maintaining or building soil organic matter to buffer the impacts of salinity and improve soil structure, and can inform producers of appropriate management options.

Phosphorus was low on many non-alluvial areas characterised by mulga (*Acacia aneura*) and ironbark (*Eucalyptus crebra*) (Jackson et al. 2012). If forage on areas of higher P is not accessible to livestock their nutrition may be deficient (Schatz et al. 2023), even if at sub-clinical levels. Conversely, the ‘reserve’ of acid-soluble P at high pH represents a bank of fertility for plants that can acidify their rhizosphere (Dinkelaker et al. 1989).

Collecting soil samples from areas of interest allowed participants to link soil properties with production – high or low. This project encouraged producers to monitor soil data to support their decision making. Our recommendation was to pick key areas that are meaningful for monitoring of soil properties every 3 to 5 years to better understand major climate drivers and longer-term land management improvements and impacts.

Acknowledgements
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Preserving and enhancing soil health in the rangelands of Uganda

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Key words: Rangeland; Rangeland health; Ecological site; Landscape attributes

Abstract

Rangelands in Uganda covers an area of 84.000Km2 which is about 44% of the country's land mass. Commonly known as the Cattle Corridor, it stretches from the south through the central region to the northeastern part of Uganda and supports pastoral and agropastoral communities.

Food insecurity in Uganda has been considered an outcome of low agricultural productivity which is attributed to the gradual decline in soil fertility originating primarily from anthropogenic causes including continuous tillage and mono-cropping as well as reduced agricultural inputs.

In our study, we highlight 2 smart agricultural technologies as alternative solutions to low soil fertility:

Organic fertilizers tend to be costly to farmers without integrated agricultural systems but some of their benefits include: preservation of soil by minimizing negative effects on the environment, exhibiting stability and resilience to a changing climate, having a beneficial effect of increasing organic matter and soil fauna and improving soil quality.

Vermicomposting is a technology that utilizes different species of earthworms coupled with microorganisms to mechanically digest the organic matter thereby enhancing mineralization. However, there is a need to apply the organic waste as the raw material to be digested; therefore, interplay of organic waste and the vermicomposting organisms is needed to achieve the mineralization.

Introduction

Rangelands in Uganda covers an area of 84.000Km2 which is about 44% of the country's land mass. Commonly known as the Cattle Corridor, they stretch from the south through the central region to the northeastern part of Uganda and support pastoral and agropastoral communities.

Food insecurity in Uganda has been considered an outcome of low agricultural productivity which is attributed to the gradual decline in soil fertility originating primarily from anthropogenic causes including continuous tillage and mono-cropping as well as reduced agricultural inputs.

The growing population has exerted pressure on rangelands due to more demand for goods and services.

The use of rangelands is intensifying, resulting in extensive rangeland degradation and desertification. The land use shift from the original tropical rainforests to savannahs and other non-agricultural activities (e.g. construction, charcoal burning, bricklaying and animal grazing) has significantly contributed to the degradation of soil. Loss of soil fertility has been manifested through loss of organic matter mainly caused by farmers removing the post-harvest biomass leaving the soil unreplenished and with a negative nitrogen balance.

It is no longer possible to apply the old soil management practices of bush fallowing and shifting cultivation that would restore fertility to the damaged soils.

To assess rangeland condition, a methodology often referred to as Rangeland Health Assessment can be performed. This provides tools that help land users interpret the landscape and react in time before land degradation becomes irreversible. Rangeland health assessment is about evaluating ecosystem processes using indirect methods to determine whether an ecosystem is at risk or healthy under the current management scheme. Constructing a rangeland health methodology requires understanding of ecosystem processes and how they are expressed in the environment.

Rangeland health is defined as the degree to which the integrity of the soil, vegetation, water and air, as well as the ecological processes of the rangeland ecosystem, are balanced and sustained. Integrity in this case refers to "maintenance of the functional attributes characteristic of a locale, including normal variability" It has replaced the terms 'range condition' and 'ecological status'

Rangeland Soils:
Rangeland soils are often characterized by low fertility, poor drainage, and rough topography.

Specific things to consider with rangeland soils:
Soil erosion
Soil erosion can cause the loss of nutrients, organic matter, and fine-size soil particles, which can decline soil fertility.
Disturbance
Some disturbance can help maintain soil health and biological diversity however, too much can be detrimental and lead to permanent ecological changes.
Livestock grazing
Livestock grazing is the most common economic use of rangelands, but may degrade rangeland health.
Rangeland degradation
Rangelands are threatened by a variety of natural and anthropogenic causes, including climate change, drought, aridity, and desertification.

Methods
Nakasongola District was selected as the study area because of its specific location in the center of the cattle corridor. The District covers an area of 4,909 km 2 and is located between latitudes 0 0 57' 44.89" and 1 0 40' 42.76" North and longitudes 310 58' 03.77" and 320 48' 00.29" East (Figure 1). Earlier studies (Nakasongola 2011) on the soils and land use in Uganda classified the soils of Nakasongola district in the driest part of Buganda Province. These rangelands were identified as a 'hot spot' with severe land degradation, pasture and water scarcity that were translating into high livestock mortality and poverty. The District has hence received national attention to help solve the environmental problems and save dependent communities

Nakasongola District is classified under the banana-millet-cotton farming system (MAAIF, 1995). Because of the less stable rainfall, there is a great reliance on annual food crops basically millet, sorghum, groundnuts, cassava, pigeon peas and maize, with cotton as a major cash crop and livestock production dominating in the drier areas of the District.

Key methods to improve soil health include: Implementing Rotational grazing practices, managing livestock stocking rates, planting diverse native plant species, use of cover crops, minimizing tillage, monitoring nutrient levels and use of fertiliser and controlling erosion through strategic vegetation placement.

We implemented all these methods on farms in the Nakasongola District of the Ugandan Rangelands and observed the effects over a period of time.

Figure 1. Uganda showing the location of Nakasongola district

Results

Rotational grazing

Moving livestock between different pastures regularly prevents overgrazing and allows vegetation to recover, ensuring even manure distribution. For example; regenerative grazing in Nakasongola district is crucial for restoring degraded rangelands and improving livestock management, particularly in the face of climate change and land degradation. By focusing on soil health and pasture productivity, it can enhance livelihoods and reduce the risk of overgrazing and its consequences.

Adaptive stocking rates:

Adjusting the number of livestock based on available forage prevent overgrazing and maintains healthy plant communities. In Uganda, studies have shown that carrying capacity can vary significantly, with the lowest carrying capacity occurring during the long dry season (June to August) and the highest during the short rain season (September to November).

For Ankole region, pastoral systems in southwestern Uganda, a stocking rate of 1.41 ha/TLU is considered sustainable

Plant diversity
Introducing a variety of native plant species with different root depths to enhance soil structure, nutrient cycling, and resilience to drought. Examples of plants include; Pongamia (*Millettia pinnata*) and Croton nuts (*Croton megalocarpus*)

Cover cropping
Planting temporary cover crops during fallow periods to protect the soil from erosion, add organic matter, and improve soil structure.

Minimal tillage
Reducing soil disturbance through minimal or no tillage practices to preserve soil structure and microbial activity.

Nutrient management
Regularly monitoring soil nutrient levels and applying necessary fertilizers strategically to avoid excesses and maintain soil balance.

Erosion control:
Implementing practices like contour planting, grassed waterways, and windbreaks to minimize soil loss from wind and water erosion.

Monitoring and assessment:
Regularly monitoring soil health indicators like organic matter content, microbial activity, and soil structure to evaluate the effectiveness of management practices

Conclusion
The benefits of improved soil health in rangelands include:

Increased forage production and quality, enhanced water infiltration and retention, improved biodiversity and ecosystem services, greater resilience to drought and extreme weather events, and reduced soil erosion.

The encroachment of grasslands by bare and woody vegetation has led to a decline in pasture biomass yield and therefore has strong implications on the sustainability of pastoral livelihoods in the semi-arid rangelands of Nakasongola. The low pasture biomass in woody understory implies that most native pasture species in the rangelands of Nakasongola are not shade tolerant and therefore increased woody encroachment will most likely wipe out indigenous nutritive pastures in the rangeland. Organic matter, nitrogen, calcium and magnesium are the most critical nutrients limiting pasture biomass. Rangeland management strategies for improving soil quality and pasture production should therefore be strongly focused at increasing the levels of these nutrients.

There is a need for intensification and transformation of cropping systems from low input to high input agriculture so as to reduce opening up of new land every season in search for fertile soils. Opening new lands for cultivation is among the most insidious practices devastating the sustainability of rangeland ecosystems.

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Pastures under pressure: restoration of high-altitude rangelands in Bhutan and Nepal

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Keywords: High altitude pasture; restoration; *Rumex nepalensis*; shrub encroachment; weeds

Abstract:
Rangelands comprising 60% of the land area in the Hindu Kush Himalaya (HKH), are predominantly managed under pastoral production systems. The high-altitude rangelands provide critical nature-based solutions to societal challenges, including climate change, biodiversity loss, water scarcity, and food security. Mountain pastoralism, characterized by the seasonal migration of livestock between different elevation pastures, significantly contributes to the economy, food and water security, nutrition, health, cultural identity, indigenous knowledge systems, and biodiversity. In mountainous countries like Nepal and Bhutan, mountain pastoralism also alleviates pressure on lowland areas where land and resources are scarce. However, over the past few decades, government restrictions on traditional pasture management practices, such as cutting and burning, have led to alpine pastures being overtaken by shrubs, significantly reducing forage quality and availability. Additionally, these pastures face severe impacts from erosion, scree flows due to melting glaciers, permafrost thaw, and intense rainfall. Transitional and winter grazing areas suffer from overuse, erosion, and invasion by unpalatable plants, resulting in poor fodder production. Shrub invasion by *Rhododendron lepidotum* and *Berberis spp* and land erosion is further diminishing the availability of high-value medicinal plants and herbs, while critical water sources are also drying up for wildlife, livestock, and herders. This degradation is negatively affecting the biodiversity and ecosystem services, leading to the unprofitability of pastoralism, youth out-migration from mountain regions, and the erosion of traditional pastoral cultures. To address these issues, we are piloting rangeland restoration projects in Tseko, Bhutan, and Shailung, Nepal. These projects employ a combination of methods, including prescribed burning, cutting, thinning, uprooting of weeds such as *Rumex nepalensis* and water management. Through these efforts, we aim to restore and sustainably manage rangeland resources, thereby enhancing ecosystem services, improving pastoral livelihoods, and preserving cultural heritage.

Introduction

Rangelands cover 60 percent of Hindu Kush Himalaya (HKH) and are home to more than 25 -30 million indigenous communities (Sharma et al. 2007). These high-altitude rangelands play a vital role in supporting pastoral livelihoods and maintaining ecological functions, including soil stabilization, carbon sequestration, water regulation, and biodiversity conservation (Joshi et al., 2013; Xu et al., 2019). Rangelands are socio-ecological systems, providing critical ecosystem services and sustaining indigenous knowledge systems (Hruska et al. 2017). The livelihoods of pastoral communities in the HKH are linked to rangeland health, as these ecosystems provide essential grazing resources for livestock. However, the increasing pressures from climate change, overgrazing, unsustainable land-use practices (Wang et al., 2019) and grazing-ban policies pose significant challenges to the sustainability of these rangelands (Singh et al. 2022). In addition, in recent decades the rapid encroachment of unpalatable shrubs and weeds in high altitude rangeland has been widely reported as one of the major causes of rangeland degradation that has drastically reduced forage availability, posing a serious threat to livestock productivity and herders' incomes (Wangchuk et al. 2013; Barsila 2022; Roomi et al. 2023). However, the sustainability of mountain pastoralism depends on the availability of high-quality fodder from seasonal pastures at different elevations. Shrub invasion and land erosion further diminish the growth and availability of highly valued medicinal plants and herbs. In some instances, pastures are fully overrun by pioneering woody species, while critical water sources for wildlife, livestock, and herders are drying up. Consequently, these trends have led to adverse effects on rangeland, making mountain pastoralism economically infeasible. Thus, an integrated approach and careful management are required to avoid negative implications of shrub encroachment and weed invasion. Several studies have reported that prescribed burning is a common tool used for rangeland management (Lohmann et al. 2014; Toledo et al. 2014). Prescribed burning frequently helps to lower the risk of wildfires, manage the spread of woody vegetation, reduce soil erosion, enhance plant diversity and wildlife habitats, and boost forage production for grazing livestock (DiTomaso et al 2010; Alcañiz et al. 2018). While some studies reported that prescribed burns implemented in the summer can benefit restoration by preventing woody encroachment while also controlling an invasive grass (Novak et al. 2021). The main objectives of our restoration trial were to assess the extent and impact of rangeland degradation in two high-altitude sites, Tseko in Bhutan and Shailung in Nepal, and implement targeted restoration interventions. In both the sites, due to the lack of proper management and other reasons, many of these pastures are degraded due to shrub encroachment and made unusable by rampant growth of *Rumex nepalensis* and other weeds species. To address these issues, we applied integrated approaches that include prescribed burning, cutting, thinning, water management, and weed removal. By combining traditional knowledge and modern restoration practices, we aim to enhance forage availability, support ecosystem services, and build resilience among pastoral communities.

Methods

The study was conducted in two high-altitude rangelands: Tseko in Bhutan and Shailung in Nepal (Figure 1 and Figure 2). In Tseko, the first restoration efforts involved multiple methods: prescribed burning of *Rhododendron lepidotum*, cutting woody shrubs such as Berberis spp. and Rosa spp., thinning blue pine (*Pinus wallichiana*), water management through the construction of water ponds, and the management of weeds like *Rumex nepalensis*. Prescribed burning trails were carried out in March, April and June 2024. During these trails, the main plant communities of the rangeland and dominant species were identified in burned fenced, unburned fenced and unburned unfenced plots. A total area covering 0.28 ha area was used for burning. Water management interventions included the construction of strategically placed water ponds to improve water availability for livestock and wildlife and increase soil moisture in the landscape.

In Shailung, Nepal, restoration was carried out in Godavari Community Forest and Kalinchowk Community Forest in May 2024.The approach focused on measuring grass recovery and determining the carrying capacity of rangelands through enclosures. We set up 10 enclosures covering the wider area, five were established at 3000 meters and five at 2900 meters. Each enclosure measured 2m by 2m, and biomass was harvested from 1-meter square plots to monitor growth. Additionally, 20 water ponds measuring 4.5m by 3 m by 0.6 m were constructed in collaboration with yak herders. These ponds were strategically placed to ensure water availability across grazing areas and enhance landscape-level water retention.

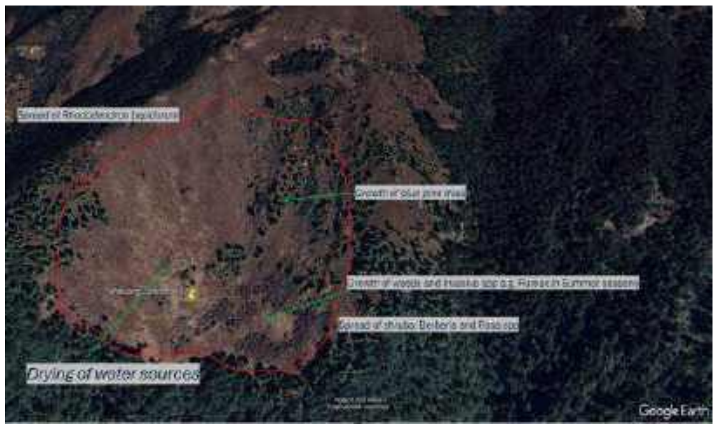

Figure 1: Restoration sites in Tseko, Bhutan

Results

Preliminary results from Tseko indicate the effectiveness of prescribed burning and cutting in improving forage yields and managing shrubs. Two months after implementing prescribed burns, the forage yield in burned and fenced plots was 4.55 t/ha compared with 4.21 t/ha in unburned, unfenced plots. In burned but unfenced plots, forage yield was significantly lower at 0.21 t/ha, likely due to grazing pressure. Fern height was tallest in burned-fenced plots, suggesting that burning facilitated fern growth while protection from grazing allowed for recovery. Cutting management effectively controlled *Berberis* spp., with regrowth heights varying from 54 cm to 190 cm, depending on site conditions. Forage biomass was significantly higher on managed sites compared to unmanaged ones, highlighting the effectiveness of active restoration practices. The *Rumex nepalensis* plant population was highest in the mown plot and lowest in the dug plot, while *R nepalensis* biomass peaked in the plot that was both mown and reseeded. Forage biomass was greatest in plots that were mown and reseeded, as well as those dug traditionally with branches of sapphire berry. In Shailung the estimated forage biomass is 366.5 kg/ha, with a utilization rate of 50% and a carrying capacity of 0.51 AU/ha, highlighting the overgrazed and degraded condition of the rangelands. With a yak population of 462, the area requires approximately 2,100 hectares of grazing land, further emphasizing the imbalance between forage demand and availability. The current biomass is measured at 145.5 kg/ha. Water ponds have shown promising results in improving water availability for both livestock and wildlife, enhancing moisture levels in the landscape, and supporting the regeneration of forage grasses.

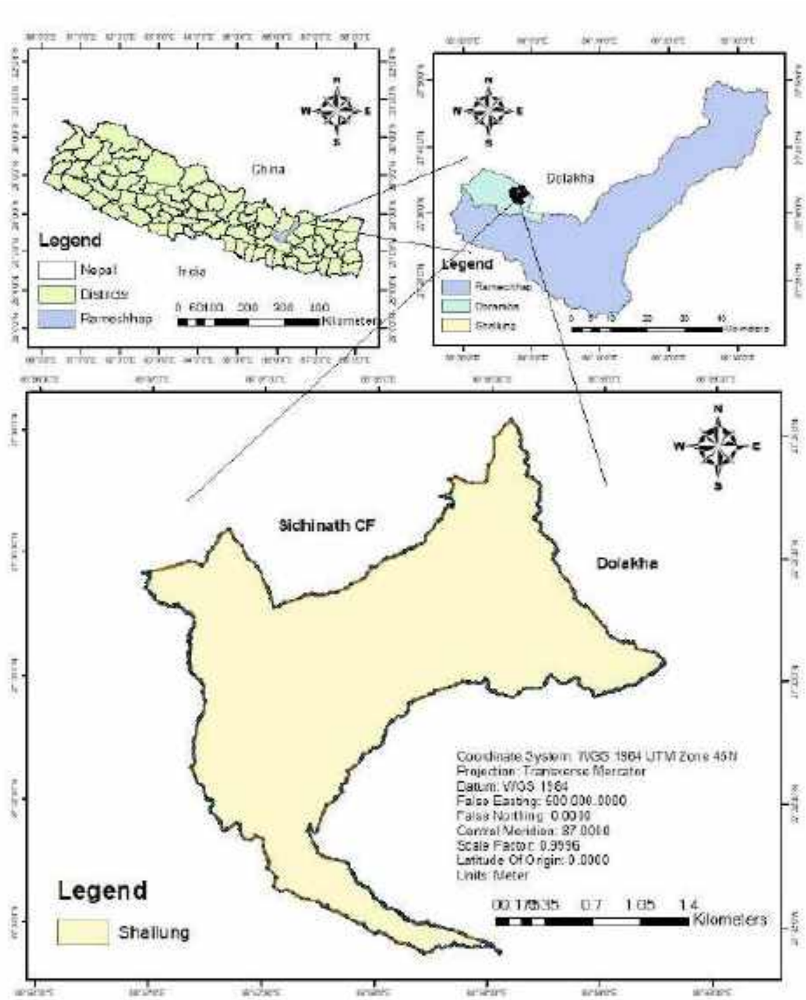

Figure 2: Restoration sites in Shailung, Nepal

Discussion

High altitude rangeland provides vital ecosystem services including biodiversity conservation, livelihood support, carbon storage and water regulation. However, they are increasingly threatened by shrub encroachment, poor management, soil erosion, overgrazing, medicinal plant extraction, and climate change highlighting the urgent need for both protecting native vegetation and restoring degraded areas. Restoring high-altitude rangelands presents significant challenges, particularly in areas with limited accessibility and rugged terrain. The pilot restoration action in Tseko, Bhutan, and Shailung, Nepal, highlight the importance of integrated strategies to tackle pasture degradation in high altitude rangeland. The initial trials demonstrated benefits such as improved forage production, reduced shrub encroachment, and enhanced water availability through a combination of prescribed burning, cutting, weed removal, water management, and active community involvement. However, restoring degraded rangelands is a long-term process requiring sustained efforts, multidisciplinary collaboration, and continued monitoring (Kuniyal et al. 2021). The initial trials conducted in the first year of action are just the beginning, and these results must be closely monitored over time to ensure their effectiveness.

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Can herbivores be part of the solution? Grazing management for rangeland restoration

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Destocking of livestock as a global phenomenon

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Key words: Degradation, overgrazing, abandonment

Abstract

Global rangelands are currently perceived as rapidly degrading because of overgrazing. Here, we report on our analysis of global stocking rates during the last 20 years. We found that regions containing 45% of the global livestock are being destocked, undergoing rapid reductions in livestock density since the 60s. On the contrary, the rest of global rangelands have exhibited a sharp increase in stocking rates. These trends intensified in the last 20 years. Our analysis shows that although almost half of the global rangelands exhibited destocking in the last 20 years, total meat consumption and per capita meat consumption have increased throughout the world. This trend resulted from increases in total number of cattle, sheep, and goat but even larger increases in pork and poultry.

We suggest that our report may lead to a shift in the rangelands paradigm from the idea of overgrazing as a dominant driver of degradation to a region-specific approach that assesses the global consequences of both overstocking and destocking for the functioning of the Earth system, including the carbon, water, and energy dimensions of global change. We conclude that it is critical to understand the global implications of these phenomena and develop management techniques for rangelands that are being overstocked as well as those that are either being abandoned and or rapidly destocked. A large fraction of rangelands research has focused on restoration, for example we, as rangeland scientist, have developed management techniques to reintroduce species that were lost because of overgrazing or eliminate invasive species. Now, we face the challenge of managing large areas that have been destocked or just abandoned. These rangelands need to be managed to avoid negative societal consequences ranging from biodiversity losses to wildfires. The challenge is large because managing abandoned rangelands is different than managing degraded lands and varies regionally.

Introduction

Rangelands represent a large fraction of the terrestrial surface, and their main use is livestock grazing (Asner et al. 2004). Moreover, 30% of the human population depend on livestock grazing for their subsistence (Steinfeld 2006). In addition, rangelands have a large impact on the global carbon cycle (Ahlström et al. 2015). The importance of rangelands is highlighted by the generalized perception that rangelands are rapidly degrading (Alkemade et al. 2013), and therefore they are losing their ability to provide ecosystem services on which large fraction of the population depends.

Here, we tested the degradation perception by evaluating changes in stocking rates in the last 20 years. Specifically, we evaluated if there were geographical patterns, with some areas of the world being overgrazed while others were not. We explored potential drivers that might explain the observed trends in stocking rates. Finally, we discuss the implications of varying global stocking rate patterns on research needs and rangeland management.

Methods

We analysed data from FAOSTAT (FAO 2024) for global trends in stocking rates for each of the 18 regions recognized by FAO that are Eastern Europe, Eastern Asia, Oceania, Western Europe, South Africa, Northern Europe, Southern Europe, North America, North Africa, South Asia, South America, Central America, including the Caribbean region, South East Asia, Western Asia, East Africa, West Africa, Mid Africa and Central Asia. The data base included different types of animals, such as cattle and sheep. We converted all the animal types into a common unit using FAO standardization technique, which considers variability in region and animal species. We evaluated changes from 2004 to 2024. We assessed meat production efficiency for each region as the ratio between meat production and number of animal units per region.

Results

Our first finding was that global rangelands are not all overgrazed. In contrast, we found that in the last 20 years, 45% of the area of global rangelands has experienced a reduction of stocking rate. Destocking in 45% of global rangelands coexist with increases in stocking rate in the rest of the world. Destocking has been occurring in Australia, North America and Europe (Table 1). In contrast, Africa, Asia, and South and Central America have exhibited increases in stocking rate.

Table 1. Rate of change of cattle for the period 2000–2021 in the ten FAO regions with the largest cattle stocks. The rate of change is expressed as the log response ratio (i.e., log (N2021/N2000)). Data source: FAOSTAT.

Region	Cattle 2000-21
Central America	0,10
Eastern Africa	0,27
Eastern Asia	-0,19
Eastern Europe	-0,19
Northern Africa	-0,05
Northern America	-0,03
South America	0,10
Southern Asia	0,05
Western Africa	0,28
Western Europe	-0,09

Once we have established trends in global stocking rates, we explored the mechanisms behind this pattern. The first hypothesis is that destocking responded to a reduction in meat consumption. However, meat consumption has increased in the last 20 years in areas experiencing both destocking and increasing stocking rates. And meat consumption per person and total consumption both have increased reflecting global increases in affluence and population.

Finally, the increase in meat production in regions experiencing destocking resulted from increases in the global efficiency of meat production (Thornton 2010). Increased efficiency has been documented in the past because of several husbandry improvements ranging from veterinary care to more water holes that result in better animal distribution (Oesterheld et al. 1992).

Discussion

Our findings have major policy and management implications. Destocking has positive and negative implications. Destocking has the potential of exacerbating biodiversity loss as demonstrated by large-scale syntheses of many studies across the world (Milchunas and Lauenroth 1993) and supported by ecological theory (Milchunas et al. 1988). Similarly, destocking leads to accumulation of standing dead that make rangelands prone to more frequent fires (Walsh et al. 2014). Destocking has also positive impacts reducing soil erosion and increasing soil-carbon stocks.

Most of the rangeland research has focused on understanding impacts of overgrazing on ecosystem functioning and developing tools to reclaim overgrazed rangelands. Therefore, our understanding of how to manage abandoned and destocked rangelands is scarcer. Policy, which is driven by research and drives research, has also mostly aimed at ameliorating the impacts of degradation resulting from overgrazing. As demonstrated through this study, the destocking of almost half of global rangelands highlights the need for greater research on the impacts of destocking on biodiversity, the carbon and water cycles as well as its impacts on albedo that directly affect the planetary energy balance. A better understanding of the effects of destocking may generate new tools to manage destocked lands in ways that match the increasing and changing demands that people impose on rangeland ecosystem services (Yahdjian et al. 2015).

Acknowledgements

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The Global Land Outlook Thematic Report on Rangelands and Pastoralists: framework and theory of change for sustainably managing and restoring rangelands

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Key words: Sustainable rangeland management, governance, land degradation neutrality

Abstract

The United Nations Convention to Combat Desertification (UNCCD) released its Global Land Outlook Thematic Report on Rangelands and Pastoralists (GLO) on 21 May 2024. The report offers a singular perspective on the sustainable management of rangelands and the critical role of pastoralists and extensive livestock systems, focusing specifically on their capacity for advancing towards Land Degradation Neutrality.

This paper offers a methodological approach to the narrative of the GLO. It starts by analysing the Driver-Pressure-State-Impact-Response (DPSIR) model of rangeland health and degradation status. It then explains the role of this model in the design of a Theory of Change for the report and the transition towards a conceptual framework for managing rangelands as social-ecological systems. Finally, the presentation links this methodology with the case studies and the actions and recommendations of the report.

Effective governance of rangelands requires a better understanding of their capacities, dynamics and the future supply and demand for their goods and services. The challenge is to ensure that these vast landscapes are managed in a sustainable manner while addressing the synergies and trade-offs under trans-disciplinary and multi-actor frameworks. This approach demands a strong scientific background but also a holistic and flexible conceptual framework that can lead to clear objectives and practical means of implementation, including policy frameworks, direct action, improved governance and better investments.

Introduction

The United Nations Convention to Combat Desertification (UNCCD) released its Global Land Outlook Thematic Report on Rangelands and Pastoralists on 21 May 2024. The report explores the links between rangelands and local communities. The report offers new entry points, possibilities, and recommendations for policymakers and other stakeholders that encourage greater attention, financial support, and investment

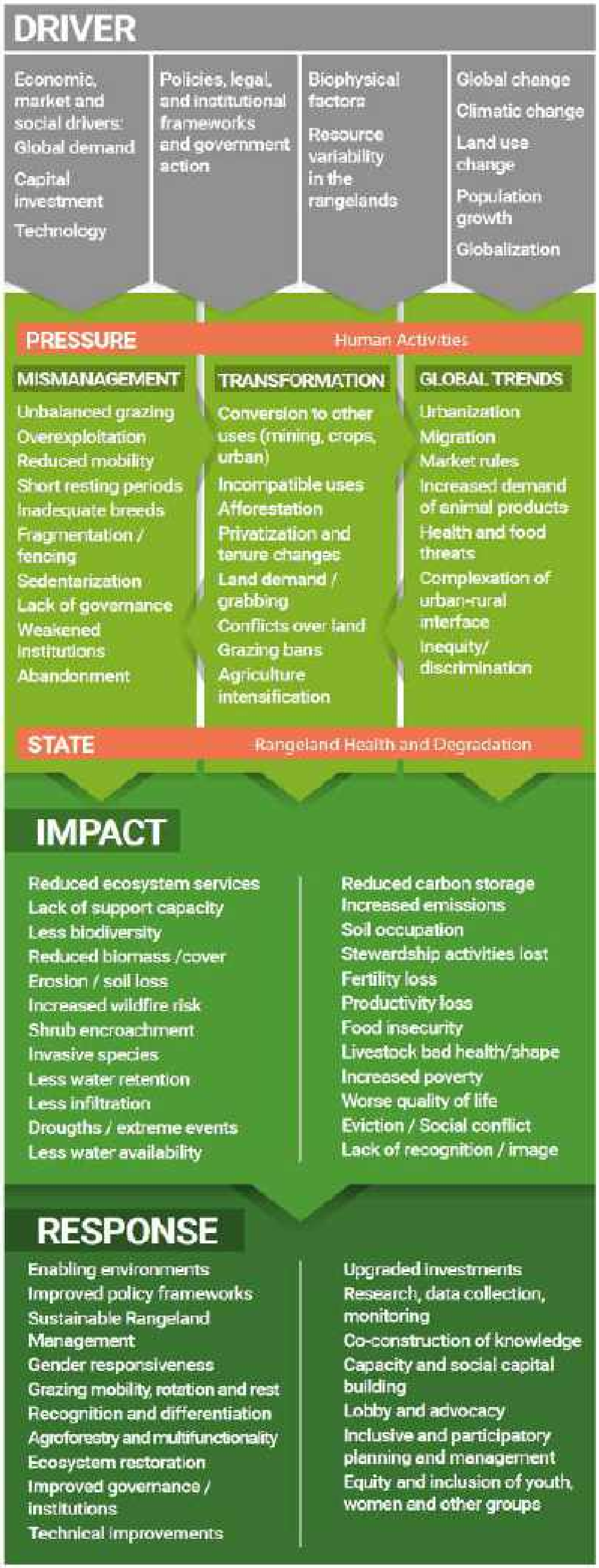

Figure 1. Rangelands' health and degradation status diagram designed for the GLO Rangelands report based on the DPSIR model

in Sustainable Rangeland Management (SRLM). It concludes that local, multi-actor, transdisciplinary, adaptive, and inclusive approaches are needed to improve the health and sustainable productivity of rangelands and the livelihoods of their stewards. The GLO Rangelands report also unravels the role and untapped potential of pastoralism and other extensive livestock management systems in reducing land degradation, contributing to just and equitable rural development and food security, protecting the rangeland commons, and generating transformational change towards climate resilient societies, while improving the health of these critical landscapes and the livelihoods of their communities.

This paper presents the methodology applied in the analysis and the narrative of the GLO seeking to encourage substantial change in the conceptual framework currently applied to combat desertification and degradation in rangelands, through sustainable management practices under pastoralist and other extensive livestock systems.

Methods

The methodology applied to sustain the rationale of the GLO Rangelands report starts with the definition of rangelands and then it is developed through three stages: health / degradation model, conceptual framework and Theory of Change. The actual methodology of building the framework for the report wasn't sequential but iterative, complementing each stage with the outcomes of the other two.

Results

The report substantiates a definition of rangelands based on grazing activity of open ecosystems by livestock and/or wild animals. Thus, they are considered as complex social-ecological systems (Hruska et al, 2017) whereby natural resources provide a broad range of goods, services, and values that must be considered in functional assessments (FAO, 2019). The base natural and semi-natural ecosystems hosting those rangelands are populated by indigenous vegetation predominantly comprised by grass, grass-like plants, bushes, or shrubs, including open forests and agroforestry systems.

The first stage consists in composing a rangeland health / degradation diagram (Fig 1) based on the Driver – Pressure – State – Impact - Response (DPSIR) model (Burkhard & Müller, 2008), which addresses complex challenges at the interface between society and the environment (Troian et al., 2021). The DPSIR model analyses rangeland health and degradation status, drivers and trends, addressing the complex trade-offs and interactions at the interface between rangelands, society and the environment.

The second stage allocates the agents and fluxes described in this model in a broader framework supporting the conceptualization of rangelands as social-ecological systems. This way, the DPSIR health / degradation model precedes the actual conceptual framework represented in Figure 2, where the elements and relationships shaping rangelands are organised through a multifunctional approach that links rangeland health and their management systems. The framework shows how they are intimately linked within the same social-ecological system. Thus, a systemic approach is needed to understand and sustainably manage rangelands, especially under pastoralist systems.

This way, the complex network of relationships among these elements in diverse political and social environments shapes the use and management of rangelands. Addressing land governance challenges opens the scope to the whole territory and to all stakeholders involved, a prerequisite for meeting national and global objectives addressed in the report (Davies et al., 2016). Accordingly, the conceptual framework allows the definition of a Theory of Change that shapes the whole report and organises their targets, means and outcomes. The complex network of relationships among these elements in diverse political and social environments shapes the use and management of rangelands.

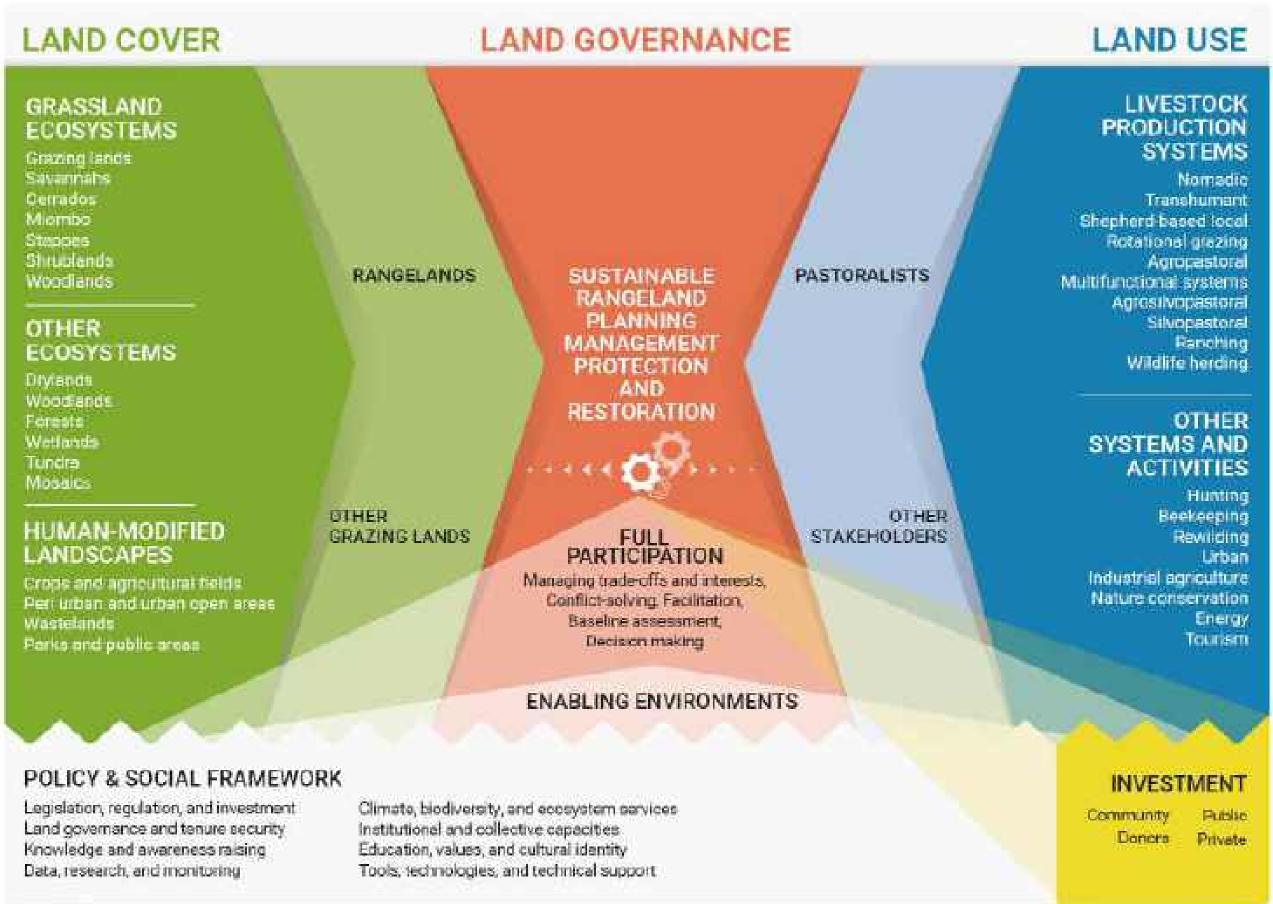

Figure 2. Conceptual framework for addressing rangelands sustainable management and governance as displayed in the GLO-Rangelands report.

Using the rangelands health/degradation model and the conceptual framework, the report was able to build a Theory of Change, displayed in Figure 3. This Theory of Change enables the development of the aims of the report, exploring the complex environmental, social, and economic dimensions that link rangelands and local communities and addressing the important role and untapped potential of pastoralism and extensive livestock management systems to contribute to a just transition, climate resilience, and more equitable rural development.

Discussion and Conclusions

There are notable disparities in the assessments of rangeland degradation which estimate its extent and degree globally. The mix of biophysical, social, and economic factors influencing land, its production, performance and health are often viewed subjectively (FAO, 2013). The estimates of rangeland degradation have changed over time, reflecting the progress made in the understanding of rangeland dynamics and indicators, assessment and monitoring tools, and management and land use systems (Onyango et al, 2021). Besides, there are still critical gaps in the knowledge, data, and interpretation of rangeland dynamics. Rangelands demand more research, data collecting and monitoring effort related to economic analysis, carbon pools, water cycle regulation, shrub encroachment and specifically their spatial and temporal use.

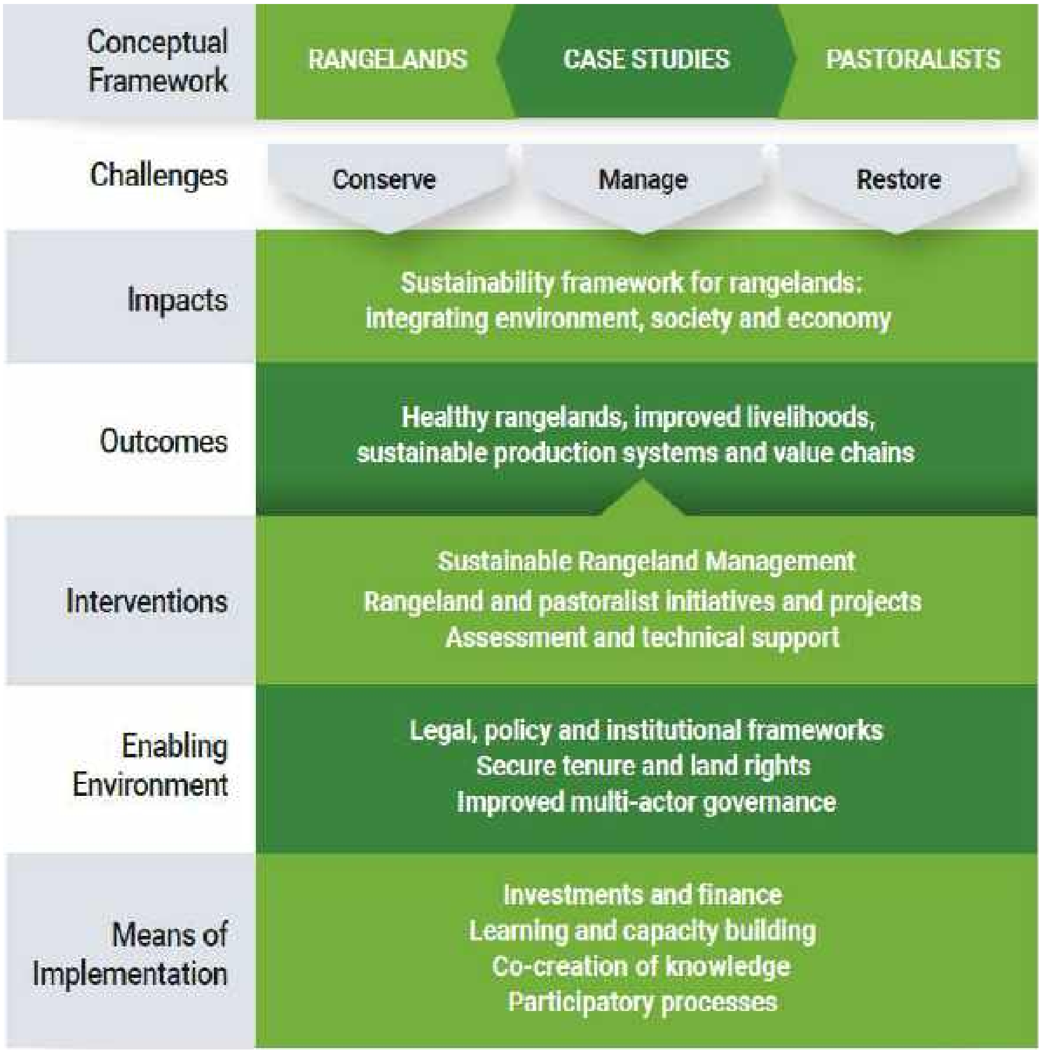

Figure 3. Theory of change developed within the GLO-Rangelands report.

The effective governance of rangelands requires a better understanding of their dynamics, capacity, and the future supply and demand for their goods and services. There has been a recent shift from the unsustainable demand for the tangible or market goods produced on the rangelands, to policies and regulations that recognise and value the wider range of services they provide to people, nature, and the climate (Yahdjian et al, 2015) The challenge is to ensure that supply and demand meet in a sustainable manner while addressing the synergies and trade-offs under transdisciplinary and multi-actor frameworks.

The complex network of relationships among these elements in diverse political and social environments shapes the use and management of rangelands. Addressing land governance challenges opens the scope to the whole territory and to all stakeholders involved, a prerequisite for meeting national and global objectives addressed in the report. However, it is important to recognise that many of the challenges confronting rangelands originate beyond local communities and are not under their control, although they should be a fundamental component of its governance.

The conceptual framework (Figure 2), complemented with the DPSIR framework (Figure 1), and the Theory of Change (Figure 3) arising from them provides the rationale for the GLO Rangelands report. This framework also underpins the global effort to protect rangelands and contributes to the effectiveness of initiatives at national and local scales. As many rangelands share common features, multi-scale perspectives and context-specific interventions can often help refine a global approach to plans, strategies, case studies and good practices. Additionally, the framework can also help to inform specific response measures, management systems, legal advances and governance schemes that can be used by different initiatives.

This framework has provided guidance for the analysis of case studies and projects collected in the report, using a common lens to address their specific features and focal points, ultimately shaping the recommendations collected in the report and its policy brief.

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Herd effect and deep ripping to restore claypans in western New South Wales rangelands

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Key words: Grazing management; herd effect; ripping; animal impact; rangeland restoration

Abstract

Historic soil degradation, primarily due to overgrazing and drought, has led to the widespread formation of bare, scalded 'claypans' throughout the rangelands of south-eastern Australia. Mechanical interventions such as ripping and water ponding have been used to restore claypans over the last ~70 years, with varying success. Strategic management of livestock to restore degraded land has increasingly gained attention in recent decades as an alternative to resource-intensive mechanical restoration methods or complete destocking. This study compared the effects of intense cattle impact (~400-600 cattle held overnight on 0.5 ha of claypan + hay) with deep ripping (a single tine, to 30 cm depth with one meter row spacings) across three replicate claypans on 'Bokhara Plains' in the semi-arid rangelands of western New South Wales (NSW), Australia. Two years following the interventions, results show a significant increase in plant cover (up to 50%) and diversity for both the cattle and ripping treatments, compared to the control (initially 0% cover), and a reduction in salinity of the upper soil profile. Differences in vegetation cover between the cattle and ripping treatments were less obvious, though there were differences in plant composition with higher species richness under the cattle treatments at some replicates. These results demonstrate the effectiveness and need for targeted management to restore scalded areas and regenerate land condition in rangeland grazing systems.

Introduction

Historic soil degradation, primarily due to overgrazing and drought, has led to the widespread formation of bare, scalded 'claypans' throughout the rangelands of south-eastern Australia (Cunningham 1987). These soils are often saline and dispersive, with sealed surfaces that constrain plant emergence, water infiltration and nutrient cycling. With no or little vegetation growth or cover, they are vulnerable to wind erosion and unable to support livestock production, and even under conservative grazing management, many have failed to recover naturally. Increasing water infiltration (and the subsequent benefits this brings by leaching salts and reducing salinity), surface soil roughness and niches for seed to establish is required to effectively restore degraded scalds (Cunningham 1987, Green 1989).

In extensive rangeland grazing systems of semi-arid NSW, Australia, this has historically often been achieved through mechanical interventions including deep ripping, furrowing or water ponding (e.g., see Cunningham 1967, 1970, Green 1989; Wakelin-King 2011). 'Herd effect', is purported to achieve similar benefits through intensive trampling (hoof action) of livestock to break the soil surface and provide the addition of nutrients and seed through livestock dung and urine (Savory 1989). However, the use of strategic livestock management (herd effect) to restore degraded land has not been scientifically trialled in NSW rangelands.

This trial sought to understand how deep ripping or high density and intensity grazing by cattle for short durations (herd effect) affects the restoration of soil and pasture on degraded scalds in north-western NSW.

Methods

The trial was located on 'Bokhara Plains', approximately 30 km north of Brewarrina, NSW Australia (29°40'29"S, 146°56'37"), on the Barwon River floodplain, Wongal Land System (Walker, 1991). The climate is semi-arid, with an average annual rainfall of 385 mm and a summer dominant rainfall pattern. Soils on Bokhara Plains are predominantly grey vertosols. Vegetation is comprised of open woodland and grasslands, with isolated whitewood and coolabah and understorey of Mitchell grass (*Astrebla* spp.), Native millet (*Panicum decompositum*), forbs, annual and perennial subshrubs (*Atriplex* spp., *Sclerolaena* spp., *Maireana* spp., *Rhagodia spinescens*). Across Bokhara Plains, and the broader landsystem, there are large areas of scalds, characterised by very low vegetation cover and saline and sodic soils. Three scalded areas across different paddocks (4 – 10 km apart) on Bokhara Plains were selected as replicates of the trial. Each replicate claypan was divided into ~0.5 ha plots which were randomly assigned one of the following treatments: 1) herd effect (cattle); 2) ripping; and 3) control (no treatment). Further detail on treatments is provided below.

Herd effect treatment

At replicates 1 and 3, cattle (400-600 Livestock units, LSU) were held overnight on plots three times between May 2022 and April 2024. At replicate 2, cattle (680 LSU) were held on the plot for two hours in April 2022 (one time only). Prior to introducing cattle, on each occasion two large haybales were spread throughout the plot to introduce organic material and increase activity and movement of livestock in the plot. Each replicate experienced animal impact at a different timepoint.

Ripping treatment

In each replicate, a single tine behind a tractor was used to rip to depth of ~30cm, in a spiral formation. Each rip line was approximately 1 m apart. Replicates 2 and 3 were ripped in April 2022, while replicate 1 was ripped in September 2022 (the same time that cattle initially impacted the herd impact plot).

Vegetation and soil monitoring

In April 2022 (prior to installation of treatments), April 2023 and June 2024, ground cover (percent cover of plant, litter, cryptogam, coarse woody debris, dung and bare ground), herbage mass and plant composition (percent cover by species) was assessed in 0.25m^2 quadrats every 10 m (replicates 1 and 3) and 15 m (replicate 2) along three transects in each treatment plot (7 quadrats per transect, 21 quadrats per plot). At five permanent locations in each plot, all species within a larger 5x5m quadrat were identified. In June 2024, seven soil cores were collected along each transect and composited by depth 0-5cm, 5-10cm, 10-20cm and 20-30cm. Salinity (electrical conductivity, ECe) was assessed through laboratory analysis (Shaw 1999; Rayment and Lyons 2011; Method 5A2b and 3A1) to estimate effects of treatments on soil salinity.

Results

Vegetation cover was greater under the cattle treatment relative to the control at two of the three replicate scalds, while the ripping treatment had a positive effect across all three scalds (Fig. 1). Compositional differences between the three treatments were most apparent in the third replicate, which included a greater proportion of native perennial grass (e.g., *Eragrostis setifolia, Sporobolus caroli, S. actinocladus, , Tripogon loliiformis)* and non-native perennial grass *(Lolium perenne*, assumed to be imported with the hay) cover in the cattle treatment than the ripping and control treatments. Species richness was greater in the cattle treatments at the first and third replicates, while the control and ripping treatments had similar richness values to each other across all replicates (Fig. 2). Two years post cattle and ripping treatment, salinity (EC) of the upper soil layers (0-20cm) at replicates 1 and 3 was lower under cattle and ripping, while differences at replicate 2 were smaller and constrained to the 0-5 cm surface layer (Fig. 3).

Discussion

Both ripping and high intensity animal impact for a short duration in combination with additional organic material (hay) had a positive impact on the restoration of degraded scalds across Bokhara Plains, increasing ground cover and plant diversity and decreasing soil salinity. The greatest response (including a reduction in the amount of bare ground and >50% increase in plant and litter cover) was apparent at the third replicate where cattle had impacted the area overnight three times in the two years prior to the final monitoring occasion. Replicate 2 experienced the least cattle impact, with only two hours of cattle impact in April 2022, more than two years prior to final sampling, and had the smallest response, similar to that of the control treatment. This variability in response highlights the potential role that the timing, duration and frequency of animal impacts to achieve desirable results and suggests achieving greater disturbance by holding livestock for longer (overnight) is more effective than one-off, very short periods of time.

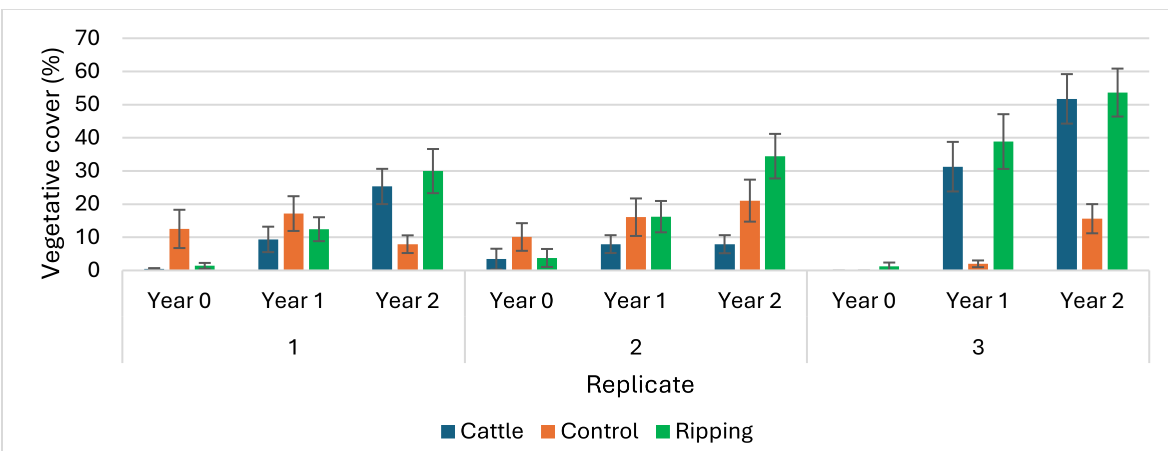

Fig 1. Average vegetative (plant and litter) cover for cattle, ripping and control treatment plots across three replicate scalds, measured prior to trial installation in April 2022 (Year 0), April 2023 (Year 1) and June 2024 (Year 2), ± 1 standard error.

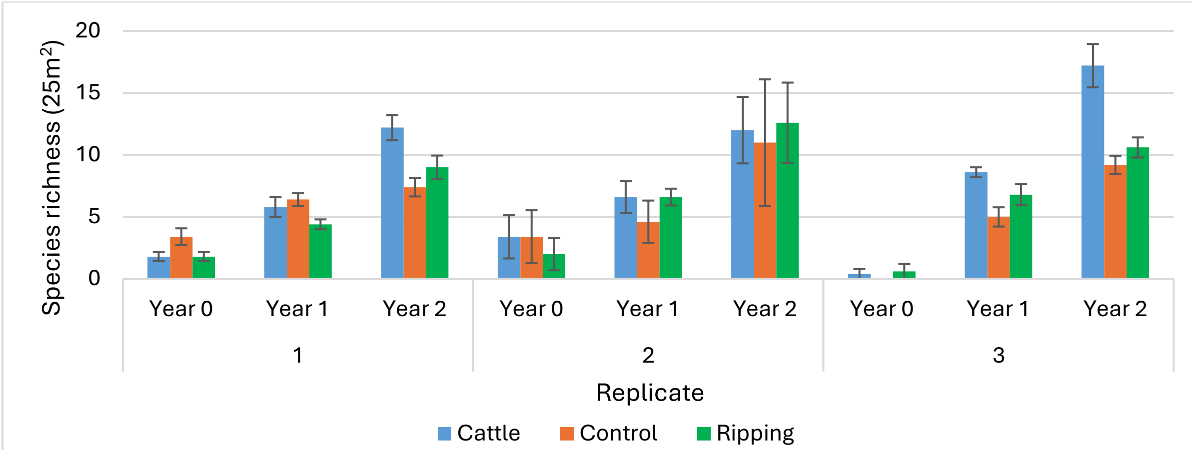

Fig 2. Average species richness (number of plants per 25m^2) for cattle, ripping and control treatment plots across three replicate scalds, measured prior to trial installation in April 2022 (Year 0), April 2023 (Year 1) and June 2024 (Year 2), ± 1 standard error.

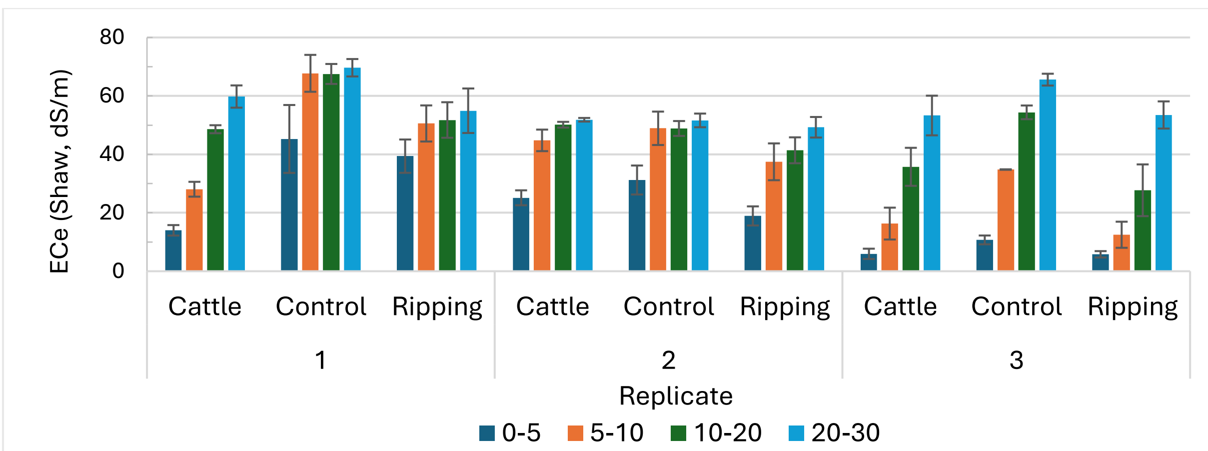

Fig 3. Electrical conductivity (ECe, Shaw 1999) of soil profile layers (0-5cm, 5-10cm, 10-20cm, 20-30cm depth) for cattle, ripping and control treatment plots across three replicate scalds in June 2024, two years after treatment, ± 1 standard error.

There are few published studies on the use of herd effect to restore degraded rangelands, and no studies we are aware of compare with mechanical restoration methods such as ripping. However, positive results observed in this study are similar to those reported by Barnes and Hibbard (2016), where forage growth was significantly greater one year following animal impact in night pens. The benefits of ripping to rangeland restoration have been documented throughout the world (e.g., Jones 1966; Miyamoto et al. 2004), however, long-term effectiveness of these treatments is often dependent on soil type (Friedel et al. 1996). The application of high-density animal impact in this study was in conjunction with addition of organic material (hay) and we are therefore unable to separate the potential impacts of herd effect and the organic material. Seed from the hay likely contributed to a proportion of plant growth observed within the herd effect treatments (e.g., *Avena sativa* and *Lolium perenne*). Studies in Australia have documented beneficial effects of addition organic materials to create patches for resource capture and germination of perennial grasses (e.g., Bean et al. 2015).

The decrease in surface salinity under the cattle and ripping provides improved conditions for plant establishment and growth, providing a positive feedback cycle as increased plant cover further reduces the draw of salts to soil surface. Periods of above-average rainfall over the duration of the trial also resulted in some improvement in the control areas in 2023 relative to that recorded in 2021, however this increase was generally greater in the cattle and ripping treatments.

These results demonstrate the effectiveness of targeted management actions in restoring scalded areas on the Darling Riverine Plains. For long term remediation of these sites, it will be important to sustain the changes that have been achieved so far by continuing to carefully manage grazing pressure of both domestic and unmanaged herbivores. Further research examining the impact of timing of animal impact (i.e, in dry versus moist conditions), duration and frequency of impact, with and without addition of organic material, and combinations of both mechanical and animal impact is recommended, alongside continued monitoring of the trial site to understand long-term benefits of the management interventions.

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Effects of different intensity grazing on ground-dwelling arthropods, especially Coleoptera

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Key words: adaptive grazing management; insects; plant leaf traits; plant community attributes; soil moisture

Abstract

In order to investigate the effect of grazing on the inherent Arthropod-Plant relationship, various adaptive intensity grazing management experiments were conducted on typical steppe in Inner Mongolia. At the community level, arthropod richness was higher in light and heavy grazing than in moderate grazing, but there was no significant difference between grazing and no grazing. Both arthropod communities and Coleoptera prefer to survive in relatively dry soil environments. The lower the plant biomass, coverage, and height, the higher the Coleoptera abundance, likely due to grazing shaping a more open feeding space for visual predators. However, dry soil and more open feeding space are accompanied by more intense grazing interference, and the stronger the direct interference, the lower the biomass of arthropods, especially Coleoptera. The direct disturbance of grazing to arthropods (involuntary feeding and trampling) may often be underestimated, these direct disturbances may mask the indirect disturbance of grazing to arthropods through plants, and grazing may cause arthropods to choose a more stable environment rather than a better one. This means that it is necessary to incorporate surface arthropod-related monitoring data into the sustainable development and utilization management system of grasslands.

Introduction

Large herbivore grazing has profound influence on soil physiochemical properties and biological communities (Lu et al. 2022), including arthropods that play a crucial role, in grassland ecosystems (Wilson 1987). On the one hand, the unconscious foraging and trampling of large livestock has a strong and direct effect on arthropods (Van et al. 2015), which is often underestimated. On the other hand, the large herbivore grazing induced variation in soil properties and plant communities can cascade to arthropod communities, and this 'bottom-up" effects (Hunter and Price 1992) of transmitting the variation in soil properties to plant communities and then to arthropod communities have been extensively investigated in grassland ecosystems (Lu et al. 2021).

The abundance and diversity of arthropods increase with the increase of plant production (Lu et al. 2021), as more food resources can support more abundant and diverse herbivores, and the increase includes increase of generalists, specialists and unidentified predators (Lu et al. 2022). In addition to plant quantity, the vegetation environment, especially height and coverage, is also an important factor affecting arthropods. Many herbivores and predators may use chemical odour sensing and/or visual media search mechanisms to find their host plants or prey rather than searching randomly (Michel et al. 2007). The changes in vegetation height and coverage can alter the complexity of vegetation structure, thus the wind in vegetation canopy and the ability of arthropods searching for the odour concentration of host plants and prey (Cardé and Willis 2008); it can also directly affect the arthropods' visual search ability for host plants and prey (Randlkofer et al. 2010). Zhu et al. (Zhu et al. 2012) also found that plant structural heterogeneity (coefficient of variation of plant height) had a greater impact than plant species diversity on insect diversity in a meadow grassland.

The aim of this study was to elucidate the influence of large herbivores grazing on arthropod communities. The following two questions were studied: (1) What are the effects of large herbivores grazing on arthropod communities or Coleoptera? (2) How are the effects of grazing on plant communities and soil water content cascaded to arthropod communities or Coleoptera? The answers to these questions will deepen our understanding of the role of arthropods in maintaining ecosystem function and help develop management strategies to protect grassland ecosystems.

Methods

Study site

This study was carried out with the Grassland Ecosystem Research Station of Inner Mongolia University, located in the Xilingol region of Inner Mongolia, China (44°15′ N, 116°31′ E, 1146 m a.s.l.), using four intensity grazing platforms (each paddock has 0, 3, 6, and 9 two-year-old sheep, named CK, LG, MG, HG; Fig.1). For specific regional climatic conditions, vegetation types, grazing designs and sampling methods for plant indicators, see (Shi et al. 2023).

Arthropod sampling and identification

The pitfall traps (plastic cups of 7cm in diameter and 7cm in depth) were used to sample the arthropods in the grasslands before the last rotational grazing of the season in August 2019, 2020 and 2021. Two trapping points, 10 m apart from each other, were set up on relatively consistent vegetation in each paddock, with three traps at each point. Approximately 5 ml of glycerol and 50 ml of 75% alcohol solution were added to each trap. The traps were placed in the grassland before 9:00am in a no-rain day for continuously collecting arthropods for 48 hours. All collected samples were stored in 75% alcohol solution, and returned to the laboratory and identified with optical microscopy according to references (Li et al. 1987). Specimens were identified to the family as far as possible, and a few unidentifiable arthropods to order. Adults and larvae were counted separately for most completely metamorphosed arthropods as they have different feeding habits. After identification, arthropods were placed on dry filter paper to constant weight, and weighted to 0.0001 g.

Soil water content

The top soil (0 – 10 cm) was sampled using the drill of 5 cm at the location close to the trapping points (3 drill at each point) after the arthropod collection and brought back to the laboratory for determining soil water content (SW) by weighing in fresh and dry after over-drying at 105 °C.

Data processing and statistics

The relative abundance (RA) of an arthropod order, i.e., the percentage of the arthropod order abundance in total arthropod abundance, were calculated. Based on the RA, We found that Coleoptera accounted for 45.54% of the total community, so we focused on Coleoptera in addition to the community. The effects of large herbivore grazing on the arthropod traits as well as sampling years were also analyzed using repeated measure analysis of variance. Plant indicators were reduced to an indicator axis VPCA by PCA analysis (58.97%). Greater VPCA represents greater plant biomass, coverage and height, while density and species richness are reversed. The effects of vegetation and soil factors on arthropod communities or Coleoptera were studied by linear or nonlinear fitting.

Results

Effects of grazing on ground-dwelling arthropod communities or Coleoptera.

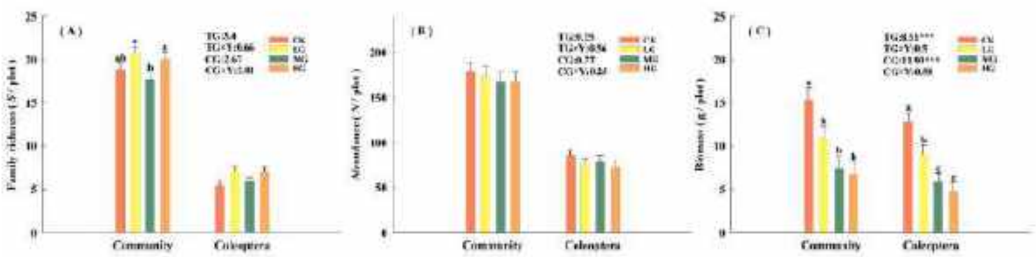

Fig. 1 Effects of different grazing intensities on ground-dwelling arthropod communities or Coleoptera. Different lowercase letters indicate significant differences between treatments (Duncan, $p<0.05$). T represents the total arthropod community; C represents Coleoptera; G stands for grazing; Y represents the year; G×Y represents the interaction between grazing and years. The number indicates the *F* value, and *** indicates $P<0.001$.

Effects of grazing on plant communities or soil water content.

Table.1 Effects of different grazing intensities on vegetation, plant leaf characters and soil. All values are mean ± standard error. Lowercase letters a, b, and c indicate significant differences in the same indicator (Duncan, $P<0.05$).

Indicators		CK	LG	MG	HG
VPCA	*PD*	345.34±15.31b	321.72±31.24b	387.15±29.7ab	454.33±23.38a
	PR	7.25±0.7bc	7±0.96c	9.5±0.86b	12.25±0.7a
	PB	225.45±6.30a	214.06±12.50ab	188.59±13.10b	141.2±15.10c
	VC	66.11±2.27a	61.99±1.96ab	57.73±1.90b	56.75±2.66b
	PH	27.75±2.02a	28.56±1.69a	21.71±0.91b	16.53±0.68c
Plant	*SD*	12.71±1.04b	14.91±0.49a	13.03±0.56ab	9.68±0.34c
Soil	*SW*	0.1452±0.0046a	0.1440±0.0051a	0.1336±0.0039ab	0.1286±0.0029b

Abbreviations: *PD*: Plant density(individual/m^2); *PR*: Plant species richness; *PB*: Plant biomass(g/m^2); *VC*: Vegetation cover(%); *PH*: Plant height(cm); *SD*: Standard deviation of plant height(cm); *SW*: soil water content(g/g).

Relationship between plant community or soil water content and arthropod community or Coleoptera.

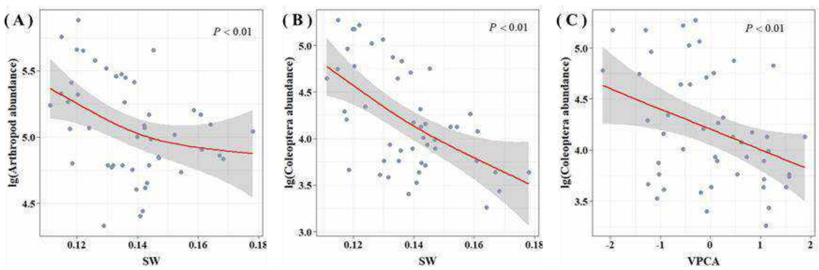

Fig. 2 Relationship between soil water content and the abundance of arthropod communities (A) or Coleoptera (B), and relationship between plant community attributes and Coleoptera abundance (C).

Discussion

Our results suggest that the difference in arthropod family richness across grazing intensities may be related with the grazing-induced changes in vegetation environment and the resources available to arthropods. In the *LG* grassland, vegetation height was uneven and structure was complex, and this type of vegetation provides a diverse living space (Zhu et al. 2012) and support a high arthropod family richness. In the *MG* grassland, the vegetation height variation and structural complexity was lower, thus support a lower arthropod family richness (Table.1). In the *HG* grassland, although vegetation structure was simple, the abundant faeces and blood of large herbivore provide more diverse food resources for scavengers and parasites (Van et al. 2015), which may be major factors for relatively high arthropod family richness in *HG* grasslands.

Grazing did not change the abundance of arthropod communities and Coleoptera, and neither community nor Coleoptera preferred moist environments. Indeed, low soil water content increases arthropod survival (O'Neill et al. 2003). But this change in soil water content is caused by grazing (Lunt et al. 2007). Similarly, grazing reduces plant biomass, plant height, and cover, which provides better hunting space for visual predators (Coleoptera) (Michel et al. 2007). The positive effects of grazing (drier soil and more open feeding space) are accompanied by stronger negative effects (trampling, unconscious feeding), and the reduction in plant biomass means fewer herbivores, suggesting that the two effects can cancel each other out to a certain extent (Van et al. 2015).

In no-grazing or light grazing grasslands, the vegetation is tall and dense, and the litter layer is thicker, which can provide adequate food (Lu et al. 2022) and a more stable living environment for arthropods (Pétillon et al. 2008). However, high grazing intensity increased the damage to arthropods caused by involuntary foraging and trampling (Wang et al. 2024), which is often underestimated. For example, while beetles' hard elytra allows them to adapt to more diverse environments (Parker 2016), beetles are also more likely to die when trampled by large herbivores. At the same time, some Coleoptera insects have faked death (Humphreys and Ruxton 2018), which may also increase the probability of being trampled to death.

Grazing reduced the biomass of arthropod community and Coleoptera. In the case of Coleoptera, which are mostly predators, this could disrupt the ecological balance of the entire ecosystem. At the same time, the direct disturbance of grazing appears to have a stronger effect on arthropods, changing the arthropod's preference for a suitable environment. This suggests that, in addition to the impact of environmental and management factors on arthropods, more attention needs to be paid to arthropod adaptation to different grassland use patterns.

Acknowledgements
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Socio-economic and ecological factors influencing herder household mobility in Mongolian Steppe

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Key words: Herder household mobility; factor analysis; ecological, economic, and social factors.

Abstract

Mongolia's heavy dependence on pastureland makes sustainable pasture use crucial. Historically, nomadic Mongolians maintained ecosystems by frequently moving livestock, a practice essential for pasture sustainability. Despite its importance, research on the factors affecting herder household mobility (HHM) is limited, especially using econometric modelling to identify and estimate these factors. This study examines socio-economic and ecological factors influencing HHM in four Mongolian provinces using pooled data econometric models.

The research addresses two main questions: 1) What social, economic, and ecological factors influence HHM decisions? 2) What policy implications arise from these factors? The study was conducted in 11 sub-districts across four provinces, using stratified random sampling based on probability. Data were collected from the same 253 households over three years in 2019, 2020 and 2022, resulting in a total of 759 observations.

The ecological factors such as the number of households sharing the same pasture (24.9%), water output in the pasture (26.7%) and drought (41.6%) promote greater mobility. Economic factors include livestock wealth, which contributes to a 45.2% increase in mobility distance. Finally, the social factors that increase mobility distance include the female household head (76.1%), the distance to the district center (57.2%), and adherence to local government plans (62.1%).

Conversely, ecological factors such as better vegetation conditions (30.2%) correlate with shorter HHM distances. Among the economic factors, increased fuel prices (54.8%) and owning a truck by a herder (18.2%) reduce mobility distance. Social factors that reduce mobility distance include larger family sizes (17.3%) and older household heads (38.2%).

The study's insights offer crucial implications for policy-making aimed at enhancing sustainable HHM in Mongolia. Understanding these factors can help devise strategies to support herder communities while maintaining pastureland sustainability, ensuring both ecological balance and the well-being of herder households.

Introduction

Pastureland provides essential ecosystem services, including livestock forage, carbon sequestration, and water flow regulation (Rodríguez-Ortega et al., 2014). However, climate change and land-use changes have negatively impacted Mongolia's rangelands, leading to reduced pastoral mobility and increased environmental degradation (Fernández-Giménez et al., 2018). In 2018, pastureland covered 71.6% of Mongolia, feeding 64.7 million livestock (Agipar et al., 2019; NSO, 2024). The rapid growth of livestock, which has more than doubled since 1990, has resulted in overgrazing, with 57% of rangelands degraded as of 2016 (Densambuu, B et al., 2018).

Sustainable pastureland management, essential for balancing ecosystem health and herder livelihoods, relies on mobility strategies such as seasonal and *Otor* movement (long distance movement) (Gonchigsumlaa & Damdindorj, 2021). Yet, since the transition to a market economy in the 1990s, mobility has declined due to privatization and weakened institutional support (Fernandez-Gimenez & Le Febre, 2006). Reduced herder household mobility (HHM) exacerbates rangeland degradation, undermining livelihoods and livestock productivity (Kerven, 2003; Humphrey & Sneath, 1999) of herder households (HHs).

This study uses econometric models to investigate socio-economic and ecological factors influencing herder household mobility in Mongolia, aiming to inform policies that enhance mobility and promote sustainable rangeland use.

Methods

The study was conducted in 11 sub-districts (core sites) across four provinces: *Tuv*, *Khentii*, *Dornod*, and *Sukhbaatar*. Using stratified random sampling, 320 HHs were selected in 2019, representing 22% of the herder population. The sample size decreased to 289 in 2020 and 253 in 2022 due to household migration, status changes, absences, endemic quarantine, and COVID-19 lockdowns. To generate balanced panel data, the same HHs were surveyed yielding 759 observations from 253 HHs over three years.

The annual total distance of HHM, measured by km (**lnDIS**[4]) was selected as the dependent variable, which we want to explain using independent variables (total distance moved for three types of HHM: between and within seasonal camp mobility and *otor* mobility (Gonchigsumlaa & Damdindorj, 2021)). We divided the independent variables into ecological, economic and social factors. **Ecological factors** include vegetation condition (**AVEG2**), rated from 1 (Very poor) to 5 (Excellent), to capture vegetation changes before and after pasture use (Fernández-Giménez et al., 2018); water availability (**WAT**), categorized as 1 (Bad), 2 (Average), or 3 (Good) (Lkhagvadorj et al., 2013); and two dummy variables for Dzud (harsh winter) (**DZUD**) and drought occurrence (**DRO**), indicating whether these disasters occurred in the previous year (Fernández-Giménez et al., 2018). **Economic Factors** include annual income of the HH, by Mongolian Tugrik (MNT) (**lnINC**); livestock number of the household, by sheep unit (**lnSHU**); number of households using the same pasture, to express the pasture competition (**lnHH**); dummy variable indicating whether the household owns a truck (**TRUCK**) (Lkhagvadorj et al., 2013); fuel price per liter (**lnFUEL**) (Gonchigsumlaa & Damdindorj, 2021); and dummy variable indicating whether the HH lost their pasture (**LPA**). Social factors include family size (**lnFM**); gender of the HH head, (0=Male, 1=Female) (**GEN**); age of the household head (**lnAGE**); HH head's number of years spent on herding livestock, as for experience (**lnEXP**); annual average distance between district center and the HH location in km (**lnDSC**); dummy variable whether the household move in accordance with the local government plans (**PLA**); and dummy variable whether the household is a member of a herder organization (**ORG**).

We run four types of econometric models for analysis including Pooled OLS, Pooled OLS with clustered robust standard error, Fixed effect model (FE), and Random effect (RE) model.

Results

Descriptive statistics

For seasonal-camp mobility, a household moved an average distance of 35.4 ± 37.05 km, with a minimum distance of 0 km and a maximum distance of 292 km. As for within-seasonal-camp mobility, a household moved an average distance of 4.5±12.9 km, with a minimum distance of 0 km and a maximum distance of 196 km. Also, for *otor*, a household moved an average distance of 12.8±41.8 km, with a minimum distance of 0 km and a maximum distance of 460 km. Overall, an average HH moved 4.8 times for 52.6±65.1 km on average, with a minimum distance of 1 km and a maximum distance of 565 km.

Robustness of Test Results

The dataset comprises panel data for 253 households over three years (T=3, N=253). Seven of the 17 explanatory variables are dummies, which could lead to multicollinearity. However, the Variance Inflation Factor (VIF) test showed low multicollinearity, with an average VIF of 1.31 (well below the threshold of 5) (James et al., 2013). Wooldridge's test for serial correlation did not detect first-order autocorrelation (Prob > F = 0.1135). Fixed Effect (FE) and Random Effect (RE) models are widely used for panel data analysis. FE models account for within-entity variation, controlling for time-invariant characteristics (Torres-Reyna, 2007), making them suitable for our dataset. In contrast, RE models assume no correlation between entity-specific effects and predictors. The Hausman test, which compares FE and RE, rejected the null hypothesis (Prob > chi2 = 0.0017), favoring FE (Hausman, 1978). To address heteroskedasticity concerns affecting Hausman test, the robust Sargan-Hansen test was also applied (Mark E Schaffer & Steven Stillman, 2006), confirming FE as appropriate (P-value = 0.0003). The restricted F-test compared

[4] In the abbreviations of the variables, if there is a "ln" then it means that the variable is natural log transformed.

FE and Pooled OLS, favoring the latter (Prob > F = 0.0000) as a more optimal model. Similarly, the Breusch-Pagan test (Prob > chi2 = 0.0000) supported RE over Pooled OLS (Vijayamohanan Pillai N., 2016). Finally, the Chow test (Prob > F = 0.0000) confirmed Pooled OLS as the best fit for the data. Based on these results, the robust Pooled OLS model was selected for analysis.

Model results

In the table below, we compared the results of four different estimators including Pooled OLS, Pooled OLS with clustered robust standard error, Fixed effect model (FE), and Random effect (RE) model.

Table 1. Results of the models: Factors affecting the distance of herder household mobility

Variables	Pooled OLS	Pooled OLS robust	FE robust (xtreg)	RE robust (xtreg)
AVEG2	-0.359***	**-0.359*****	-0.184***	-0.255***
lnHH	0.201***	**0.201*****	0.198***	0.208***
WAT	0.237*	**0.237***	0.0766	0.160
DZUD	0.0147	0.0147	0.0248	0.0212
DRO	0.348***	**0.348*****	0.268***	0.294***
lnINC	-0.0168	-0.0168	-0.00512	-0.0109
lnSHU	0.275***	**0.275*****	-0.000853	0.205***
TRUCK	-0.201*	**-0.201***	-0.157*	-0.166*
lnFUEL	-1.583***	**-1.583****	-0.863	-1.123
LPA	0.0378	0.0378	0.0564	0.0275
lnFM	-0.211***	**-0.211*****	-0.202*	-0.164*
GEN	0.566***	**0.566*****	0.461*	0.517***
lnAGE	-0.657***	**-0.657*****	0.444	-0.402**
lnEXP	0.0008	0.0008	-0.276***	-0.0883
lnDSC	0.373***	**0.373*****	0.688***	0.458***
PLA	0.483***	**0.483*****	0.253**	0.356***
ORG	0.129*	0.129	0.0481	0.0811
Constant	14.62***	**14.62*****	5.980	10.34*
Observations	759	759	759	759
R-sq: within	N.A	N.A	0.1294	0.1053
R-sq: between	N.A	N.A	0.1116	0.2463
R-sq: overall	N.A	N.A	0.1132	0.1985
R-sq	0.2087	**0.2087**	N.A	N.A

* p<0.15, ** p<0.10, *** p<0.05

Source: Results of Stata software, OLS analysis of data from 759 herder households

As shown in the table, the difference between default and cluster-robust standard errors for the Pooled OLS model was minimal, likely due to the short panel data. A notable exception was the variable “ORG,” which was not significant at the 15% level under robust errors. The model’s coefficient of determination (R^2 = 0.2087) indicates that 20.87% of the variation in mobility distance is explained by the included factors. The relatively low R^2 value in the pooled OLS model indicates that while the included variables explain a portion of the variation in household mobility, other unobserved factors likely play a significant role. Variables such as the education level of the household head, the annual income, access to diversified or improved livelihood opportunities etc. Despite this modest R^2, most variables were statistically significant, with 12 showing meaningful effects at 85-95% confidence levels.

Ecological Factors: Vegetation condition after pasture use (AVEG2) negatively influenced mobility distance (-0.359***), while factors like increased household competition for pasture (lnHH), water availability (WAT), and drought occurrence (DRO) had positive effects, with mobility distance increasing by 24.9%, 26.7%, and 41.6%, respectively.

Economic Factors: Wealth (lnSHU) positively affected mobility distance (0.275***), while owning a truck (TRUCK) (-0.201*) and rising fuel prices (lnFUEL) (-1.583*) reduced it.

Social Factors: Family size (lnFM) (-0.211***) and the age of the household head (lnAGE) (-0.657***) reduced mobility distance, while female household head (GEN) (0.566***), distance from the district center (lnDSC) (0.373***), and adherence to local government plans (PLA) (0.483***) positively influenced mobility.

Discussion

Research on herders' mobility often focuses on ecological factors, with less attention given to socio-economic drivers. Mobility is a crucial strategy for utilizing unevenly distributed forage and sustaining livestock. Herders understand long-term pasture dynamics but struggle with short-term changes, risking ecosystem health if traditional knowledge is lost (Oyundelger et al., 2024, *unpublished manuscript*).

Short-distance mobility is often constrained by limited grazing areas within administrative units, exacerbating pasture degradation. However, reciprocal grazing agreements can mitigate this (Fernandez-Gimenez & Le Febre, 2006). Mobility strategies, such as fall *Otor*, are effective in reducing the impacts of climate shocks like Dzud (Baival & Fernández-Giménez, 2012).

Economic constraints, including high fuel costs and limited labor, also influence mobility. Wealthier households with larger herds tend to migrate farther (Fernández-Giménez, 2001), while those lacking resources are less mobile (Baker & Hoffman, 2006). Policy interventions like the proposed Pastureland Law and improved pasture use planning can enhance sustainable mobility and resilience (Fernández-Giménez et al., 2018).

Strategic shock management, supported by modern tools such as savings and insurance, could further strengthen herders' resilience. Policymakers should focus on integrating these strategies while fostering collective action through Pasture User Groups (Kasymov et al., 2023).

Based on the research result two policy implications were derived. Firstly, the successful implementation of pasture use planning is critical for fostering pastoral mobility and mitigating overgrazing. Local administrations must take an active role in regulating pasture use and determining the timing of seasonal movements. While ecological factors and traditional practices influence mobility, local administrative organizations should establish clear schedules for seasonal movement in collaboration with herders. This ensures that winter and spring pastures are well-maintained and protected post-migration. Coordination with Pasture User Groups and herders' communities is essential to enforce these schedules and promote sustainable pasture management practices. Secondly, developing supportive infrastructure such as water points, livestock corridors, and seasonal shelters is essential to enable herders to move efficiently between pastures. Policies should incentivize adherence to established mobility plans and provide resources for maintaining infrastructure. Integrating these measures with broader sustainable rangeland management policies will help reduce competition for resources, improve pasture conditions, and ensure the long-term viability of pastoral livelihoods.

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Linking rangeland condition to grazing management practices: lessons learnt from champion farmers in the grassland and savanna biomes

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Key words: Savanna, Grasslands, Rangeland Management

Abstract

Sustainable management of rangelands plays a key role in rangeland health and the opposite leads to degradation with implications for livestock production. This study explores the relationship between rangeland condition and rangeland management practices among champion farmers within grassland and savanna biomes in South Africa Sixty champion farmers, representing diverse livestock enterprises, were selected through workshops involving government officials, researchers, and agricultural organizations. The selected farmers were interviewed using semi-structured questionnaires, to establish their rangeland management strategies. Questions were framed around (i) current state of the rangeland in the farm (ii) farm management strategies (iii) changes over time. The vegetation condition of the farms, was assessed using a combination of ground-based techniques, including cover abundance and step point. Cover abundance was measured in 10 X 20 m plots, while the step point technique utilized 100 m line transects. Data collected from these methods provided insights into veld condition scores, grazing capacity and species diversity. A total of 35 grass species across different ecological groups were identified, with Increaser II species being the most dominant, suggesting previous over-grazing but showing signs of improvement with the presence of Decreaser species such as *Themeda triandra*. The average grazing capacity was 9.1 ha per large stock unit (LSU), with 72% of farms in good condition, indicated by an average veld condition score of 60%. These positive outcomes are attributed to the farmers' knowledge and experience in veld management. The farms with moderate rangeland condition, averaging 50% veld condition score, attributed this to limited extension support, land availability, and woody plant invasion. Key findings highlighted the importance of appropriate stocking rates, rotational grazing, and veld resting for sustainable livestock production. Overall, this study underscores the critical role of effective grazing management practices in maintaining rangeland health and provides valuable lessons for other farmers in similar biomes.

Introduction

Sustainable management of rangelands plays a key role in rangeland health and the opposite leads to degradation with implications for livestock production. Moyo (2008) notes that patterns of rangeland use and management differ according to ecological areas, tenure systems, institutions and traditional practices.

A good rangeland management strategy should take into account both the ecological processes and economic viability (Hawkins et al. 2017). The most common grazing management strategies in South Africa include rotational grazing, seasonal herding, holistic planned grazing (HPG) and continuous grazing. Rotational grazing formally implies that the rangeland is subdivided (fenced) into small areas called paddocks or camps and that the livestock are moved from one camp to another at different times of year. The camps not in use are rested to allow the grasses to renew energy reserves, rebuild vigor and deepen their root systems, so as to ensure maximum production in the long term (Oates et al., 2011). Briske et al. (2008) reports that one of the aims of such a grazing system is to improve species composition, which is achieved during the resting periods. Seasonal herding also applies the same principle as rotational grazing, however instead of the use of fences to define areas that should be grazed at certain times of the year, the herders make the informed decision based on their knowledge of the rangeland. HPG is a rotational, time-controlled grazing strategy that is commonly known as high-density, short-duration stocking (Skovlin 1987; Butterfield et al. 2006). This method employs high-density livestock management with fences or herders, imitating the natural movement of wild herbivore herds to improve rangeland condition and the health of the animals (Savory and Butterfield 2016). In this grazing system, timing is everything and livestock are kept bunched up and moving so that they cannot return to the same plant for a second bite (Kruger, 2012). HPG requires high levels of infrastructure and manpower, hence in South Africa it has mostly been applied successfully in the commercial sector but is not considered a viable strategy for communal rangelands (Hawkins et al. 2017). Lastly, continuous grazing means that the entire grazing land is grazed throughout the year, including during the dry season. Since grazing management strategies are described as 'planned efforts by rangeland managers to leave some grazing areas unused for at least a part of the year', continuous grazing is viewed by some as the absence of a grazing management strategy (Howery, 2000). The benefits of continuous grazing as opposed to rotational grazing include its low capital investment requirements because there is less need for fencing and the provision of water. Additionally, livestock do not have to be moved from one camp to another, making management decisions simpler (Beetz and Rinehart, 2010). This study explores the relationship between rangeland condition and rangeland management practices among champion farmers within grassland and savanna biomes.

Methods

Study Site Description

The study was conducted within the savanna and grassland biome, which combined, occur in 8 provinces, except for the Western Cape province (Figure 1). The savanna biome is the largest biome in South Africa covering about 33% and represents complex landscapes that are made up of a mosaic combination of grasses, umbrella shaped trees and shrubs (Furley, 2016). The biome is divided into dry and wet/meisic savanna receives seasonal rainfall that ranges from 400 – 1000 mm and 800 – 2000 mm respectively. While the grassland biome is the second largest biome in South Africa and covers 29% of South Africa's land area. The grassland biome is dominated by grasses and have relatively few large trees and shrubs. Bulbs and forbs. The biome receives annual rainfall which ranges from 400mm – 2000 mm.

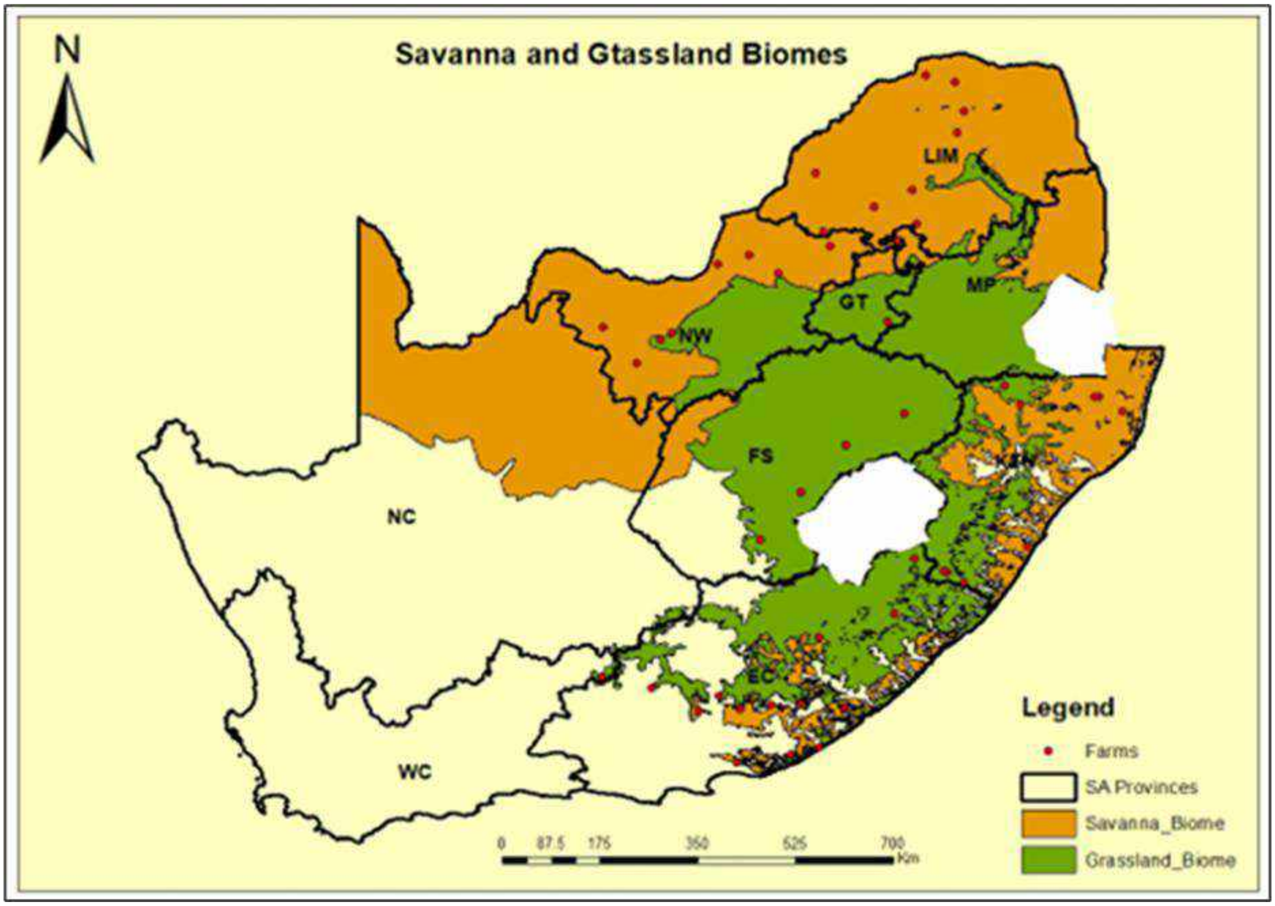

Figure 1: Biome Map showing the savanna and grassland biomes as well as the locations of surveyed famers across the provinces.

Farmer surveys

In-person interviews were conducted with 60 farmers who were selected within the grassland and savanna biomes. The selection process involved multiple stakeholders who were working closely with the farmers in the respective provinces (agricultural extension officers, researchers, retired scientist etc.). Farmers who met the selection criteria were then contacted for their consent to participate in the study and these included both male and female farmers, represented across the different livestock farming enterprises (large, small and game stock) and the different production systems (communal, small-scale and commercial). A semi-structured questionnaire with open-ended questions framed around (i) current state of the rangeland in the farm (ii) farm management strategies and (iii) changes over time, were administered to participating farmers.

Vegetation survey methods

A combination of ground-based techniques, employing an agronomic approach (cover abundance) (Westfall et al. 1996) and ecological approach (Step point) (Hardy and Tainton 1993) were used to assess the vegetation condition of the 60 farms that were selected for this study (35 in the savanna and 25 in the grassland biome). These two techniques were used concurrently at each site chosen as representative of various homogenous vegetation units. Due to temporal and spatial constraints, only two or three sites were surveyed in each farm or communal grazing area. At each site a 250 m transect (5 x 50 m) was laid out where the step-point method was conducted. Along each transect, grass species were identified and recorded as either a hit (when the spike strikes into the plant) or nearest plant (when the spike hit next to a particular plant species). Bare ground was recorded if no grass species were found within a 0.5 m radius from the point. Through the step-point method, Ecological Index (EI) was determined by classifying species into their ecological index groups (Vorster, 1982). The EI was then used to determine veld condition score (%) and grazing capacity (ha/LSU) for every sampled site (farm).

For the cover abundance sampling technique, plots of 10 X 20 m ($200m^2$), were used. All identifiable grass, tree and shrub species rooted in each of these plots were identified following Westfall et al. (1996). This method was used to determine plant canopy cover which is based on mean crown diameter and mean crown-to-crown spacing, derived from Edwards (1983). The mean crown diameter was used to determine cover using Plant Number Scale (Westfall et al. 1996), while the transect width was based on 4/5th of the intra-species mean crown-to-crown gap. The number of individuals of species of interest were counted within this transect length and width to determine individual species frequency.

Results and Discussion

Results from the interviews showed that a majority of farmers participating in this study have grazing plans which are informed by their rangeland condition and 70% (especially commercial and land reform farms) used a rotational grazing system. This grazing system was favoured because it allows the rested areas sufficient time to recover. The farmers shared that they divided their farms into three or more camps with each having drinking water. According to some farmers, they rotate their animals three to four months between camps depending on the condition of the grass. Other types of rangeland management systems used by farmers included herding, holistic planned grazing and adaptive management. The communal areas that were part of this study shared that they used herding to conduct rotational grazing without fences. Eighty-two percent of the farms surveyed keep livestock records and regard it as the best way to manage livestock. About 85% of the farmers mentioned that they keep rainfall records which assist with predicting droughts so proper planning can be implemented. They mentioned that they collected their rainfall data from their rain gauges and weather Apps. Microsoft Excel was the most favoured program for record keeping, while some used different phone applications. Farmers indicated that keeping farm records is important for proper planning, managing risks and overall management of their farms. The access and use of different information sources also emerged as a way to supplement the farmer's knowledge on good management practice. The most used sources of information included the internet, farming magazines and agricultural agencies. There were a few farmers who also make use of drones and remote sensing on their farms. According to one farmer, he uses drones for security purposes, monitoring watering points, livestock and even vegetation.

The results from the vegetation surveys showed that the average grazing capacity, veld condition score and farm size varied among the different farming systems (Table 1). Based on the grazing capacity and veld condition score the commercial and land reform farms were in good condition while the communal farms were in moderate condition. A total of 35 grass species across different ecological groups were identified, with Increaser II (grass species that increase when the rangeland is over grazed) species being the most dominant, suggesting previous over-grazing but showing signs of improvement with the presence of Decreaser (grass species that decrease in population when grazing pressure increases) species such as *Themeda triandra*.

Table 1: The average farm size, cover abundance and average veld condition score of the different farming systems.

Farming system	Average Farm size (ha)	Average Grazing capacity (ha/LSU)	Average veld condition score (%)	Veld condition status
Commercial	2180	6.7	61	Good
Land Reform	1056	8.8	63	Good
Small scale	897	11.9	52	Moderate

Conclusions

Farmers have shown they possess the knowledge and skills to manage their livestock and rangelands under the different tenure types and farming systems. The best lessons learned from farmers in these biomes was on the importance of applying good veld management principles in order to maintain the rangeland in a good condition.

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Water ecology and management in rangelands

Exploring trade-offs between water and carbon linked to woody encroachment in a native semi-arid grassland, Eastern Cape, South Africa

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Key words: Eddy covariance; woody encroachment; ecosystem carbon regulation; ecohydrology; ecosystem water use efficiency

Abstract

Woody encroachment has been widely documented in rangelands over approximately the last century. It is generally believed that this increase in aboveground biomass leads to increases in C sequestration, which, due to deeper rooting systems and leaf area of trees, implies a cost in terms of water availability due to increased evapotranspiration. To explore the evidence for this hypothesised trade–off in functionality, we installed a pair of identical eddy covariance flux towers in a native semi–arid C_4 grassland and an adjacent encroaching *Vachellia karroo* woodland in the Eastern Cape, South Africa, with otherwise similar site characteristics, and compared carbon © and water budgets over the period September 2019 to February 2022.

The woodland was marginally more productive than the grassland, but these C gains were offset primarily by disproportionately large dry season respiration effluxes, resulting in the grassland sequestering 65% more C than the woodland (389 g m^{-2} vs. 235 g m^{-2}) over ~20 months of concurrent data. Differences in water use were negligible, however, with the woodland evapotranspiring just 9% more water than the grassland (845 mm vs. 775 mm), equivalent to 78% and 70% of total rainfall (1103mm), respectively. Ecosystem water use efficiencies were essentially identical over the study period (2.7 g C m^{-2} [kg H_2O]$^{-1}$), with the grassland slightly more efficient in the dry season (2.6 vs. 2.5 g C m^{-2} [kg H_2O]$^{-1}$).

We found no evidence to support the hypothesis of a trade–off between C and water linked to encroachment at our sites. Given the complexity of ecohydrological and biogeochemical responses to vegetation shifts in these systems, however, and the wide variation in results reported in previous work, there is a clear need to replicate similar studies across broad environmental and climatic gradients towards improving understanding of these processes and developing coherent policy for rangeland management in the context of global change.

Introduction

Woody encroachment and proliferation has accelerated over the last century, understood to be a response to changing land management, biogeochemical, and climate drivers (O'Connor et al., 2014). This process has been particularly rapid in drylands, defined as regions with an aridity index of < 0.65 and characterised by open ecosystems typically comprising a dynamic complex of woody C_3 plant functional types and C_4 grasses (Archer et al., 2001). These systems account for nearly half the terrestrial land surface and, despite comparatively low levels of productivity relative to tropical and boreal forests, they play a major role in regulating the global C budget because they are so extensive globally, thus dominating the trend and inter-annual variability of the land sink (Ahlström et al., 2015).

Carbon dynamics in drylands are typically complex and non–linear, oscillating between net sources/sinks over seasonal and annual timeframes in response to management, high rainfall variability, and frequent drought. However, although the mechanisms are poorly understood and detailed accounting in many regions lacking (Biederman et al., 2017). Evidence of the effects of encroachment on C regulation in these systems is equivocal, and previous studies have reported increases, decreases, or no change in C sequestration rates relative to original vegetation types, because factors including rainfall thresholds, species functional traits, time since encroachment, and soil type all interact to mediate biogeochemical responses to varying degrees (Barger et al., 2011; Hughes et al., 2006).

Similarly, while increases in woody cover have been shown conclusively to lead to elevated water use and associated declines in catchment yields due to higher leaf area and deeper rooting systems of trees relative to grasses (Le Maitre et al., 2020), much of this work has focused on commercial forestry and alien invasive species in mesic and humid environments; the pattern is less clear in dryland systems. Impacts of vegetation shifts on the water balance tend to decrease with aridity, with semi–arid systems occupying a transitional zone along this continuum, and for which ecohydrological processes are least well understood (Huxman et al., 2005).

Despite these uncertainties, policy and planning relating to encroachment in drylands is often predicated on the assumption that higher aboveground biomass associated with increases in woody cover generally leads to increased C sequestration, reduced catchment runoff based largely on ecohydrological theory and extrapolation of data from different climatic regions and non-native species (Department of Environmental Affairs, 2019). Broad generalisations that do not account for the complexity of biogeochemical and ecohydrological responses to vegetation shifts in these systems hinders the development of effective responses to accelerating global change in these systems.

In South Africa, approximately 10 % of the land surface has experienced woody encroachment to varying degrees since the 1990s, with highest rates recorded in semi-arid and dry sub-humid grasslands and savannas with annual rainfall > 500 mm (Skowno et al., 2017). *Vachellia karroo*, a deep–rooted nitrogen fixing legume, is among the most prolific of approximately 40 identified encroaching species in the northern and eastern parts of the country. We compared ecosystem C and water budgets using paired eddy covariance technology in a native semi–arid C_4 grassland and adjacent encroaching *V. karroo*–dominated woodland in the Eastern Cape Province of South Africa over a period of ~30 consecutive months, to evaluate potential trade–offs in functionality linked to woody cover increases in these systems.

Methods

A pair of identical open–path eddy covariance systems was installed on a commercial livestock ranch near Adelaide in the Eastern Cape, South Africa, (-32.742, 26.471; ~770 m.a.s.l), and data analysed for the period 1st September 2019 to 28th February 2022. The towers provide high frequency (10 Hz) measurements of mass (CO2) and energy (sensible and latent heat) exchanges above vegetation canopies averaged over 30-minute intervals and integrated over footprint areas of several hectares.

The flux sites are separated by a distance of 890 m and located on flat or gently undulating topography. Soils are shallow (~0.75 m) and consist of a clay/loam complex over Beaufort Series sandstones. Mean annual precipitation is 730.4 (±158) mm, with mild dry winters (JJA) and hot, relatively humid summers (DJF) (Koppen classification *Cfa*). Rainfall is strongly seasonal, with ~70 % occurring over the austral spring and summer/early autumn months (Oct–Mar). Mean annual temperature is 17.7 (±3.2) ºC, with warmest temperatures in January (22.5 [±0.8] ºC) and coolest in July (13.2 [±1.5] ºC).

Vegetation at the grassland comprises a variety of perennial C_4 grasses, with several dwarf shrub species present in low abundances, and a sward height of ~0.4 m in the growing season. The woody component at the encroached site is dominated by *V. karroo*, with cover ranging from ~20–40 % and a mean canopy height of ~5 m; the herbaceous layer comprises largely continuous cover by a range of C_4 grass and forb species. Both sites are utilised for grazing by domestic livestock and wild game at stocking rates of ~4 ha LSU^{-1}.

Results

Daily net ecosystem C exchange (NEE), gross primary production (GPP), ecosystem respiration (R_{eco}), and evapotranspiration (ET) at each site are shown in FigureA; intermittent power and sensor failures over the total 912 days of measurement resulted the loss of 28% of data (254 days) from the grassland tower (GRA), predominantly during the 2020/2021 and 2021/2022 growing seasons, and 5% of data (43 days) from the tower at the woodland site (VKA) in the 2019 dry season; a total of 615 days concurrent data were obtained, comprising 230 and 385 days of growing and dry season data, respectively.

Both systems generally functioned relatively similarly in terms of C and water regulation, with similar flux phase and amplitude over the 615 days of concurrent data. Near–complete failure of late spring rains in 2019, corresponding with the end of a severe multi–year regional drought, resulted in a truncated 2019/2020 growing season, with marked declines in physiological activity well into summer of that year, but with some recovery evident from January 2020 onwards. VKA was almost uniformly marginally more productive than GRA over the 615 days, with 8% higher total gross photosynthetic uptake (2278 vs. 2103 g C m^{-2}). These C gains were offset by relatively larger respiration losses at VKA, however, with a total efflux of 2042 g C m^{-2} relative to 1713 g C m^{-2} (16%), resulting in 65% more C sequestered at GRA (389 vs. 236 g m^{-2}) over the 615 days. Water use at the two sites reflected differences in productivity, with just 9% more ET measured at VKA than GRA (845 vs. 775 mm), equivalent to 78% and 70% of total rainfall, respectively, over this period (1103 mm), and the difference assumed to have been converted to surface runoff.

The bulk of the difference in the C and water budgets between the two systems is explained primarily by dry season physiology, however; while both gross C uptake and ecosystem respiration were higher at VKA in both seasons, the difference in total dry season respiration efflux between the two systems was double that measured in the growing season (220 vs. 109 g C m^{-2}, respectively), resulting in 93% more C fixed in the dry season at GRA (114 vs. 8 g C m^{-2}) relative to 17% more in the growing season (275 vs. 228 g C m^{-2}) (Figure 1). Seasonal differences in water use between the two systems reflected this trend, with 16% more ET measured at VKA in the dry season (341 vs. 288 mm at VKA and GRA, respectively) relative to 3% more in the growing season (504 vs. 487 mm).

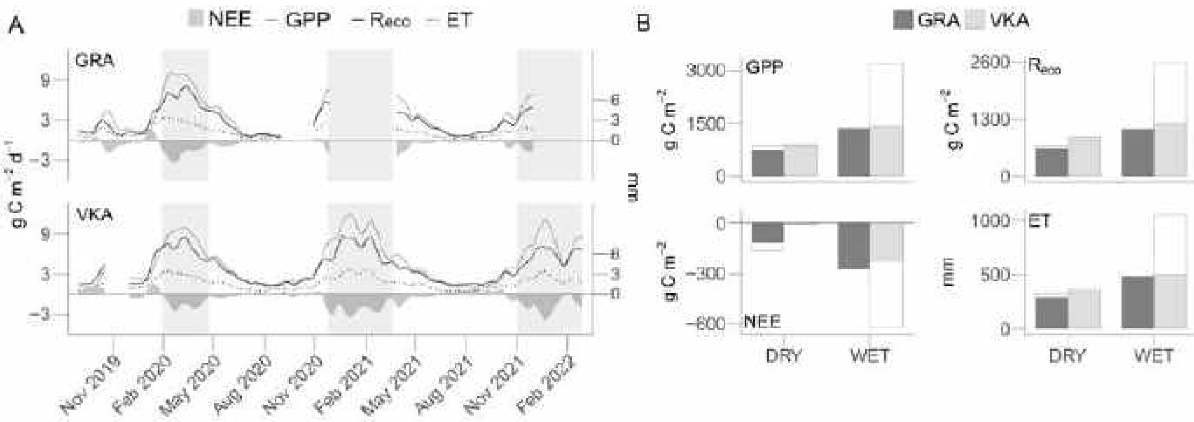

Figure 1: Daily NEE, GPP, R_{eco}, and ET measured at GRA and VKA over the study period; vertical grey bars indicate growing seasons (A). Total C and ET fluxes measured in dry (n = 385 days) and wet seasons (n = 230 days) over periods of concurrent data availability; white bars indicate sums calculated based on all available data at respective sites (B).

Growing season evaporative indices, calculated as the ratio of ET to precipitation, were almost identical (0.62 and 0.64 at GRA and VKA, respectively), with effectively all available rainfall utilised in the dry season (0.9 and 1.07, respectively), although the ratios of E:T in respective systems and seasons are undetermined. Ecosystem water use efficiencies (WUE_E), expressed as the ratio of daily GPP (g C m^{-2}) to ET (kg H_2O m^{-2}), over the study period were essentially identical (2.7 g C m^{-2} [kg H_2O]$^{-1}$); GRA was marginally more efficient in the dry season (2.6 vs. 2.5 g C m^{-2} [kg H_2O]$^{-1}$), however, with growing season values of 2.8 g C m^{-2} [kg H_2O]$^{-1}$ at both sites.

Discussion

Despite higher levels of productivity linked to increases in woody biomass at VKA, the grassland sequestered significantly more C than the woodland, attributable primarily to disproportionately larger dry season respiration effluxes at the former. The source of the additional dry season C losses at VKA is unclear, but since differences in GPP measured in each system were consistently relatively marginal, we anticipate that these likely originated from microbial decomposition of soil organic matter and necromass, although the underlying mechanisms would require further investigation. Reflecting differences in productivity, differences in total water use between the two systems were negligible and presumably explained by shallow soils and the absence of subsurface water at the flux sites, which constrains competitive advantage in terms of access to water conferred by deeper tree rooting systems relative to grasses in semi-arid environments. In this regard, topoedaphic and physiographic (upland vs. riparian) contexts are likely to be key factors in predicting the water use impacts of woody cover increases in water limited systems (Huxman et al., 2005).

Our data do not support claims of increased C sequestration and water use linked to encroachment in these systems, with the grassland sequestering 65% more carbon than the woodland at similar water use efficiencies. Given the complexity of ecohydrological and biogeochemical responses to vegetation shifts in drylands, and wide variation in results reported in previous work (Barger et al., 2011; Biederman et al., 2017; Hughes et al., 2006), our results underscore the need to replicate similar studies across environmental and climatic gradients to improve understanding of these processes and develop coherent policy for effective rangeland management in the context of global change.

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Put your money where success has been – a rapid review of interventions to improve pastoral land condition in the southern rangelands of Western Australia

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Key words: regeneration techniques, evaluation, WA Goldfields

Abstract
The paper reports on a six-day study trip of rangeland regeneration efforts implemented between 1984 - 99 in the Goldfields Region of Western Australia (WA). Results of land regeneration efforts have been influenced by the extent and severity of degradation, fragility of soil type, episodic flooding and drought, and the degree of total grazing pressure (TGP) control. Locally endemic plant species fared better than sown native species. The long-term effect of cultivation has been variable as have the benefits of shallow water ponding. The benefit of any cultivation has depended on the proximity of seed source areas of native species. Plant establishment has been improved where the water ponding has made the surface soil more sodic and cracked. Deeper, longer-lasting ponding behind bulldozer-built banks has been effective in rehabilitating rangelands. A small study of fracturing hardpan with explosives has shown benefits. Measurement of Mulga (*Acacia aneura*) trees planted in water-ponded areas has allowed an assessment of mean annual increments of carbon that could inform future carbon farming initiatives in the rangelands.

Introduction
The WA Department of Primary Industries and Regional Development (DPIRD) Southern Rangelands Revitalisation Program (SRRP) supports pastoralists to improve land condition for livestock production. The SRRP is reviewing rangeland regeneration efforts to understand their short and long-term effectiveness, which will benefit pastoralists and other rangeland uses. The southern rangelands of WA have experienced long term degradation, with a mean of 25% in poor condition, and one per cent being severely degraded and eroded (SDE) (DAFWA 2017). More productive types of pastoral land have a greater proportion of degradation, reducing productivity and profitability. Government and land managers have spent decades trying to improve land condition on this very small area of SDE to the detriment of focusing on the management of the whole landscape. The best publication from WA on mechanical range regeneration remains Addison (1997). This bulletin describes many of the cultivation techniques used in the Goldfields and was informed by experience gleaned from sites such as those visited in this study.

The Goldfields has seen many changes over the past thirty or so years. Many pastoral leases are now held by mining companies and overseas financial interests with fewer owned by family entities. Climate change is leading to higher mean temperatures throughout the year, lower winter rainfall with increased occurrence of drought, and more intense rainstorms and, therefore, more flooding events (BoM 2024). There were several areas with mature dead Mulga, which is attributed to severe drought and high temperatures experienced in 2019 (Paul Axford, pers. comment). The feral goat eradication program (1993-8) temporarily reduced grazing pressure. Wild dogs and dingoes are no longer controlled and effectively ate the local sheep industry, driving the change to cattle production. Dogs, dingoes and an extended dry period (2019 – 2023), have greatly reduced grazing pressure by native and feral species. On our 1,000 km trip through the Goldfields, we saw a total of four kangaroos. Many pastoralists have entered into carbon farming projects based on the regeneration of above ground biomass.

Methods

Prior to our 6 day tour (21 – 26 October 2024) we obtained whatever old research plans, site assessments, reports, monitoring records and relevant papers we could find. A desktop assessment used time lapse remote sensing images to detect change, confirm locations to visit, and inform rapid assessment methods (Table 1).

Table 1. Range of rapid assessment techniques employed

Types of assessment / measurement employed	How assessments were used
Visual observations	Assess persistence of earthworks and influence on regeneration
Time lapse remote sensing	Assess direction of change
Photographs with GPS locations	Current condition and allowing for future re-assessment
Photos of monitoring sites	Present reassessment (need original monitoring photos)
Drone footage	Gradations in cover and soil conditions - for future detailed assessment
Report soil surface changes	Assess effects of water on cultivations and ponding banks
Soil penetrometer tests	Assess any long term benefits of cultivation
Plant species, locations and sizes	Assess effects of water ponding on plant establishment and growth
Trial plant / species survival	Assessment of plant species that established and matured
Native plant colonisation	Effects of cultivation and proximity to seed source areas
Cross section across ponds	Measure land slope and bank height
Canopy and height measurements of Mulga trees of known age	Assessments of annual increments in above ground biomass & carbon content that might inform future carbon farming and water ponding initiatives

Results

We assessed regeneration sites on 5 leases, one in the Southern Goldfields where the Mallen niche seeder was trialled, and 4 in the north-eastern Goldfields which variously received broad scale disc pitting, chisel ploughing, seeding, grader built banks and dozer built banks. Photo records show all the sites prior to treatment were in poor condition or SDE. Project files consistently identify a common purpose of demonstrating methods to rehabilitate degraded and eroded areas. North-eastern Goldfields rainfall in the year of assessment was greater than the median and above average. For the 6 years prior, it was below the median and average.

Cultivations and soils
Soil cultivation aims to provide a seedbed for plants to establish, and can extend winter and summer growth periods by increasing the amount and longevity of water infiltrating the rooting zone. Our penetrometer tests showed infiltration benefits from initial cultivation had been lost. On disc pitting cultivation from 1985, 14 pitted sites had a mean penetrometer depth of 6.8cm compared to 20 non-pitted sites that had a mean depth of 6.2cm. Disc pitted sites from 1984 on a more alluvial site adjacent to a waterway showed mean (n= 10) penetrometer readings of 8.2cm (pitted) and 4.6cm (non-pitted).

Most sites in the north-eastern Goldfields were on hardpan plain land units with shallow, restricted soil depth over hard pan. These areas once supported preferential grazing. (The Nambi site in Humpy paddock was an alluvial plain that exhibited saline and/or sodic conditions.) These are some of the most challenging areas to rehabilitate. Soil profiles commonly contained ironstone gravel. As cultivated soil fretted or eroded away, gravel was left behind on the soil surface.

Plant establishment
Fencing off trials from all forms of grazing is essential, as is fence maintenance if long term observations are to be made. The exclosures on Mungari (near Kalgoorlie) and Sturt Meadows (Browns Paddock) have remained stock proof, which allowed us to make some observations. Accessions of *Atriplex amnicola* (573, 577, 580, 586, 588 and 949) planted on cultivation by a Mallen niche seeder (Malcolm and Allen 1981) in the Browns Paddock exclosure established well, but were only assessed in 1985, the year they were planted. Judging by remains of stems, a few of each accession (4 to 12 plants) lived a long time, but eventually succumbed to local conditions. Alternatively, plants of some species sown by a Mallen niche seeder at the Mungari exclosure on Gumland Land System in a slightly wetter, more sheltered site have survived or have completed their life cycle and produced seeds. However, plants have not spread away from the cultivated lines.

Surviving examples of the species sown on Mungari include *Atriplex vesicaria, A. bunburyana, A. nummularia,* and *Maireana pyramidata*. Other species have since established inside the exclosure, including *Cratystylis subspinescens, C. conocephala, Eremophila scoparia, Maireana georgii, Ptilotus exultatus, P. obovatus* and *Aristida contorta*. This and other locations where native species established on cultivated areas close to native seed sources may reflect that successional processes cannot be bypassed entirely by cultural interventions (Hacker 1989).

Different forms of ponding banks
'Accidental' shallow ponding in the Mungari exclosure caused by cultivation on the contour by the Mallen niche seeder, has made the soil more sodic and has increased cracking. This has caused a dense establishment of the colonising species mentioned above.

Grader-built ponding banks were established on Sturt Meadows around 1985-86. In the large catchments, such as flow through Browns and Top Bullock paddock on Sturt Meadows, overtopping runoff has washed away much of the soil from the grader-built banks, leaving a gravelly strew and a bank with minimal elevation (5-20cm). Most ponds remain bare, but, in places sufficient soil moisture has been retained to allow the establishment over time of a range of native species. As an example, along a 250m length of bank we found 8 *Acacia aneura* (Broad leaf), 1 *A. aneura* (Narrow leaf), 7 *A. craspedocarpa*, 6 *A. tetragonophylla*, 2 *Senna* spp, and 1 each of *Eremophila fraseri, Marsdenia australis* and *Solanum lasiophyllum*.

We visited bulldozer-built banks at Melita and Sturt Meadow Stations. The Melita banks were designed and supervised by John Law to reduce erosion and rehabilitate the area by impeding runoff and increasing soil infiltration. An explanation is provided in Law 1993. The work was a collaboration between the mining industry, pastoral industry and government. One of the first changes attributed to the banks was increased aquifer recharge. This caused Heron Well on the east side of the highway that that had been dry for a long time to start producing water again (John Law, pers. comment). Of the interbank areas, the banks decreased the length of slope for all locations typically increasing the stability of soil surfaces and vegetation density. The banks caused water ponding for approximately 5% of the overall area. This varied between interbank areas from less than 5% to up to 25%. Ponded areas experienced the greatest increase in vegetation density and size. It has taken several years before the banks have started to show their benefit. This was partly due to feral goat grazing some years ago (Jim Addison, pers. comment). Remote sensing scenes of the banks from April 2005 and July 2024 show a great improvement in the cover by native plants, particularly Mulga and halophytes (Fig. 1). Plants near the bank were twice as tall as those further away and had more than double the canopy area.

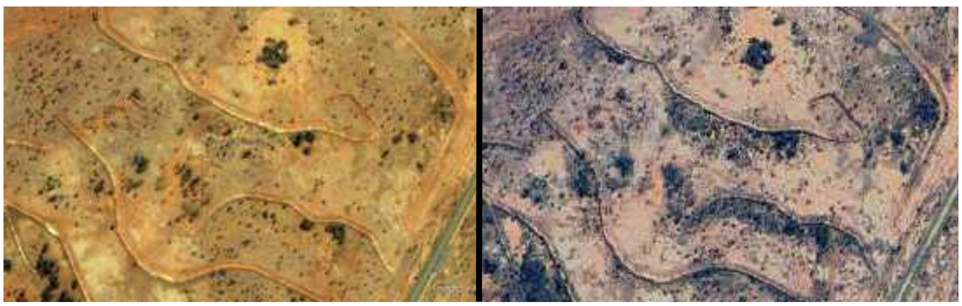

Fig 1. Centre of Melita 'Big Banks' system. Google Earth images in April 2005 (left) & July 2024 (right)

The bulldozer-built banks / ponds at Sturt Meadows were constructed as part of a research program of a consortium of Japanese universities. Here local trees (*Eucalyptus camaldulensis, A. aneura, E. salubris*) were planted in 1999 to assess growth rates. The site was on hardpan on severely degraded land that had been part of a stock route. On one research site the hardpan under all but one of the ponds (Pond 5) was fractured using explosives (Shiono et al. 2007). While many trees in all the other ponds have continued to grow, most trees in Pond 5 are dead. So, fracturing the hardpan (with explosives) will assist aquifer recharge, plant establishment, root penetration and plant nitrogen nutrition. Landscape rehydration works can be sub-surface as well as on the surface!

Based on an assessment of annual increments in above ground biomass and carbon achieved from Mulga trees of known age within ponding banks at Sturt Meadows, we estimated that a Mulga tree density of 10 trees/ha growing within ponding banks could sequester 0.4-3.0 tonnes C/100ha/yr. A density of 40 trees/ha within ponding banks might sequester 1.6-12.0 tonnes C/100ha/yr.

Discussion, Conclusions and Implications

Obtaining regeneration records was challenging and when available, mostly hard copy held variously by the Department, former Department staff, and lessee. Located records will be digitised before more records are lost. Some records may be found in journals (e.g. Williams 2002).

Of the areas that 39 to 41 years ago received cultivation, seeding, or grader banks, many have sustained minimal regeneration. It is hypothesised some initial plant germinations did not persist due to either degraded soils and landforms, limited natural seed sources, seasonal conditions, grazing impacts, or a combination of these. The data to explain the relative importance of ecosystem drivers was limited. The big banks sustained the greatest regeneration. The cost of bulldozer-built ponds might be hard to justify. However, where they have multiple uses (aquifer recharge, carbon farming, range regeneration) they may be of economic benefit, especially where pastoral and mining interests work together for mutual benefits.

Ongoing management and TGP control are essential. Wild dog predation has reduced grazing pressure from kangaroos and goats. This may assist control of TGP to improve outcomes from future regeneration events. Regeneration work should be preceded by investigating soil conditions (e.g. hardpan presence and depth, salinity and sodicity) and catchment characteristics. Addison (1997) contains some guidelines for cultivation under various soil conditions. Cultivation should be proximal to native seed source areas to extend the regeneration of native species while foregoing the expense of seed of less well acclimatised species. Grader-built banks are likely suited only to small catchments with controllable runoff to prevent overtopping.

Many regeneration efforts focus on the most noticeably degraded areas where recovery is slowest (Hacker 1989, Addisson 1997). Improvements to grazing systems and strategically located works (mechanical and land management) to arrest the progression of erosion into better condition asset areas, may provide a faster and greater return on investment. Short funding periods of up to three years acted against effective holistic planning and implementation which requires a long term (20-30 year) program.

Acknowledgements

The paper is dedicated to the late John Law who pioneered the design and practice of deep ponding banks in the WA Goldfields. DPIRD funded the fieldwork and paper. We are grateful to Paul and Peter Axford (Sturt Meadows Station), Northern Star Resources Ltd, Glencore, Zenith Australia Investment Holding Pty Ltd for supporting the project; Jim Addison, Tony Crook and Samantha Van Wyngaarden for local information; Phil Thomas for historical records; and Dr Hideki Suganuma, representing the Japanese Project at Sturt Meadows Station, for project information and permission to include growth assessments of Mulga trees on their sites.

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Managing groundwater in South Australia's rangelands

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Key words: groundwater; pastoral; water metering; stock consumption; arid

Abstract

Ground water is the only reliable water source in the Far North of South Australia with approximately 70% of the water take coming from the Great Artesian Basin (GAB). Management of the GAB resources is critical to the health of ecological communities including GAB Springs and the viability of the pastoral, mining and tourism industries in the South Australian Arid Lands region. Demands on the GAB are likely to increase in the future due to the projected growth in mining, petroleum, and geothermal industries.

Much of South Australia's pastoral region falls within the Far North Prescribed Wells Area where water take is managed through licenced allocation. The South Australian Licenced Water Use Metering Policy requires licensed water to be taken through an approved method. Water meters are the default method for accounting for groundwater take however alternatives to water metering can be considered and documented within a meter implementation plan.

With guidance from an advisory group consisting of pastoral industry members with an interest or experience in groundwater management, along with government representation, field trials are in progress testing water accounting solutions against key criteria of reliability, practicality, cost and accuracy.

Trial sites have been selected to ensure water accounting methods are tested across a variety of land types, hydrogeological conditions, and consider water consumption of native and feral animals. The results of the field trials will guide development of policy and accounting methods that meet the requirements associated with managing a prescribed groundwater resource in a way that does not significantly impact a pastoral business; ideally adding value to the businesses such as improved understanding of stock water requirements and water point management and security.

The presentation will provide background on groundwater policy in South Australia and an overview of the field trials including progress and learnings.

Introduction

South Australia's Far North Prescribed Wells Area (FNPWA) is an area of over 315 000 square kilometres covering much of the South Australia's arid area (Fig. 1). Groundwater is the principal source of water for town water supply, domestic, watering stock, petroleum and mining production purposes. The springs fed by the Great Artesian Basin aquifers support rare and vulnerable flora and fauna protected under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) and hold significant Aboriginal cultural values.

Pursuant to the Water Resources Act 1997, the wells in the Far North PWA were declared as prescribed wells on 27 March 2003 as a means of encouraging responsible use of groundwater. Subsequently a Water Allocation Plan (WAP) was developed in accordance with the Natural Resources Management Act 2004 enabling a licencing and compliance system to manage the groundwater resources, to ensure extraction is undertaken in a sustainable manner and to protect the Great Artesian Basin springs.

Licenced stock allocations are determined at a rate of 100 L per day per head of cattle and 20 L per day per head of sheep with an additional buffer of 20% to account for water use by native and feral animals from stock watering points (SAAL Board 2021). Groundwater extraction by the Pastoral industry for stock and domestic purposes is estimated to be 15% of the overall groundwater extraction in the Far North PWA (SAAL Board 2021). However, despite South Australia's policy that all licenced water use needs to be metered (DEW 2019), measurement of the actual use has not been implemented, contributing to significant uncertainty in water balance calculations and groundwater modelling.

The Accounting for Groundwater Take in the Far North PWA project has been developed in response to community concern, raised in 2019/20 during consultation on the Water Allocation Plan for the FNPWA, about the potential impact of water metering on pastoral businesses in the Far North. Concerns centred on the practicality and cost to purchase, install, maintain and monitor meters in remote areas, compounded by the number of bores many landholders utilise and the high temperature and pressures experienced in the central and northern areas of the PWA.

Whilst metering of water extraction is considered the most accurate method of determining take, alternative approaches to water accounting, including non-meter options, can be considered in accordance with principle 1.7 of the SA Licensed Water Use Metering Policy which is flexible and recognises on-ground regional implementation issues. Flexibility provisions including alternatives for metering must be documented in a meter implementation plan (MIP) for a prescribed water resource and made publicly available.

SA Arid Lands (SAAL) Landscape Board and Department for Environment and Water (DEW) are investigating various water accounting options including alternatives to water metering to enable development of an appropriate MIP (referred to as a Water Accounting Implementation Plan in the WAP) for the FNPWA.

Landholder participation in the planning and conduct of the Accounting for Groundwater Take project will be critical to ensure the trial is representative of the on-ground conditions.

Methods

Project Governance

The delivery of the Accounting for Groundwater Take project is reliant on groups and units within government and the community. A supportive program governance framework was developed to provide the structure, decision making process, roles and responsibilities for managing the program.

An advisory group of 5 pastoralists and property managers in the FNPWA was established through an expression of interest (EOI) process. All had an interest and experience in groundwater management for cattle and/or sheep enterprises. A chair for the group was selected from outside the pastoral region to ensure neutrality and to bring a different perspective to the group. The advisory group is also supported by staff from the SAAL Board and DEW.

The group met regularly at the early stages of the project to establish and investigate water accounting options; provide advice regarding the suitability of potential water accounting methods for trialling in the Far North; and support the trials, including identifying participants, expertise and reviewing progress.

Field Trial Methodology and Selection

Six trial sites (pastoral leases, 'stations') were selected for this project; three from Expressions of Interest and three "shoulder tapped" to ensure a broad array of stock, hydrogeological and geographical land systems were captured in the trial sites. The stations selected have both hydrogeological conditions with high artesian temperatures and pressures, and non-artesian conditions where water extraction was by submersible pump connected to solar power. Having a diversity of land systems recognises stock water requirements will vary with grazing conditions, vegetation type and water quality. Figure 1 provides the location of the participating stations within the FNPWA, with the different scenarios of the 6 stations provided in Table 1.

Within the stations, trial sites were carefully selected to maximise the trial's success in determining stock water consumption. Fenced paddocks with no open water storage such as dams or waterholes were chosen. Bores and associated water points (tanks and troughs) and water distribution pipework were required to be in good condition and free of open or uncontrolled flows. Stock type and number, including stock movements into or out of the paddock, had to be known and recorded.

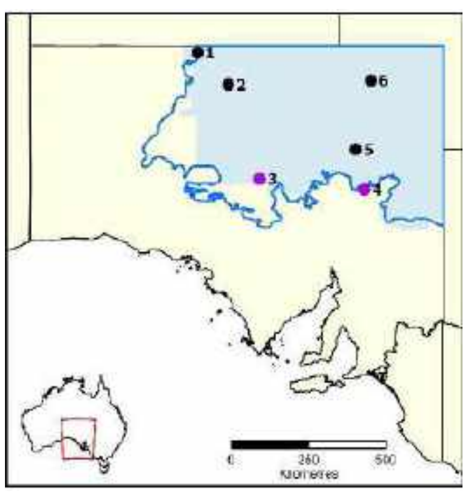

Fig. 1. Location of participating stations (numbered) in the Far North PWA (blue shading); extent of the Great Artesian Basin (blue line); black markers = cattle enterprises, purple = sheep enterprises.

Table 1. Water accounting monitoring scenarios

Station	Stock-Cattle Consumption	Stock-Sheep Consumption	Sub Artesian (pumped bore)	Artesian Bore	Artesian Bore - high temp./pres.
1	✓		✓		
2	✓		✓		
3		✓ (Merino)	✓		
4		✓ (Dorper)	✓		
5	✓			✓	
6	✓				✓

Water meters of varying types are utilised in all trials to-date, to enable monitoring of water consumption, to determine the accuracy of an alternate accounting method and to assess reliability of the meter itself. Meters are connected to telemetry where practicable to enable remote access to the data. Video or still photos from field cameras installed at water points enables identification of water consumption from non-native (e.g. camels and horses) and native animals. Rainfall, temperature and evaporation data was also collected, either on-site at the water points where sensors are installed, or from the nearest Bureau of Meteorology (BOM) weather station.

The land managers at each station provided regular information during the trials including; stock numbers and movement, stock type (e.g. heifers, calves), presence of surface water after rain events, manual instrument reads and assistance with trouble shooting.

Trials have progressively commenced since 2023 and will run for a minimum of 18 months subject to weather conditions. Trials may need to run significantly longer if the seasons are mild or experience above average rainfall.

All findings and observations will be documented and a report will be provided to the Department for Environment and Water to assist the development of a Water Accounting Implementation Plan suitable for the region. This plan may include one or potentially multiple approved water accounting methods that can be adopted by a licence holder depending on their on-ground conditions.

Results

At time of writing Station 2 and 3 (Fig. 1) had commenced trials with preliminary results obtained. Both trials aimed to determine stock water consumption by measuring the total water usage within a paddock and dividing that by the known head of stock. Footage from field cameras enabled analysis of other animal take from the waterpoint/s.

Water Usage - Cattle

Over 12 months from November 2023, water usage from the Station 2 field trial has ranged from 28 L/head of cattle during the cooler months to 79 L/head during summer, with an average of 38 L/head. Field cameras have identified that other animals including camels, kangaroos, reptiles, birds and dingoes are also drinking at the water points.

Water Usage - Sheep
The Station 3 trial commenced in August 2024 and based on the first 3 months water take has averaged 5 L/head of sheep. This includes other take identified in video by kangaroos and a small number of cattle that have managed to push through fences and accessed the water points at times.

Equipment Reliability
A total of 7 installed turbine water meters have been utilised in the trials to date, operating without issue once successfully installed and configured.

Troubleshooting has been necessary at both trial sites with difficulties in correct installation of meters and connection to telemetry and has been complicated by the remoteness of the sites which has significantly delayed site preparation.

One equipment failure has been experienced to-date with a single water meter no longer reporting to telemetry. Field investigation is required to confirm the cause of the issue.

Equipment Cost
The equipment cost of individual trials was anticipated to vary depending on the accounting method and existing infrastructure. Equipment (meters, cables, telemetry components) for individual trial sites were expected to cost between $5000 and $15000 depending on number of water points and meters.

The cost of installation of the trials has been higher than estimated averaging over $15,000. The additional costs can be contributed to additional equipment needed to install meters and link-in with either existing or new telemetry.

Professional installation of meters will be implemented for future trial sites which is expected to increase the cost of each trial by $8,000 - $15,000 depending on the number of meters and pipework modifications required.

Discussion
Early trial results for the first 2 stations indicate water take for cattle and sheep is significantly less than the 100 L per day per head of cattle and 20 L per day per head of sheep as prescribed in the Far North WAP. This includes take by other animals, both native and non-native, evaporation and other losses such as regular trough maintenance.

The results to date are very site specific given the size and diversity of the SA Arid Lands Region. The locations of this study have also not been in drought conditions and other trial sites may return different usage numbers which will need to be considered against the many factors that may influence the results, such as stock breed, age, weather and the on-ground conditions.

While the results are insufficient for in-depth evaluation there are early learnings on water usage for the active trial sites and observations on technical, logistical matters and costs associated with installing meters and other technology in the pastoral region.

While equipment reliability has generally been good over the relatively short time the trials have been running, the lack of services and the remoteness of the area has complicated and delayed installation, troubleshooting and repairs, contributing to the costs of the trials being higher than originally estimated.

All findings and observation will be documented and will assist the development of a Water Accounting Implementation Plan suitable for the region.

Acknowledgements
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Creating and enhancing green spots in the arid zone of western NSW, Australia

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Key words: green spots; rangeland rehabilitation; habitat

Abstract

Arid zone biodiversity adheres to a boom-bust cycle. During periods of ample surface water and vegetation, species reproduce quickly and spread across the landscape (boom period). In contrast, during extended dry periods (bust period), species numbers decline and retreat to locations that remain moist, called "green spots". Green spots vary in size and extent, from individual landscape features, such as gilgais, ephemeral wetlands and creek line waterholes to extensive healthy floodplains.

Widespread degradation occurred in the arid zone of western NSW between the period of the 1890s to the late 1940s, creating legacy erosion issues. Present day degradation occurs to a lesser degree, which impacts on green spots, reducing their size and extent.

This project created and/or enhanced green spots on six pastoral properties in arid western NSW, creating a total of 37 localised green spots and rehydrating 850 ha of floodplain. Rangeland rehabilitation earthworks were used in an expanded way to create more persistent green spots, rather than solely for groundcover establishment for pastoralism.

Introduction

The arid zone of western New South Wales (NSW) experiences periods of substantial surface water and vegetation, separated by very dry conditions of irregular length and severity. Surface water and vegetation become increasingly rare as dry conditions prevail. The areas that remain moist within this vast and dry landscape are called green spots. Green spots vary in size and extent, from individual landscape features, such as gilgais, ephemeral wetlands and creek line waterholes to extensive healthy floodplains. Relictual populations of native animals become reliant on green spots as the dry period progresses (Woinarski 1992) competing with domestic livestock who also rely on these areas. The unpredictable nature of the boom and bust cycle can have severe consequences for the quality and extent of green spots.

Widespread degradation occurred in western NSW between the period of the 1890s to the 1940s (Condon 2002a). For example, during the 1940s drought, Beadle (undated) recorded creek line waterholes, previously 20 feet deep, filled with sediment due to accelerated erosion in the hinterland. Present day degradation occurs to a lesser extent and severity (Condon 2002b) with causes being: livestock grazing behaviour (Pringle and Landsberg 2004); excessive total grazing pressure and infrastructure development (Pringle et al. 2011) and historic over-stocking causing legacy erosion (Fanning 1994). These factors potentially cause the destruction of green spots by the erosional process described by Pringle (2006).

The erosional process starts with increased runoff due to lack of groundcover combined with nickpoint development. A nickpoint is an incision on the natural land surface where flows concentrate resulting in increased erosive power. Causes of nickpoint formation are varied, some examples are: cattle paths lowering the outlet sill of a wetland, "unplugging" the wetland; or a farm track cut into natural ground level which channelises flows. Nickpoints can develop into headcuts, where water falls over a vertical face causing undercutting and collapse of the wall. A headcut progresses upslope, along the path of strongest flow, resulting in gully erosion. These flow paths are the green spot areas, and once a headcut expands through them, they disappear and are replaced with a dryland system (Pringle 2020). This erosional process can occur quickly, with headcut retreat rates of up to 32 metres per annum being measured in western NSW (Graves et al. 2024).

Western Local Land Services (WLLS) implemented a project in 2023 to create and enhance green spots on six pastoral properties in the arid zone of western NSW. WLLS is a government agency concerned with improving both agricultural productivity and management of natural resources. WLLS has experience in implementing arid rangeland rehabilitation works, the primary purpose of which is to control erosion and establish groundcover for pastoralism (Green 1989). This project sought to expand the use of these rehabilitation techniques to include environmental/biodiversity outcomes through creating longer lasting refugia while controlling erosion and improving groundcover.

Methods

Funding provided by the Environmental Trust of NSW enabled projects to be undertaken on six pastoral properties in western NSW (NSW Environmental Trust 2024). Participants were identified based on previous involvement with rehabilitation projects and capacity to deliver.

Project areas were chosen in collaboration with land managers and were either existing green spots that were being threatened by gully expansion or previous green spots that had been severely degraded.

Green spots can be either localised or extensive. To create localised green spots, a dimensional approximate definition was formed based on existing, healthy green spots in the project areas. A green spot was defined for this project as a depression that holds water for at least one month, with a minimum depth of 0.5m and a minimum area of 50m^2, keeping the surrounding vegetation green for longer. Extensive green spots are healthy floodplains which hold water after flows have ceased. In this project, perched floodplains, which no longer receive floodwater due to dewatering caused by gully headcuts, were rehydrated, creating extensive green spots.

Design and layout of projects incorporates a drainage ecosystem perspective, creating and/or enhancing green spots in appropriate locations (Tinley and Pringle 2014a; 2014b) using heavy earthmoving machinery to construct earthen banks. A range of techniques were used, which included check banks, diversion banks, champagne banks, water ponding (Harrison 1994; Quilty 1972a,b; Rhodes 1987) and variations of these techniques based on the author's experience and practice (Theakston and Anderson 2023).

Results

Over the six projects, 37 localised green spots were created in the form of wetlands/waterholes which met the defined minimum dimensions of 0.5m depth and 50m^2, and approximately 850 ha of perched and degraded floodplain was also rehydrated.

Goodwood Station Green spot project

One example of creating localised green spots and rehydrating a floodplain to address legacy erosion occurred on Goodwood Station, owned and managed by Zane and Louise Turner. In western NSW, erosional processes were triggered by the introduction and mismanagement of domestic stock over 140 years ago (Fanning 1999) and current land managers are largely dealing with the resulting erosion.

The project area is a valley side, supporting banded chenopod vegetation with contour patterned small ephemeral waterholes, locally known as gilgais. Apart from the contour-patterned gilgais, the area also has a cluster of relatively deep gilgais (up to 0.8 metres deep) covering 3 hectares, creating a healthy green spot (photo c). Shallow, sinuous drainage lines dissect the area and in their uneroded state contain ephemeral waterholes upheld by sediment sills, forming corridors of green spots (Pringle &Tinley 2003). However, in the current state, instead of shallow sinuous channels, the drainage lines are erosion gullies (photo b) due to firmly established erosional processes as described by Pringle (2006). Any green spots that may have existed along the drainage lines have disappeared due to channel incision and headcut retreat "unplugging" moist areas. Furthermore, the gully is widening due to bank undercutting and collapse and expanding due to lateral gullies, with retreating headcuts threatening to dewater the cluster of deep and healthy gilgais.

The cluster of deep gilgais was an isolated green spot, separated by 1.6 kms from the closest other healthy green spot, located in the valley floor creek line. This creek line contains numerous waterholes up to 1.0 metres deep once creek flows cease (photo a). The project involved creating a corridor of 16 localised green spots connecting the valley floor waterholes with the cluster of deep gilgais. At the same time, re-hydrating 80 ha of a narrow floodplain along the shallow drainage line, recreating sinuous flow.

The average distance between the re-created green spots is 192 metres (83m–410m). The section of the drainage line with the larger gap of 410 metres was healthier and less incised, therefore it was considered not necessary to re-create any green spots along this length.

A total of 7,450 metres of banks were constructed, including large check banks combined with diversion banks intersecting the incised drainage line (shown on figure 1). These are larger banks of 1.0 metre high with a base width of 5.0 metres. Water ponding and champagne banks were constructed (not shown in Figure 1 for sake of simplicity) to rehydrate the narrow surrounding floodplain. Champagne banks are short diversion banks (<100 metres long) which direct flows away from incised drainage lines. They spill the flows from one bank to the other, spreading the water away until a safe re-entry point is found into the drainage line, whilst creating sinuous flow.

The earthworks for the green spot projects were only recently completed, so there is not yet evidence of groundcover and biomass responding positively. However, based on a recent study looking at water ponding in similar landscapes and climates, it is expected that the landscape treated in this project will respond in similar positive ways. In this study, the highest average biomass for ponded sites was 2161 (+- 650) kg/ha, compared to the control area of 254 (+-54) kg/ha (McDonald et al. 2022). Similar results are expected for the water ponding areas within the green spot projects given sufficient rainfall and time.

Discussion

Arid rangeland rehabilitation works have traditionally focused on improving ground cover and vegetative biomass. To achieve maximum groundcover and biomass, the ideal water ponding depth is established at 10 cm. Deeper ponding depths cause waterlogging of soil and encourage the growth of water adapted plants not suitable for pastoralism (Rhodes 1987). This project intentionally increased ponding depth to a minimum of 0.5 metres to encourage water adapted plants and provide longer lasting surface water to create a more diverse habitat.

The design of the green spot projects also includes water ponding banks and diversion banks that pond shallow water (less than 10cm) to improve groundcover and biomass, which is especially suited to pastoralism. This project expands the potential of arid rangeland rehabilitation works to include not only groundcover establishment for pastoralism, but also creation of longer lasting green spots to provide habitat for small native mammals.

The longer lasting green spots have been created in degraded, incised drainage lines. The incised line is up to 1 metre lower than the natural land surface and by constructing a check bank across the incised line, a pond is formed, which becomes the green spot. The check bank with its corresponding diversion bank directs flows onto the adjacent floodplain which rehydrates the area and creates sinuous flows. The actively eroding features can be used to create positive environmental outcomes alongside pastoralism.

Green spot destruction is a major cause of arid small mammal decline (Morton 1990), and by expanding the use of arid rangeland rehabilitation works to address environmental goals, in addition to pastoral goals, it is possible to create and increase suitable habitat to support arid small mammal populations. The distance between re-created green spots should be such that arid small mammals can travel. Frank and Soderquist (2005) recorded a Stripe-Faced Dunnart (*Sminthopsis macroura*) covering 300 metres in one night and Moseby and Read (1998) recorded Bolam's Mice (*Pseudomys bolami*) moving on average 187 metres (110m-374) in a few hours, utilising burrows or shelters. It is considered by ecologist that 200 metres is within the travel range of most arid small mammals (James Val, pers. comment). These travel distances serve as a guide to the distance between re-created green spots, especially if the object is to extend the range of suitable habitat.

WLLS will be conducting fauna monitoring on these projects to determine whether small mammals find and utilise the newly created habitat.

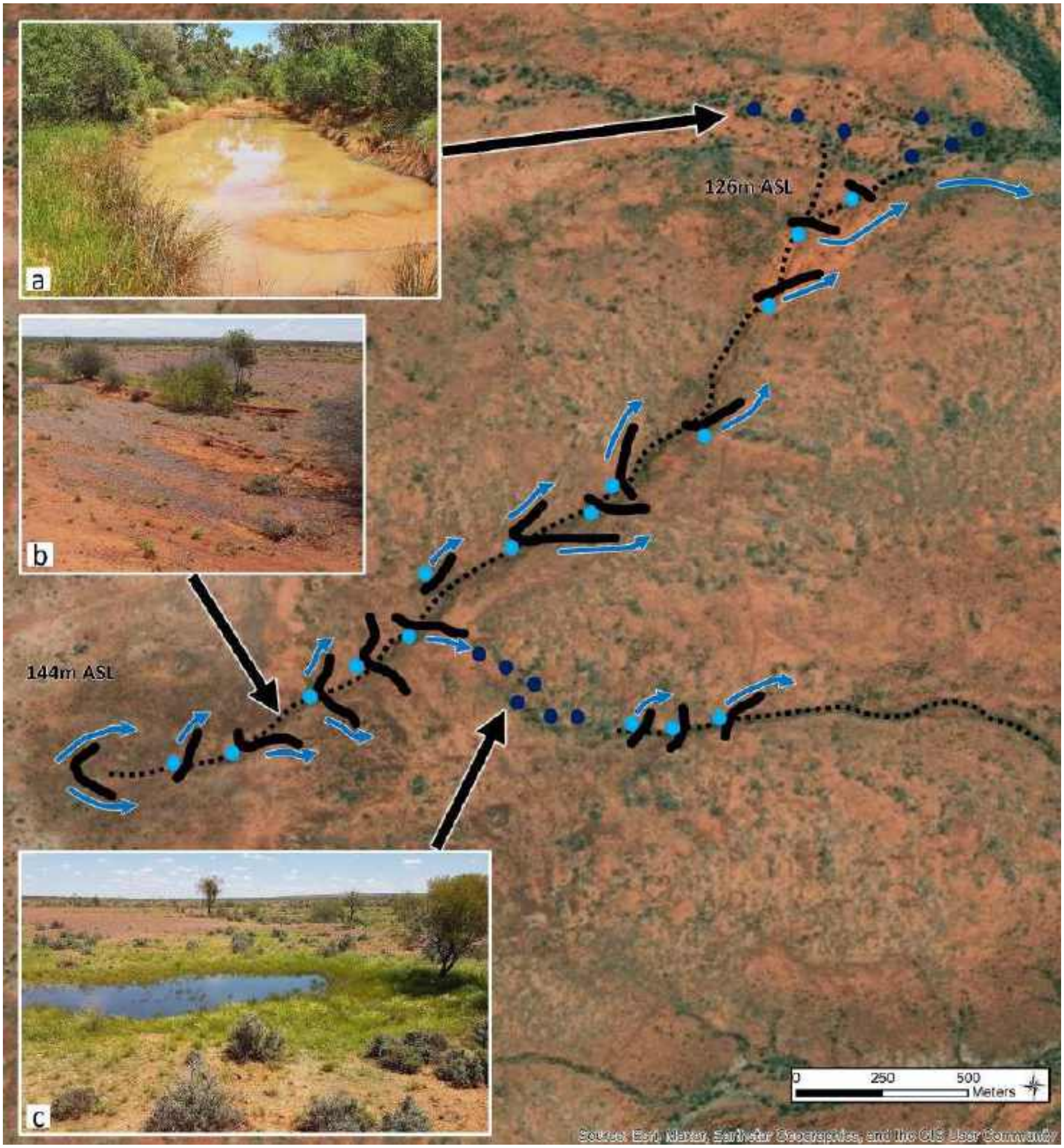

Figure 1: Simplified layout of Goodwood green spot project. Solid black lines represent check banks combined with diversion banks which pond water in the incised gully, creating localised green spots, then release flows onto surrounding floodplain. Dotted line represents incised gully. Blue arrows represent flows. Dark blue points represent existing, healthy green spots. Light blue points represent re-created green spots, creating a corridor of green spots. photo a) creek line waterholes. photo b) incised drainage line. photo c) cluster of deep gilgais.

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Assessing sediment diatoms for water quality index in the protected wetlands of Vettangudi Bird Sanctuary, India

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Keywords: Temporary Pond Ecology - Biological water quality – Phytoplanktons and Diatoms Diversity – Biotic interactions – Physical conditions of pond water

Introduction

Assessing water characteristics through key quality parameters is essential for understanding the ecological health of rangeland resources and forms a critical foundation for effective freshwater pond monitoring. Aquatic plant organisms, particularly phytoplankton—primary producers that include blue-green algae, green algae, diatoms, desmids, and euglenoids—significantly influence the chemical composition of water, a key determinant of productivity. Among these, diatoms and microflora are recognized as essential primary producers and serve as critical indicator species, providing valuable insights into the ecological health of inland freshwater pools (Lougheed et al., 2015).

Biomonitoring ponds by analyzing the assemblages of microflora and microfauna is an essential tool for assessing pond health, as these assemblages are strongly influenced by pollutant loads. Understanding the potential role of diatom algae in regulating water quality is particularly important in ponds with high levels of biological interaction. This knowledge is fundamental for developing effective management guidelines and ensuring the sustainability of freshwater wetland ecosystems.

The time-dependent hypersensitivity of diatoms to environmental changes (Stevenson, 2014) underscores the importance of thoroughly understanding the complex relationships between physico-chemical water quality parameters, thereby enabling more effective assessment of pond conditions. In the present experimental pond, avian diversity was identified as a significant biotic interaction affecting the pond ecosystem (Mahesh et al., 2018).

Although numerous studies have explored diatom diversity in relation to water quality in freshwater wetlands, there remains a significant knowledge gap concerning biotic interactions, particularly allocanthous pollution, and their impact on water quality as indicated by diatom presence in ephemeral ponds. To address this gap, the present investigation aimed to relate the physical conditions and chemical composition of pond substrata to the presence of diatoms, recognized indicators of water quality parameters.

Water samples were collected from three adjoining temporary ponds within the Vettangudi Bird Sanctuary, Sivagangai District, Tamil Nadu, India, to achieve this objective.

Study area

The Vettangudi Bird Sanctuary (latitude 10º 06.57'N, longitude 78º 30.81'E) encompasses three temporary drainage ponds: Vettangudipatty, Chinna Kollukudipatty, and Periya Kollukudipatty. For this study, the Periya Kollukudipatty (PKD) pond was selected as the experimental site. The sanctuary is in the villages of Vettangudipatty and Kollukudipatty within Thiruppathur Taluk, Sivagangai District, Tamil Nadu, India. The PKD pond hosts many migratory birds annually, primarily between November and February. Additionally, it serves multiple purposes for local communities, including domestic use, irrigation through channel systems, collection of fuelwood, minor forest products, and cattle grazing during the summer when the ponds dry up.

Methodology

Water samples were collected from three randomly selected points in the experimental pond between November 2013 and March 2014. Sampling was conducted at 06:00 hours during each collection period using clean plastic bottles. The samples were then transported to the laboratory for further analysis. Sampling and analytical procedures followed the standard methods outlined by Beutler et al. (2005). The pH of the water was measured using a pH meter (Elico, India), and water temperature was recorded immediately after sampling. Total Dissolved Solids (TDS), conductivity and dissolved oxygen (DO) were analyzed using a water analyzer kit (Systronics, Model No. 371).

Bulk water samples were filtered through a phytoplankton net with a mesh size of 45 microns and preserved using 4% formalin and Lugol's iodine solution. Diatom species were identified and photographed using a Euromex light microscope (Holland) at 1000× magnification. At least 500 valves per slide were counted and identified to the species level. Special hyrax mounts were used to prepare slides, and the morphological structures of the diatoms were observed under the microscope. Species identification was carried out based on the manuals by Anand (1988) and Karthick et al. (2013).

Results and Discussion

The physico-chemical condition of water determines the planktonic status of an aquatic ecosystem. The analyzed water quality parameters (Table 1) clearly indicate a gradual increase in alkalinity from January 2014 toward the end of the sampling period. This increase was accompanied by a deterioration in water quality, as evidenced by elevated levels of total dissolved solids (TDS), salinity, acidity, and alkalinity. Notably, higher dissolved oxygen (DO) levels were observed during January, February, and March 2014, which can be attributed to the inflow of fresh rainwater replenishing the pond. Diatom algae-produced oxygen is known to facilitate the bacterial degradation of polycyclic aromatic hydrocarbons (PAHs), phenolics, and organic solvents in benthic environments. However, as organic nutrient levels in water bodies increase, DO tends to decline (Manral and Khudsar, 2013). Additionally, the aggregation of microalgae and diatoms during this period likely contributed to reduced DO levels.

Table 1: Water quality variables, analyzed from the water samples, collected from the PKD pond surface water during the water availability period (November 2013 to March 2014). Values are mean ± SE; (n=3)

Sampling months	pH	DO (ppm)	TDS (ppm)	Salinity (ppt)	Conductivity (µS)	Acidity (mg/l)	Alkalinity (mg/l)
Nov-13	7.07 ±0.04	7.68 ±0.01	241.7±0.6	0.14±0	133±0.21	14.67±1.1	79.33±0.37

Dec-13	7.29 ±0.04	5.87 ±0.01	115.7±0.2	0.13±0	218±0.51	12±0.9	139.33±0.67
Jan-14	8.87 ±0.02	7.77 ±0.04	760± 0.6	0.81±0	1410±1.4	35.33±2.3	34.03±0.83
Feb-14	8.75 ±0.02	7.8 ±0.05	1630± 1.4	1.71±0	2970±1.6	40.67±1.2	85.33±1.4
Mar-14	8.94 ±0.01	8.73 ±0.03	1580± 1.21	2.07±0	3520±3.5	43.33±1.2	91.33±0.2

A high TDS level is indicative of eutrophication in aquatic systems, often resulting from increased nutrient inputs, such as excreta from migratory birds sheltering in the pond during the study period. This eutrophic state was further confirmed by the presence of pollution indicator microalgae species, including *Cosmarium contractum*, *Lepocinclis sphagnophila*, *Spirogyra webri*, and *Oscillatoria okeni*.

Data analysis revealed monthly variations in total diatom cell counts and species diversity at the Vettangudi Bird Sanctuary Pond (VTG pond). Of the 32 species identified across 20 genera of phytoplankton, including diatoms and microalgae, 20 species belonged to Bacillariophyceae, 8 to Chlorophyceae, 5 to Cyanophyceae, and 2 to Euglenophyceae. The pond's nutrient loading, primarily driven by the migratory bird population, classifies it as dystrophic. Pond physico-chemical properties, including elevated organic matter, CO_2 levels, and high pH, were responsible for supporting specific phytoplankton communities (Jena et al., 2013).
The dominance of Bacillariophyceae was attributed to the alkaline pH conditions. This finding aligns with studies by Shetty and Gulimane (2023). The presence of *Spirogyra sp.* further confirms the eutrophic nature of the experimental pond, consistent with observations by Adesalu and Nwankwo (2008). Additionally, the occurrence of *Lepocinclis sphagnophila* indicates high levels of organic pollution, while *Cosmarium contractum var. minutum* reflects neutral pH conditions, suggesting the existence of pure water environments within the pond.

Throughout the sampling periods, poor water quality was evident from both physical and chemical analyses, supported by the presence of pollution-indicating species such as *Spirogyra webri*. This species thrives in lentic environments, forming thick mats on the pond surface, which deplete oxygen levels and lead to anaerobic conditions. Cyanophycean species such as *Anabaena torulosa* were also observed, with their intercalary heterocysts facilitating nitrogen fixation.

The results highlight the importance of linking species occurrence and diversity indices to water quality parameters. The findings have broader implications for temporal and spatial wetland management and can inform the development of rangeland conservation guidelines for fragile freshwater ecosystems. The preference and tolerance of microalgae assemblages for specific habitats are largely dependent on the physicochemical characteristics of the aquatic environment, outcompeting other algal groups in such conditions.

The alkaline range detected during the study (Table 1) aligns with findings by Vijay Baskar et al. (2009), which suggest that alkaline conditions promote phytoplankton proliferation. The presence of *Chlamydomonas macrosphera*, *Chlorella vulgaris*, and *Phormidium tenue* indicates polluted water conditions, while *Pithophora oedogonia* (a Chlorophyceae member) forms thick algal mats on stagnant water surfaces. Additionally, *Amphora coffeaeformis* is known to accumulate herbicides like mesotrione (Valiente Moro et al., 2012). The increased conductivity levels observed during the study were likely due to nutrient enrichment from migratory avian populations (Khanthong et al., 2023), consistent with observations at the PKD pond.

Table 2: Diatoms and microalgae sps. occurrence at the Vettangudi Bird Sanctuary Pond during the experimental period

S. No	Botanical name	Family	Nov 2013	Dec. 2013	Jan. 2014	Feb. 2014	Mar. 2014
1	*Achnanthes coarctata var elliptica*	Bacillariophyceae					
2	*Anabaena torulosa*	Cyanophyceae				√	
3	*Caloneis intermidia*	Bacillariophyceae					
4	*Chlamydomonas macrosphera*	Chlorophyceae				√	
5	*Chlamydomonas pseudopolypyrenoidea*	Chlorophyceae			√		
6	*Chlorella vulgaris*	Chlorophyceae					
7	*Cosmarium contractum var minutum*	Chlorophyceae	√				
8	*Frustulia saxonica*	Bacillariophyceae				√	
9	*Lagerheimia quadriseta*	Oocystaceae					
10	*Lepocinclis sphagnophila*	Euglenophyceae			√	√	√
11	*Microspora loefgrenii*	Chlorophyceae				√	
12	*Navicula capitatoradiata*	Bacillariophyceae	√				√
13	*Navicula cuspidate var ambigua*	Bacillariophyceae					
14	*Navicula dissipata*	Bacillariophyceae				√	
15	*Navicula minuscule*	Bacillariophyceae	√				
16	*Navicula papula*	Bacillariophyceae	√			√	√
17	*Navicula subhyncocephala*	Bacillariophyceae				√	
18	*Nitzschia archibaldii*	Bacillariophyceae				√	
19	*Nitzschia cincta*	Bacillariophyceae					
20	*Nitzschia kutzinghiana*	Bacillariophyceae					
21	*Nitzschia palea*	Bacillariophyceae					
22	*Nitzschia sigma*	Bacillariophyceae	√	√	√		
23	*Nitzschia tryblionella var levidemis*	Bacillariophyceae					
24	*Oscillatoria limnotica*	Cyanophyceae	√				√
25	*Oscillatoria okeni*	Cyanophyceae		√	√	√	√
26	*Phacus parvulus*	Euglenophyceae	√				√
27	*Phormidium tenue*	Cyanophyceae			√		
28	*Pinnularia viridis*	Bacillariophyceae					
29	*Pithophora oedogonia*	Chlorophyceae	√	√	√	√	√
30	*Spirogyra webri*	Chlorophyceae	√	√	√	√	√
31	*Spirulina labyrinthiformis*	Cyanophyceae	√	√	√	√	
32	*Synedra ula*	Bacillariophyceae					

Conclusion

The study of diatom diversity and inventory reveals that the water quality of the PKD pond is deteriorating, as indicated by the analyzed physico-chemical parameters and the observed diatom assemblages. The heavy pollution and resultant eutrophication at this site are primarily attributed to biotic interactions with migratory birds utilizing the pond ecosystem. However, some moderation of the pollution load was observed due to oxygen emission by diatoms, along with the contribution of Chlorophyceae microalgae, which play a foundational role in the aquatic food chain.

This study highlights the need for further analysis of diatom diversity indices and additional physico-chemical parameters. Such investigations would provide valuable insights to develop specific management guidelines aimed at maintaining water quality, a critical feature in rangeland ecosystems. The sensitivity of algae to changes in water quality makes them valuable bioindicators of the physical and chemical characteristics of aquatic environments. These indicators could also be applied to similar water bodies to aid in the restoration and conservation of dystrophic ecosystems, preserving their ecological integrity.

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Effect of planting configurations and irrigation regimes on yield, quality, and economic returns of alfalfa-grass mixtures

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Key words: alfalfa-grass mixtures; weevil; irrigation; net present value; alternate row planting

Abstract

Alfalfa (*Medicago sativa* L.) is the most important forage crop grown globally. Alfalfa is often called "Queen of Forages" because of its high productivity, great animal performance, and superior nutritive value. However, producers/ranchers face several challenges such as high and inefficient use of water, alfalfa weevil infestation, and bloat problems in grazing livestock. A field study was conducted in 2020-2021 and 2021-2022 growing seasons to compare forage productivity, nutritive value, alfalfa weevil abundance, and economic returns of monocrop alfalfa and different seeding ratios of alfalfa-grass mixtures planted at different planting configurations under full and deficit irrigation. Treatments included monocrop alfalfa, 75-25% mixture, 50-50% mixed row planting, and 50-50% alternate row planting of alfalfa with each of three perennial cool-season grasses (orchardgrass, tall fescue, and meadow bromegrass) under full and deficit irrigation. Full irrigation plots received 100% ETc (crop evapotranspiration) for the whole season while deficit irrigation plots received 100% ETc for the first harvest and 60% ETc for subsequent harvests. The study design was split plot with irrigation as whole plot factor and cropping system (monoculture and mixtures) as subplot factor. Results show that intercropping alfalfa with grasses irrespective of planting configurations produces similar forage yield to monocrop alfalfa. Deficit irrigation reduced forage yield. Forage nutritive value was generally higher in monocrop alfalfa, however some mixtures produced similar nutritive value as monocrop alfalfa. Intercropping alfalfa with grasses reduced alfalfa weevil numbers. The 75-25% mixture of alfalfa and tall fescue under full irrigation produced the highest net present value. Deficit irrigation reduced costs but did not result in high net present value compared to full irrigation. Alternate row planting with orchardgrass under deficit irrigation produced similar net present value to full irrigation. Increasing unpredictability of the weather due to climate variability can make deficit irrigation a more viable and sustainable option.

Introduction

Alfalfa is the most important forage crop in the US and the fourth (6.7 million hectares) largest crop in terms of area harvested, behind corn (32.9 million hectares), soybean (30.4 million hectares.) and wheat

(15.1 million hectares) (USDA, 2020). Alfalfa has a deep taproot system allowing it to extract water from deeper depths than other forage species. It is therefore very tolerant to drought conditions. Nevertheless, alfalfa water use is high due to the its long growing season and dense canopy. About 13 cm of water is required to produce 1000 kg of alfalfa (Wright, 1988). The primary consumptive use of water by alfalfa is evapotranspiration, which is a function of the crop characteristics, weather conditions and water content in the rhizosphere. Highest yield of forage is obtained when water supplied to alfalfa from precipitation and irrigation meets the evapotranspiration needs of the crop. Alfalfa-grass mixtures are recommended as a management strategy to boost forage yield and increase profitability. Mixtures utilize resources more efficiently (Liu *et al*., 2018), resulting in higher yields compared to monocultures. Alfalfa-grass mixtures are known to improve nutritive value of forages (Adjesiwor *et al*., 2017). The seeding ratios and planting pattern of alfalfa-grass mixtures may be one of the strategies to increase yield in mixtures, but this has not been extensively explored. Alfalfa-grass mixtures also have the potential to reduce alfalfa weevil numbers. The primary objective of the study is to investigate forage productivity, nutritive value, alfalfa weevil abundance, and economic returns of monocrop alfalfa and alfalfa-grass mixtures under different planting patterns and different irrigation regimes.

Methods

The experiment was conducted from 2020 to 2022 at the University of Wyoming James C. Hageman Sustainable Agriculture Research and Extension Center (SAREC) near Lingle, Wyoming. Most of the precipitation at the study site occurs between March and October. Soil samples were collected in the summer of 2020 before planting. Soil was analyzed for pH (8.4), OM (1.8), $N–NO_3$ (30 mg kg^{-1}), P (22 mg kg^{-1}), and CEC (20.4 meq/100g). Treatments included monocrop alfalfa, 75-25% mixture, 50-50% mixed row planting, and 50-50% alternate row planting of alfalfa with each of three perennial cool-season grasses (orchardgrass, tall fescue, and meadow bromegrass) under full and deficit irrigations (Table 1). Full irrigation plots received 100% ETc (crop evapotranspiration) for the whole season while deficit irrigation plots received 100% ETc for the first harvest and 60% ETc for subsequent harvests.

The study design was split plot with irrigation as whole plot factor and cropping system (monoculture and mixtures) as subplot factor. Irrigation scheduling was based on alfalfa crop evapotranspiration (ET_c). Daily ET_c values were calculated using the American Society of Civil Engineers (ASCE) Standardized Reference ET Equation (Allen *et al.*, 2005) and alfalfa crop coefficient (K_{cr}) values (Allen & Pereira, 1998) (Equations 1 and 2). Four biomass harvest samples were taken for each treatment plot and oven-dried at 60°C for at least 48 hrs. Dry weight of samples was measured and recorded as weight per unit quadrat area, which was then used to estimate forage yield per hectare (kg ha^{-1}). Oven-dried samples were ground in a mill with a 1-mm mesh. Forage nutritive value parameters, including crude protein (CP), acid detergent fiber (ADF), neutral detergent fiber (NDF), and in vitro dry matter digestibility (IVDMD) were analyzed using Near-Infrared Reflectance Spectroscopy. Alfalfa weevils were collected using a sweep net, with ten sweeps taken from each plot. The economic value (dollar per hectare) of each treatment was determined through a net present value (NPV) analysis. Analysis of variance (ANOVA) was performed on forage dry matter yield and nutritive value data. A mixed effect model with alfalfa-grass mixtures with irrigation regime as fixed effects and block as random effect was used. Significance was declared at $\alpha = 0.05$, and post hoc mean separations were made using Tukey HSD test.

$$ET_c = K_{cr} \times ET_{rs} \ldots\ldots\ldots\ldots\ldots\ldots 1$$

$$ET_{rs} = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{C_n}{T+273} u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + C_d\,u_2)} \ldots\ldots\ldots\ldots\ldots\ldots 2$$

where, ETrs = reference evapotranspiration (mm d^{-1}); Rn = calculated net radiation at the crop surface (MJ m-2 d^{-1}); G = soil heat flux density at the soil surface (MJ m^{-2} d^{-1}); T = mean daily temperature at 1.5 to 2.5-m height (°C); u_2 = mean daily wind speed at 2-m height (m s^{-1}); es = saturation vapor pressure at 1.5 to 2.5-m height (kPa), calculated for daily time steps as the average of saturation vapor pressure at maximum and minimum air temperature; ea = mean actual vapor pressure at 1.5 to 2.5-m height (kPa); Δ = slope of the saturation vapor pressure-temperature curve (kPa °C-1); γ = psychrometric constant (kPa $°C^{-1}$); Cn = numerator constant (K mm s^3 Mg^{-1} d^{-1}) and Cd = denominator constant (s m^{-1}). Units for the 0.408 coefficient are m^2 mm MJ^{-1}.

Results

All mixtures produced forage yield similar to the monocrop (Table 1). Intercropping with 25% grass increased forage yield by 8% compared to monocrop alfalfa under full irrigation. Under deficit irrigation, the 50Alf+50OG-AR mixture had the highest forage yield (Table 1). Full irrigation resulted in higher forage yield (Table 1). Although alternate row plantings were not significantly different from mixed row plantings under deficit irrigation, they generally yielded more for all grass species. Monocrop alfalfa had the highest CP content, significantly higher than all mixtures except 50Alf+50TF-AR (Table 1). Monocrop alfalfa had lower NDF concentration than all mixtures except 50Alf+50TF-AR. Monocrop alfalfa recorded similar dry matter digestibility as all mixtures except 50Alf+50MB and 50Alf+50OG_AR. All mixtures recorded lower alfalfa weevil count compared to the monocrop alfalfa (Table 1). The highest count of alfalfa weevil was observed in the monocrop alfalfa while the lowest count was found in alternate row planting of mixtures. The 75Alf-25TF mixture under full irrigation yielded the highest NPV, while the lowest NPV was observed in the 50-50 alfalfa and meadow bromegrass mixture under deficit irrigation (Table 1).

Table 1. Forage yield, forage nutritive value and alfalfa weevil count of different proportions of alfalfa-grass mixtures under full and deficit irrigations at SAREC from 2021 to 2022.

†Alf, Alfalfa; OG, Orchardgrass; TF, Tall fescue; MB, Meadow bromegrass; AR, Alternate row planting; FI, Full Irrigation; DI, Deficit Irrigation; CP, Crude Protein; NDF, Neutral detergent fiber; ADF, Acid detergent fiber;

Alfalfa-grass mixtures	2-yr average forage yield		CP	NDF	IVDMD	Alfalfa weevil count		Net present value	
	FI	DI				2021	2022	FI	DI
	kg ha^{-1}		——— g kg^{-1} ———			# per sweep			
100Alf †	8845 abcd	7826 ab	266 a	360 b	792 a	10.8 a	41.4 a	$3260 abcd	$3144 abcd
75Alf+25OG	9456 ab	7009 ab	247 bc	380 ab	775 ab	8.3 bc	31.7 b	$3583 abc	$2486 bcd
75Alf+25TF	9729 a	6372 ab	251 b	401 a	775 ab	8.3 bc	33.1 ab	$3853 a	$2142 d
75Alf+25MB	9528 ab	6706 ab	248 bc	397 a	774 ab	9.7 ab	35.1 ab	$3692 ab	$2410 bcd
50Alf+50OG	8998 abc	7337 ab	244 bc	399 a	775 ab	7.8 cd	28.3 bc	$3311 abcd	$2792 abcd
50Alf+50TF	8185 bcd	6405 ab	246 bc	384 ab	779 ab	6.6 de	26.3 bcd	$2852 abcd	$2271 d
50Alf+50MB	8956 abcd	6226 b	250 b	396 a	743 c	5.5 e	27.0 bcd	$3299 abcd	$2066 d
50Alf+50OG-AR	7595 cd	7930 a	235 c	397 a	770 b	5.5 e	20.8 cd	$2448 bcd	$3153 abcd
50Alf+50TF-AR	7448 d	6902 ab	255 ab	360 b	779 ab	5.9 e	21.3 cd	$2363 cd	$2537 bcd
50Alf+50MB-AR	8708 abcd	7337 ab	245 bc	386 ab	774 ab	6.9 cde	18.0 d	$3176 abcd	$2833 abcd

IVDMD, Invitro dry matter digestibility. Within columns, means followed by the same letter are not different at α= 0.05.

Discussion

The superior yield of orchardgrass mixtures compared to other mixtures under deficit irrigation may stem from its compatibility with alfalfa. Casler (1988) noted that alfalfa-orchardgrass combinations exhibit greater vigor, ground cover, and regrowth compared to mixtures with smooth brome or ryegrass. This compatibility enhances resource use efficiency, contributing to the superior performance of the orchardgrass mixture under deficit irrigation. Full irrigation resulted in higher forage yield compared to deficit irrigation due to better leaf growth and photosynthesis (Zargar *et al.*, 2017). Under water stress, stomatal closure and reduced leaf expansion limit photosynthesis (Zargar et al., 2017), lowering forage accumulation. Although alternate row plantings were not significantly different from mixed row plantings under deficit irrigation, they generally yielded more for all grass species, likely due to reduced interspecies competition for resources like water (Lafrenière & Drapeau, 2011). The similarity in CP levels between monocrop alfalfa and 50Alf+50TF-AR is likely due to the decreased grass proportion in the 50Alf+50TF-AR mixture. Forage grasses such as meadow bromegrass, tall fescue and orchardgrass typically have higher NDF concentrations than alfalfa (Adjesiwor *et al.*, 2017; Aponte *et al.*, 2019). As a result, mixing these grasses with alfalfa increased the NDF content in the mixtures. The lower weevil counts in mixtures may result from grasses interfering with the insects' visual cues (Meyer and Raffensperger, 1974) or due to emigration of the insect from the mixed stands (Roda *et al.*, 1997). This emigration might also be driven by volatile compounds produced by the grasses (Smith *et al*., 1992). The high NPV in the 75-25 alfalfa-tall fescue mixture was mainly driven by significant total revenue, which compensated for the higher costs.

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Controlling the invaders

Birds, lagomorphs, rodents, and patterns of *Juniperus osteosperma* recruitment

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Key words: diplochory; juniper seed dispersal; woodland expansion; woodland infilling

Abstract

Juniper woodland infilling and expansion, considered threats by rangeland managers, is driven by seed dispersal. We studied the roles of birds, lagomorphs, and rodents in *Juniperus osteosperma* recruitment in the Great Basin of western Utah, USA. Recruits were disproportionately in shrub microhabitats. Birds disperse no seeds, lagomorphs almost exclusively disperse seeds to open interspaces, and only rodents disproportionately cache in shrub microhabitats. Results suggest the primary driver of recruitment is seed-caching rodents.

Introduction

Conifer expansion into sagebrush shrublands in the western USA is of concern to rangeland managers, contributing to a reduction in shrub and grass cover, increased erosion, decreased soil water, and more (Chambers et al. 2014, McIver et al. 2014). In the Eastern Great Basin this process is driven primarily by *Juniperus ostesperma*, a monoecious conifer producing modified "fleshy" cones containing a single seed; cones dry within weeks, slowly dropping to the ground over an extended period (Schupp et al. 1995, Zlatnik 1999).

Key to juniper expansion is seed dispersal, especially where seeds are deposited, which determines the biotic (e.g. seed predators, mycorrhiza) and abiotic (e.g. microclimate, soil water) environments recruits encounter and thus recruitment probability (Schupp and Fuentes 1995, Schupp et al. 2010). *J. osteosperma* seed dispersal is not well understood, but lagomorphs (Schupp et al. 1995) and rodents (Dimitri et al. 2017) reportedly disperse their seeds. Further, Juniperus spp. are extensively dispersed by birds (Chambers et al. 1999). As a first step in assessing the role of seed dispersal in *J. osteosperma* recruitment, we quantified (1) the microhabitat pattern of recruitment and (2) the microhabitat pattern of seed deposition by birds, lagomorphs, and rodents. We compare patterns of recruitment and dispersal to determine the disperser group(s) most likely driving *J. osteosperma* recruitment.

Methods
We conducted this study in a 2-ha (100 x 200 m) juniper woodland plot in west-central Utah, USA, (39º 53’ 19” N, 112º 08’ 58” W, 1774 masl), a region with hot, dry summers and cold, wet winters. We distinguish four microhabitats: 1) “Juniper,” beneath the canopy of a live *J. osteosperma*; 2) “Dead Juniper,” beneath the canopy of a dead *J. osteosperma*; 3) “Shrub,” beneath the canopy of a shrub; and 4) “Open,” interspace without woody cover. We quantified proportional microhabitat cover with the Line Intercept Method (Fiala et al. 2006) along 40, 100 m transects across the plot. We located, marked, and measured all *J. osteosperma* recruits (≤1 m height) and recorded their microhabitat. We noted “seedling caches,” where two or more recruits grew adjacent, assuming adjacent recruits likely came from a cache. We investigated seed dispersal by birds with timed watches of tree clusters during winter when cones are fresher and frugivorous bird density and diversity are highest. We assessed dispersal by lagomorphs by collecting pellets by microhabitat type along a 2-m wide 440 m long transect connecting 15 random points across the plot. Pellets were dissected to quantify seeds/microhabitat. Dispersal by rodents was sampled by coating cleaned, filled seeds with fluorescent powder and placing a set of 30 seeds in a petri dish in the middle of a powder-filled plate. Seeds were set at sunset. Before sunrise we returned and searched using an ultraviolet light, following powder trails and marking disturbed sites. We returned later to search flagged locations for caches. Analyses were based on comparing actual microhabitat distributions with expected distributions based on proportional cover of microhabitats using simple Chi-square tests conducted by hand.

Results
Recruits were not randomly distributed (n=263, Table 1). The dominant microhabitat was Open, while Shrub was substantially lower. However, recruits were much more frequent than expected beneath Shrubs and much less frequent than expected in Open.

Table 1. The proportion of each variable represented by each of the four identified microhabitat types. Significance refers to the significance of a Chi-square comparing the actual microhabitat distribution of variables (e.g. recruits) with the expected distribution based on proportional cover of the microhabitats; that is, the expected distribution if the variable (e.g. recruits) is distributed independently of microhabitat type.

	Proportion				
Variable	Juniper	Dead Juniper	Shrub	Open	Significance
Microhabitat Cover	0.16	0.02	0.25	0.58	N/A
Recruits	0.16	0.00	0.67	0.18	P<0.05
Seedling Caches	0.19	0.00	0.75	0.06	P<0.05
Bird-dispersed Seeds	--	--	--	--	--
Lagomorph-dispersed Seeds	0.04	0.00	0.00	0.96	P<0.05

Rodent-dispersed Caches	0.07	0.00	0.80	0.13	P<0.05

In over 100 person-tree-hours of observations the only bird species feeding on *J. osteosperma* cones was the Juniper Titmouse (*Baeolophus ridgwayi*), a seed predator (Fuentes and Schupp 1998).

In contrast, lagomorphs dispersed seeds (Table 1). We collected 692 pellets; 9% contained 1-4 intact seeds each for a total of 76 seeds. Many more of these seeds were dispersed to Open and fewer to Shrub than expected.

We addressed the role of rodents in *J. osteosperma* recruitment using the microhabitat distribution of "seedling caches" and of seed caches. We estimated 16% of recruits were in "seedling caches," which were disproportionately beneath Shrub (Table 1). We located 30 seed caches; congruent with the distribution of "seedling caches," many more were located beneath Shrub than expected, while very few were in Open (Table 1).

Discussion

Frugivorous birds are considered the most important dispersers of juniper, dispersing many seeds and depositing them beneath woody vegetation which is thought to facilitate establishment (e.g. Dimitri and Longland 2017, Isla et al 2024). Our evidence suggests that rodents fulfill this role in *J. osteosperma* – only dispersal and caching by rodents explains the microhabitat pattern of recruitment.

Both "seedling caches" and seed caches support the role of rodents. In both cases, caches were disproportionately frequent in Shrub and disproportionately infrequent in Open. The seed caches we located represent the first of potentially many sequential caching events. Rodents pilfer juniper seed caches, and although they consume some and larder hoard others, many are recached (Dimitri and Longland 2022). If caches in our system are pilfered, rodents apparently disproportionately recache beneath shrubs, reducing the number of seeds available for germination without altering the microhabitat distributions.

As noted, many believe that microhabitats beneath woody vegetation are favorable for juniper recruitment. Experimental seed sowings in our plot showed inconsistent, slight germination and survival benefits in Shrub relative to Open, with a small significant benefit in some cohorts during some sampling periods but not in others (Schupp et al., unpublished data). This benefit is insufficient to drive the pattern of recruitment. Facilitation appears to enhance rather than cause the distribution of recruits.

Although our work occurred within a woodland and does not directly address expansion into shrublands we can make informed speculation. First, although some rodents are restricted to woodlands, others use both woodlands and shrublands (Dimitri and Longland 2017) and likely contribute to local expansion at the ecotone through short-distance dispersal. Further, more rapid expansion might be due to diplochory, or two-stage dispersal, as has been suggested for bird-rodent diplochory of *J. occidentalis* (Longland and Dimitri 2016), with lagomorphs initially dispersing seeds out of the woodland and rodents subsequently harvesting seeds from faeces and caching some beneath shrubs. Although the density of seeds in lagomorph faeces drops off rapidly with distance from woodland edge, lagomorphs can disperse some seeds long distances into shrublands (Schupp et al. 1997). This could produce scattered reproductives far in front of the woodland that can create expanding nuclei of woodlands through local dispersal, a process known to accelerate tree movement (Clark et al. 1998).

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Use of axillary buds and other demographic parameters to evaluate control strategies for perennial invasive grasses.

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Key words: Smooth bromegrass; Kentucky bluegrass; defoliation, drought, burning.

Abstract

Cool-season perennial invasive grasses are a primary management concern on northern Great Plains rangelands in the USA. Management strategies to reduce these grasses often do not consider underlying mechanisms that can explain responses. One potential way around this constraint is evaluating axillary buds, which are meristematic tissue that provide the basis for future productivity. Our research projects evaluated responses of axillary buds of two perennial invasive grasses to different management strategies. In the first experiment, axillary bud numbers per m^{-2} were collected in the spring and fall of 2020 and 2021 from plots with ambient rainfall plus 2 different simulated drought intensities (30 and 60% of the ambient rainfall intercepted). Half of the plot under each rainfall intensity was burned, and the other half was left unburned. Both burning and moderate drought reduced the number of Kentucky bluegrass (*Poa pratensis* L.) axillary buds m^{-2} to 60% of the controls; however, the impact of burning changed with season and drought intensity. Regardless of burning or drought treatment, there were still over 400 active axillary buds m^{-2} suggesting a large pool of potential meristematic tissue was available for future growth. In the second experiment, smooth brome (*Bromus inermis* L.) tillers were clipped at vegetative, tiller elongation, and reproductive stages, and the number of axillary buds, tillers, and rhizomes (total outgrowth) was estimated in the fall over a 3-year period. Both total outgrowth and proportion of axillary buds that became outgrowth were greater when smooth brome was defoliated in the reproductive phase than when it was defoliated twice in the vegetative phase, suggesting the timing of defoliation may aid in smooth brome control. Both experiments suggest that evaluating the response of axillary buds and other demographic parameters provides mechanistic insights into the potential effectiveness of different management strategies for controlling invasive perennial grasses.

Introduction

Invasion by C_3, non-native, perennial grasses has been identified as one of the major challenges facing rangelands in the northern Great Plains of the US (Hendrickson et al., 2019). In particular, two grasses, smooth bromegrass (*Bromus intermis* Leyss.) and Kentucky bluegrass (*Poa pratensis* L.) have rapidly increased (Hendrickson et al., 2021) with negative impacts on species diversity and resilience (Hendrickson et al., 2021; Toledo et al., 2014). Burning and defoliation (Hendrickson and Lund, 2010) have both been evaluated as potential control methods for these two species.

Below-ground bud banks, made up of axillary buds located at the base of perennial grasses, are a major source of population resilience in the Great Plains (Ott et al., 2019). Because of the importance of these bud banks to vegetative renewal, evaluating how axillary buds and tiller respond to different control treatments can provide insight into their effectiveness. We used vegetative outgrowth and axillary bud numbers to evaluate the responses of smooth bromegrass to defoliation and Kentucky bluegrass to burning and drought.

Methods

Both studies reported in this paper took place at the Northern Great Plains Research Laboratory (46.767085^0 N; -100'908629^o W) on loamy ecological sites (Sedivec et al., 2021). Fifty smooth bromegrass tillers were randomly assigned to 5 different defoliation treatments in three different ungrazed exclosures in 2018, 2019 and 2020 (n=30 tillers treatment^{-1}). Tillers were defoliated 1) once in the vegetative stage; 2) twice in the vegetative stage; 3) in the elongation stage; 4) in the reproductive stage; or 5) left undefoliated. Tillers were collected at the end of the field season and brought back to the laboratory where total tillers and rhizomes were counted (Total Outgrowth).

Drought and defoliation treatments were initiated on nearby sites in 2017 and continued through 2021. Each site had nine 2x2 m plots that were 1) exposed to ambient precipitation; 2) had 30% of ambient precipitation intercepted using plexiglass gutters or 3) had 60% of ambient precipitation intercepted. In addition, half of each plot was burned in the fall of 2017, 2019 and 2020. In May and November of 2020 and 2021, a cm^{-2} sample was collected using a soil probe and brought to the laboratory where is was cleaned and stained using a 0.1% 2,3,5-tripehnyl tetrazolium chloride (TTC) solution (Hendrickson & Briske, 1997). Stained buds were considered active and counted.

Results

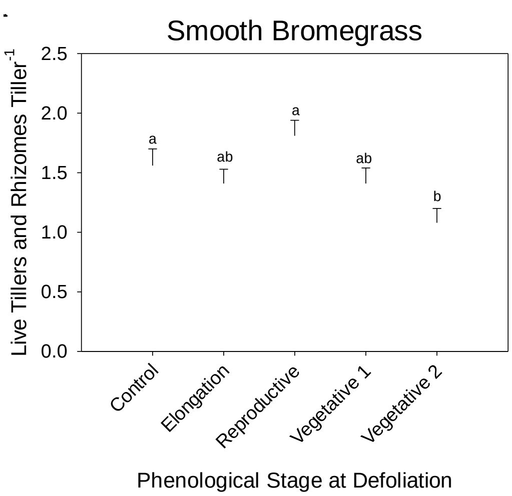

Figure 1. Number of live tillers and rhizomes for smooth bromegrass tillers defoliated at different phenological stages. Different letters over the bars indicate significant differences at P≤ 0.10.

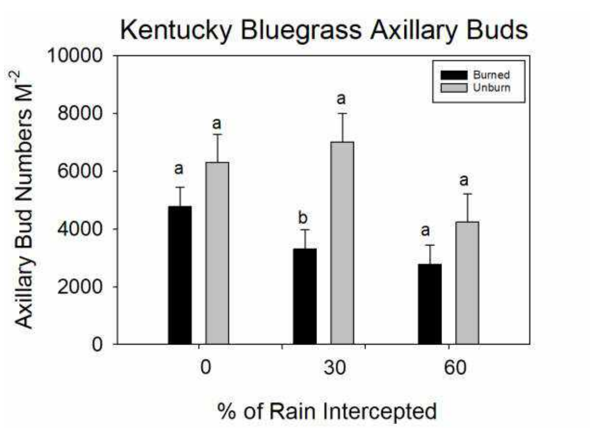

Figure 2. Number of Kentucky bluegrass active axillary buds per m^{-2}. Different letters over the bars indicate significant differences between burned and unburned plots at P≤ 0.10.

Smooth Bromegrass Defoliation

Defoliating smooth bromegrass twice in the vegetative stage reduced outgrowth (live tillers and rhizomes) compared to undefoliated controls and defoliating in the reproductive stage (Figure 1). However, outgrowth on a $tiller^{-1}$ basis still exceeded 1 indicating that outgrowth still exceeded the number required for population persistence.

Kentucky Bluegrass Response to Drought and Burning

Kentucky bluegrass had a burn by drought interaction. Axillary buds were significantly reduced by burning when 30% of the ambient rainfall was intercepted (Figure 2). Axillary bud number m^{-2} on the unburned treatments was lower when 60% of the ambient rainfall was intercepted compared to 30% ($P = 0.0575$).

Discussion [Conclusions/Implications]

Outgrowth, such as tiller and rhizome numbers, and axillary bud numbers should not be used to predict future meristematic outgrowth for these two invasive perennial grasses. For both examples, the invasive grass has adequate amounts of outgrowth or axillary buds to maintain their populations into the future. Environmental variables also impact demographic processes as demonstrated by the reduction in axillary bud numbers on the unburned portions of the rain intercept plots when 60% of ambient precipitation was intercepted compared to 30%. However, the data suggest that demographic attributes can be used to identify potential treatments or to explain why certain control measures are more successful. For example, smooth bromegrass outgrowth suggests that grazing when the grass is reproductive may increase its tiller numbers. Similarly, burning appears to reduce the number of axillary buds in Kentucky bluegrass suggesting a potential mechanism for the success of burning as a control for Kentucky bluegrass (Ereth et al., 2017; Hendrickson and Lund, 2010).

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It's not the plants you can see but those you can't see: managing Australia's rangelands means managing pest rabbits

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Key words: Oryctolagus cuniculus; regeneration; suppression; palatability; monitoring

Abstract

European rabbits are thought to have colonised most of Australia's vast rangelands by about 1910, leaving destitute pastoralists, decreased livestock production and a degraded environment in their wake, resulting in an-going need to manage and rehabilitate these critical environments. At a broadscale, rabbit control has been implemented, with varying degrees of success, using a variety of biocontrol agents most notably myxomatosis in the 1950's and more recently rabbit haemorrhagic disease virus. Native perennial vegetation still shows these recruitment pulses due to a modern awareness that seedling survival tolerances of palatable species can be as little as one rabbit/km^2. Such low rabbit density was achieved with initial impacts of the viral biocontrols, and where land managers have undertaken landscape scale warren destruction. Utilising GPS mapping of rabbit warrens we mapped the native vegetation recruitment following destruction of approximately 28,000 warrens by a bulldozer with long ripping tines at Thackaringa Station in western NSW. Using the remotely sensed Normalised Difference Moisture Index on the 22,545 ripped and GPS-mapped warrens at Thackaringa has detected a differential recovery trend in areas where rabbits have been eradicated. Based on this initial analysis, it suggests that the potential benefits for landscape-scale restoration of native vegetation, ecological recovery, pastoralism and potential carbon storage may be appreciable. However, satellite sensors are optimised for vegetation that is not the dominant signal for the Australian geographies, necessitating the exploration of tailored analysis methods to address the unique complexities of Australia's diverse ecosystems.

Introduction

Australia's rangelands, spanning six million square kilometres and comprising 81% of the continent. Notwithstanding those in the tropical north, the remainder is inhabited and severely impacted by the pest European rabbits (*Oryctolagus cuniculus*), which became established in Australia in the mid-19th century and had colonised these rangelands by 1980 (Stodart and Parer 1988). By the late 19th century, the rangelands faced devastating rabbit plagues. By the early 20th century, the extent of rangeland degradation was seen in state legislation such as South Australia's Sand Drift Act of 1923 (Ratcliffe 1938). The battle to manage the overgrazing of the pest rabbits had its first significant success in the 1950's due to the introduction of the myxoma virus as a biocontrol agent (Fenner and Fantini 1999). The most recent significant reduction in rabbits coming with the 1995 establishment of rabbit haemorrhagic disease virus (RHDV1/GI.1) (Mutze *et al.* 1998) and then the 2014 emergence and rapid establishment of RHDV2/GI.2 (Hall *et al.* 2015) with associated rabbit reductions (Mutze *et al.* 2018).

Primary environmental benefits have been the associated recovery of some native rangeland vegetation (Burrell *et al.* 2017) and threatened fauna species (Pedler *et al.* 2016). However, though the iconic rabbit plagues have ended, rabbit impacts on rangeland vegetation remain. Recent research documents the extreme sensitivity of many species of palatable native vegetation to rabbit grazing at densities as little as one per square kilometre, where 40% of mulga (*Acacia aneura*) seedlings were eaten (Henzell 2002). At the very minimal ≥ 0.005 rabbits km^2 palatable rangeland species such as *Acacia carneorum*, *Eremophila alternifolia*, *Allocasuarina luehmannii* and *A. verticillata* cannot successfully reproduce and establish new plants (Mutze *et al.* 2016). In the management of the rangelands, the impacts of rabbit grazing have been shown to generally be much more significant in impact on native vegetation recruitment and hence availability than pastoral factors such as water points and stock grazing (Mutze 2016).

To achieve effective landscape-scale rabbit control and the associated recovery of native rangeland vegetation, biodiversity, and pastoral benefits, landholders have undertaken major rabbit warren mapping and destruction works. The objective of this study was to examine the impact of the large-scale destruction of rabbit warrens on the presumptive increase in native vegetation based on remotely-sensed estimates of Normalised Difference vegetation Index (NDVI) before and after ripping.

Methods

This study was undertaken on Thackaringa Station which is located in arid rangelands of western NSW. Of approximately 28,000 rabbit warrens that were ripped, a total of 22,545 were mapped using a Garmin handheld GPS. Once mapped, rabbit warrens were destroyed using a Cat D8/9 bulldozer with c. 120 cm ripping tines spaced 75 cm apart. The primary objective of these activities was to achieve a significant reduction in rabbit numbers and promote the recovery of native vegetation. The ripping of these warrens largely occurred yearly between 2000 to 2004 (Fig. 1).

Google Earth Engine was used to facilitate the extraction of NDVI, enabling precise temporal and spatial analysis of changes in vegetation and soil moisture. The satellite sources used included the Landsat series 5, 7, and 8 and Sentinel-2, which provided multispectral signals. Cloud anomaly removal was conducted using a combination of cloud masking algorithms, including the Sentinel-2 Quality Assessment Band and Landsat Collection 1 Level-1 QA tools. Additionally, shadow detection was applied to minimise anomalies, and a median compositing approach was used to mitigate the influence of sporadic cloud cover. Further data cleaning included radiometric correction to standardise reflectance values across different time points, enhancing the reliability of the derived vegetation indices. Control data were derived from non-ripped comparable areas, which were identified based on similar soil types, vegetation profiles, and climatic conditions as the ripped areas. These control regions were selected to ensure a valid comparison, accounting for any external variables and providing a baseline to determine the direct impacts of rabbit management interventions.

To evaluate changes in vegetation and moisture, data derived from the satellite sources described in the previous paragraph was used. The Normalised Difference Vegetation Index (NDVI), Soil Adjusted Vegetation Index (SAVI), and Normalised Difference Moisture Index (NDMI) were extracted for each warren site and the comparative control areas. These indices were analysed over a temporal span from before warren destruction through to most recently available satellite imagery. Monthly composite values for NDVI, SAVI, and NDMI were calculated by taking the median value of all valid observations within each calendar month for each polygon. This approach minimises the impact of remaining atmospheric contamination or bidirectional reflectance distribution function effects. The resulting monthly time series data for each index (NDVI, SAVI, NDMI) were analysed to identify patterns and trends. The presence and period of seasonality were assessed by examining the autocorrelation function for each index's time series. To distinguish long-term trends from seasonal variations, a seasonal decomposition using LOESS (Locally Estimated Scatterplot Smoothing) was applied to each time series. Further analysis specifically compared trends before and after 2004, as this year marked the completion of the main phase of systematic warren destruction across the study sites.

Results

Remote sensing analysis across the 22,545 mapped and ripped rabbit warrens at Thackaringa station revealed significant, sustained changes in vegetation cover and near-surface moisture dynamics over the 1988-2022 period. Vegetation indices showed clear recovery trends following the period of intensive warren destruction. The Soil-Adjusted Vegetation Index (SAVI) trend, which corrects the Normalised Difference Vegetation Index (NDVI) for soil brightness influences, closely tracked the NDVI trend throughout the period, confirming that the observed greening was not primarily a soil-reflectance artefact. Both indices exhibited peaks around 2000 and again in the mid-2010s (reaching approximately 0.30 for SAVI and 0.20 for NDVI), punctuated by a major dip around 2010-2011 corresponding to drought conditions (SAVI < 0.15, NDVI < 0.10).

In stark contrast, the Normalised Difference Moisture Index (NDMI), representing surface moisture, displayed a markedly different trajectory, particularly after 2004 and the major wet event of 2010-2011. While NDMI values fluctuated around a moderately positive baseline (e.g., averaging near +0.08 to +0.10) in the earlier part of the record, the trend shifted dramatically downwards following the 2010-2011 peak (around 0.15), declining to negative values (averaging near or below -0.02) after 2012 and remaining persistently low despite subsequent periods of vegetation recovery. This pronounced decoupling between the recovering vegetation greenness indices (NDVI, SAVI) and the declining moisture index (NDMI) emerged most strongly post-2010/11, coinciding with a very wet year in the period after intensive warren destruction efforts. This divergence was reportedly absent from matched, unripped control polygons. Seasonal decomposition using LOESS and autocorrelation analysis confirmed strong annual cycles in all indices, but the sustained post-2010 NDMI decline represents a significant trend shift beyond typical seasonal or inter-annual variability. These patterns suggest that increased water uptake by recovering perennial vegetation drew down upper soil profile moisture more rapidly than replenishment occurred, establishing a new, lower NDMI baseline in the treated areas.

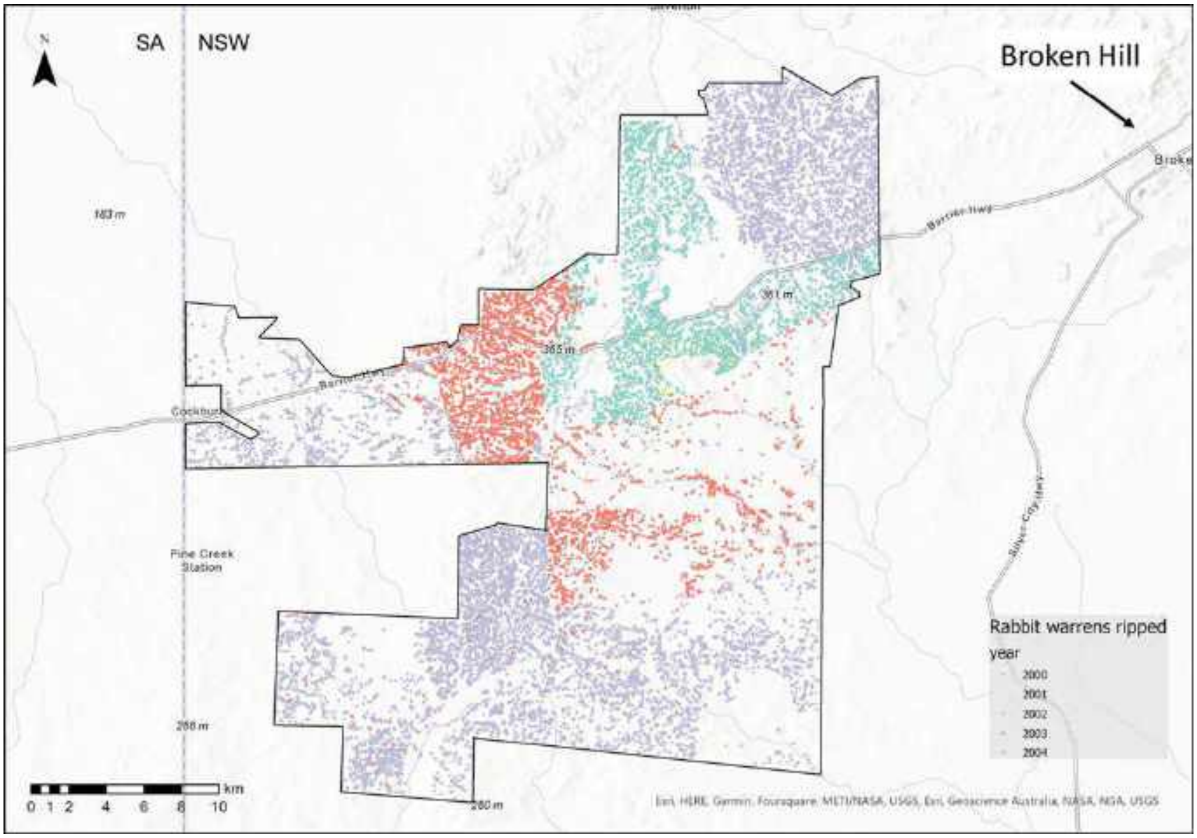

Figure 1: 22,545 mapped rabbit warrens, subsequently destroyed, on Thackaringa station (NSW).

Discussion

These findings demonstrate that landscape-scale rabbit warren destruction at Thackaringa station induced significant shifts not only in vegetation cover but also in local water balance dynamics. By facilitating the recovery of groundcover, primarily perennial vegetation, the intervention led to increased NDVI and SAVI values, indicative of greater photosynthetic biomass. Concurrently, the marked and sustained decrease in NDMI suggests increased evapotranspiration rates associated with this recovering vegetation kept near-surface soil layers significantly drier compared to the pre-treatment or early treatment period. This outcome aligns with observations from semi-arid exclusion studies, where the establishment of shrubs and perennial grasses modifies soil moisture regimes compared to denuded or annual-dominated systems.

The observed decoupling between the vegetation indices and NDMI post-intervention is critical. Because SAVI is specifically designed to minimise soil background influences on the greenness signal, its continued recovery alongside a declining NDMI strongly supports the interpretation that increased plant water uptake, rather than a spectral measurement artefact or simple lack of rainfall, drove the reduction in surface moisture detected by NDMI. This fundamentally alters the site from a quasi-fallow state around former warrens to one characterised by active hydrological cycling through established perennial vegetation.

Future research should aim to quantify these component changes more explicitly. Utilising products like Digital Earth Australia's Fractional Cover, which partitions satellite pixels into green vegetation, non-photosynthetic vegetation (dry/dormant), and bare soil components, could provide a more detailed understanding of how vegetation structure changes relate to water use. Furthermore, the advanced hyperspectral sensors aboard the Kanyini mission offer potential to refine these analyses by resolving specific spectral features related to plant pigments, water content, and dry matter, potentially improving discrimination even in complex semi-arid vegetation communities. Integrating these advanced remote sensing capabilities with ongoing adaptive management strategies, including follow-up warren control, can provide land managers with near-real-time feedback on both vegetation recovery status and associated water dynamics, strengthening the ecological and economic rationale for sustained rabbit management in Australia's rangelands.

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Restoring the Banni grasslands: a model for combating invasive species, supporting natural ecosystem and empowering pastoral communities

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Keywords: Restoration; India; Invasion; Prosopis juliflora

Abstract

The Banni grassland is Asia's largest grassland ecosystem, harbors unique flora and fauna, and supports over 8000 pastoral households. The pastoralists herd an indigenous buffalo breed "Banni" and have been practicing a semi-nomadic style of pastoralism for more than 500 years. This unique protected grassland is dotted with seasonal wetlands, saline-mix highly nutritive grass species, and some good patches of *Acacia nilotica* trees in some villages. In recent decades, encroachment particularly by the invasive species *Prosopis juliflora*, threatens this biodiversity hotspot by invading 50% of land. Woody shrub encroachments, converting the grasslands into woodland, is a trend witnessed globally, and harms unique biodiversity and traditional livelihoods of indigenous communities. Community Forest Management Committees (CFMCs) under the Forest Right Act 2006 have taken a multi-pronged approach to restore Banni grasslands. Through brush management techniques, they have restored over 3000 hectares across 18 villages in the last four years. The post monsoon grassland surveys were conducted by Sahjeevan's team using the random quadrat sampling method and data was analyzed to assess changes in the vegetation cover affected by invasive species. These efforts have shown remarkable recovery in vegetation cover of herbs and grasses up to 91%, species diversity up to 12 times, and biomass production up to 3.4 times in restored plots compared to invaded areas. Additionally, removal of this exotic invasive species in Nani Dadhdhar village has not only supported growth of the native tree *A.nilotica* but also amplified the population of itfourfold in the past four years. In Dedhiya village, biochar, made in Kon-Tiki kilns from *P.juliflora*and incorporated in the soil increased yield of grasses and herbs by 1.87 times compared withuntreated plots. Biochar not only helps boost soil health but also acts as a long-term (perhaps 2000-years) carbon sink and generates carbon credits. This restoration model exemplifies the power of community-driven conservation. It tackles invasive species, mitigates climate change and empowers pastoral communities, offering a blueprint for similar ecosystems worldwide.

Introduction

The Banni Grassland in Gujarat, India, is Asia's largest grassland, known for its unique semi-arid ecosystem with seasonal marshes and diverse flora and fauna. It is home to tree species like *Acacia nilotica*(L.) Willd. ex Delileand *Salvadora persica*L.; and provides habitat for fauna adapted to its conditions, including the spiny-tailed lizard (*Saara hardwickii*) and desert fox (*Vulpes vulpes pusilla*)(Bharwada and Mahajan 2012; Nerlekar et al. 2022). This grassland supports 22 local communities spread in 48 villages. The pastoralists of this area are called 'Maldharis', whose livelihoods depend on animal husbandry. They have selectively bred the Banni buffalo and Kankrej cow, which are highly valued across India (Nerlekar et al. 2022; Ravi and Krishnan 2024). For the Maldharis, the grassland's diversity is vital to their pastoral practices and sustains their primary income source (Ghosh et al. 2015).However, over 50% of the grassland has been invaded by *Prosopis juliflora*(Sw.) DC., a non-native tree introduced about 140 years ago to combat desertification. *P. juliflora* now spreads at an estimated rate of 25 km² per year, disrupting native ecosystems (Ravi and Krishnan 2024;Tewari et al. 2000). Species such as *P. juliflora* have contributed to the uniformity of plant communities globally, causing alterations in native ecosystems and displacing local flora and fauna (Mungi et al. 2019; Simberloff et al. 2013).

Community-led Restoration Efforts

To address the *P. juliflora* invasion, Community Forest Resource Management Committees (CFRMCs) formed under Forest Rights Act, 2006 have undertaken large-scale restoration efforts. These committees, empowered to conserve and manage forest resources, are working with Sahjeevan, an NGO focused on pastoralism and biodiversity conservation to clear *P. juliflora* from invaded areas since four years. Using brush management techniques, CFRMCs have restored over 3,000 hectares across 18 villages. Sahjeevan's team conducts post-monsoon surveys to monitor changes in vegetation cover and assess the success of restoration efforts.

The Role of Carbon Markets in Restoration

Carbon markets have been instrumental in funding restoration efforts in the Banni grassland. These markets allow the trading of carbon credits, with each credit representing one tonne of reduced, sequestered, or avoided carbon dioxide or greenhouse gases (Climate Promise 2022). In Banni, the biomass from uprooted *P.juliflora* was converted into biochar, generating carbon credits that were sold on international platforms. Biochar is produced through the pyrolysis of organic material in low-oxygen conditions, transforming plant waste into a stable form of carbon. When integrated into soil, biochar enhances soil fertility and provides long-term carbon storage with a mean residence time of about 2,000 years (Glaser et al. 2009; Kuzyakovet al. 2009). Biochar was also applied to grasslands in Dedhiya village to examine its impact on the natural regeneration of native grasses and herbs, aiming to promote healthier vegetation recovery and soil quality in restored areas.The total area restored under this pilot was 1100 hectares, which translated into 1530 credits produced from 695 tonnes of biochar. Here, one tonne of biochar has generated 2.2 carbon credits, consequently, 1530 tonnes of CO_2 were sequestered from the 1530 carbon credits. This biochar is currently stored underground within a grassland area. Further research is underway to investigate the large-scale application of biochar to the soil of the Banni grassland. The revenue generated from selling these carbon credits was utilized to fund large-scale restoration efforts

Methods

Sampling Design and Data Collection to check effect of restoration

In this study, a random quadrat sampling method was employed to assess species diversity, vegetation cover, and biomass productivity using a1 x 1 m frame for precise data collection. Five quadrats of these dimensions were randomly placed in eithercontrol plots (with *P.juliflora* present) and restored plots across 18 villages and data was recorded. For biomass analysis, herbs and grasses within each quadrat were clipped, and samples were collected for productivity assessment.

Assessment of Acacia nilotica Population

Despite Banni's grassland ecosystem, Nani Dadhdhar village hosts a thriving patch of the native tree *A. nilotica*. Restoration efforts four years ago aimed to support this tree population. Recently tree population was surveyed, where trees were categorized into three height classes: up to 1 meter, 1-5 meters, and over 5 meters and counted, allowing us to estimate the population structure and growth distribution of *A. nilotica* across height classes (This native tree counting drive was conducted with the assistance of local youth from the village. Fifteen young participants were involved, each assigned a specific paint color (three different colors) corresponding to particular tree height groups. They counted and marked each tree to ensure no duplication occurred during the survey).

Effect Assessment of Biochar Inoculation on Grassland Productivity

In the restored plot of Dehiya village, a biochar inoculation experiment was conducted to evaluate its effect on grassland productivity. Biochar mixed with soil was applied in 2 x 2 m fenced cages to prevent grazing interference. Two types of cages were set up: one with biochar-treated soil with dosage of 4 kg/ 2 x 2 m and another as a control (untreated soil). Each cage type was replicated six times. After 45 days, plants grown within the cages were harvested and analyzed to assess biomass productivity.

Results

Table 1 presents the ecological parameters assessed across 18 villages, comparing restored plots to control plots. The restoration efforts demonstrated significant improvements in vegetation cover, with *Gorewali* village achieving an impressive 91% cover, followed closely by *Mithadi*village at 88.4%. Species diversity also benefited from restoration, with *Dedhiya* village exhibiting a remarkable increase of up to 12 times in species diversity. The removal ofinvasive specieshas reduced competition for resources among native flora, resulting in biomass production of native grasses and herbs increases of up to 3.4 times in restored plots compared to the invaded areas of *Adhiyang* and *Bhagadiya*.

The eradication of *P.juliflora* in Nani Dadhdhar village has facilitated the growth of *A. nilotica*, leading to a fourfold increase in its population over four years. The survey recorded 2,029, 1,665, and 711 individuals in height categories of up to 1 meter, 1-5 meters, and over 5 meters, respectively. Trees exceeding 5 meters are estimated to be five to six years old, while those under 1 meter are recent recruits established within the last year and a half. This highlights the positive impact of restoration efforts.

Innovative approaches have further strengthened these restoration models. In *Dedhiya* village, biochar produced from *P.juliflora* in Kon-Tiki kilns was applied to soil in experimental plots prior to the monsoon season. Post-monsoon data revealed biomass production of 164 g and 88 g per m^2 in treated and untreated plots, respectively, indicating a 1.87-fold increase in the yield of grasses and herbs in the biochar-treated areas compared to untreated ones.

Discussion

The restoration of the Banni Grassland underscores the significant ecological and socio-economic benefits of controlling *P.juliflora* invasion. Our findings demonstrate substantial gains in vegetation cover, species diversity, and biomass productivity in restored plots, indicating the success of community-led restoration efforts. The removal of *P. juliflora* reduces resource competition, enabling native species to thrive, as evidenced by the fourfold increase in *A. nilotica* populations in Nani Dadhdhar village. This native resurgence highlights the effectiveness of the restoration and suggests positive outcomes for ecosystem functionality and biodiversity.

Table 1: Ecological parameters assessed across 18 villages of Banni grassland

Sr. No.	Name of village	% Vegetation cover in restored plot	% Vegetation cover in control plot	Total cover increased (%)	Species diversity in restored plot	Species diversity in control plot	diversity increased (X	Dry biomass production in restored plot (ton/ha.)	Dry biomass production in control plot (ton/ha.)	Productivity increased (X time)
1	Adhiyang	81	52	55.8	35	21	1.7	0.81	0.24	3.4
2	Pareti	44	35	25.7	13	8	1.6	-	0.38	-
3	Gorewali	65	34	91.2	32	14	2.3	1.41	1.04	1.4
4	Berado	62	44	40.9	13	9	1.4	0.33	0.34	1.0
5	Moti Dadhdhar	68.6	68.33	0.4	20	11	1.8	1.91	0.58	3.3
6	Mithadi	81	43	88.4	26	7	3.7	0.92	0.65	1.4
7	Lakhara	81	74.4	8.9	20	8	2.5	1.01	0.66	1.5
8	Sheth Vandh	66.7	52	28.3	27	16	1.7	0.93	0.79	1.2
9	Dedhiya	56	30	86.7	24	2	12.0	0.87	0.29	3.0
10	Nani Dadhdhar	63	58	8.6	24	8	3.0	0.58	0.20	2.9
11	Panavari	59.4	46.67	27.3	25	12	2.1	0.74	1.3	0.6
12	Vagura	78.4	63	24.4	25	9	2.8	-	0.82	-
13	Sherva	81.6	47.5	71.8	30	14	2.1	1.31	0.5	2.6
14	Mota Sarghu	95.4	80.7	18.2	6	4	1.5	0.38	0.42	0.9
15	Nava Sarghu	61.2	59	3.7	10	11	0.9	-	0.43	-
16	Bhagadiya	59.2	53	11.7	27	14	1.9	2.70	0.80	3.4
17	Chhachla	68.2	39.3	73.5	14	8	1.8	0.69	0.34	2.0
18	Gadiyado	92.4	79.7	15.9	30	19	1.6	0.90	0.94	1.0

Meta-analyses of biochar applications reveal significant biomass increases with 41% in woody plants and 10–30% in agricultural crops (Thomas and Gale 2015). Our findings also show biochar's effectiveness, boosting biomass yield by 1.87 times in treated plots and enhancing soil fertility for long-term carbon sequestration. This supports plant growth and aligns with global climate goals, promoting sustainable ecosystem restoration funded by the carbon market.

Our study aligns with existing research, which highlights the broader advantages of invasive species management for ecosystem services, such as clean air and water, and benefits to local livelihoods through resources like grazing (Medvecká et al. 2018; Vilà et al. 2011). The involvement of local communities, especially the Maldharis, is essential, as their knowledge complements scientific strategies and fosters sustainable land management supported by literature, showing that community engagement is pivotal for long-term conservation success (Berkes 2004; Agrawal and Gibson 1999).

Future research should focus on long-term monitoring to assess ecosystem recovery, socio-economic impacts, and the risk of re-invasion. Policymakers should consider incorporating community-led restoration models into broader conservation strategies, promoting biodiversity conservation and supporting local economies. The successful restoration of the Banni Grassland demonstrates the potential of integrated management approaches to rehabilitate degraded ecosystems and secure community support for sustainable development.

Conclusion

This study underscores the successful community-driven restoration of the Banni Grassland, highlighting significant ecological improvements following the removal of an invasive species *P.juliflora*. Restoration efforts have notably increased vegetation cover, species diversity, and biomass productivity, with a strong resurgence of native tree*A. nilotica*. The active participation of Maldhari communities has been crucial, leveraging their traditional knowledge for sustainable land management. Biochar application in grassland has further enhanced soil fertility and long-term carbon sequestration. Continuous monitoring and management by the community is essential to prevent re-invasion and ensure habitat sustainability. This model illustrates the potential of integrated restoration strategies, driven by local communities and supported by carbon credits, to enhance ecosystem resilience and support local livelihoods.

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Evaluation of treatment type and grass species for restoring Artemisia-dominated rangelands in the Great Basin of North America

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Key words: sagebrush; restoration; grasses; rangeland; wildfire

Abstract

Decades of research and management activities have focused on restoring Artemisia-dominated rangelands. Future climate projections suggest that drought and wildfire may become more frequent; therefore, being able to restore rangelands following these events is critical for the future maintenance of ecological services. We initiated two studies, one focusing on assessing treatment types (chaining, drill seeding, and aerial seeding) for post-fire restoration, and in a separate study, we evaluated 52 grass species that were opportunistically exposed to drought and fire over seven years to determine which groups of species are resilient to these drivers. The treatment analysis relied on the Rangeland Analysis Platform tool to evaluate how burned areas responded to treatment by examining the cover estimates of functional groups before and after treatment. The functional groups varied significantly in their responses to different treatments. Overall, we discovered mild successes in perennial grass and forb establishment. Conversely, postfire invasive annual forbs and grasses were more dependent on pretreatment conditions than treatment type. We also concluded that restoration success may depend more on pretreatment conditions than treatment type. Our results also demonstrate that a wide array of plant materials can establish, persist, and resist cheatgrass (B. tectorum) invasion through drought and fire and that species selection for restoration should be based on their possession of functional traits that can meet management objectives. Thus, in the future, managers attempting rangeland restoration must carefully consider pretreatment conditions and select species for restoration based on functional traits that ensure the resilience of rangelands.

Introduction

Rangelands in the Great Basin of Western North America are subjected to frequent drought and wildfire at sporadic intervals. Sagebrush rangelands are being invaded by invasive annual grasses such as Bromus tectorum, which alter ecological processes and fire regimes (Mack 1981; Bradley et al. 2018; Young & Clements 2009; Davies 2011). Land managers are tasked with trying to restore these altered rangelands. Therefore, we first determined the outcomes of post-fire rehabilitation efforts across Northwestern Utah; to do this, we wanted to understand if post-fire treatments decreased annual forb and grass cover while increasing perennial grass and forbs; and shrubs. As range managers look forward to the future, they must grapple with the effects of climate change in altered ecosystems while maintaining ecological services provided by rangelands, such as livestock grazing, wildlife habitat, biodiversity, and carbon sequestration. Therefore, rangeland managers must choose the proper restoration species to rehabilitate degraded ecosystems, which is an essential part of the restoration process (Asay et al. 2003; Booth and Jones 2001). Land managers and restoration practitioners face difficult decisions when deciding which perennial grasses to plant for restoration. However, little research has been done on the ability of individual species and varieties of perennial grass species to survive and regenerate after fire and drought stress. Our study sought to shed light on which species and varieties are most effective at coping with wildfire, drought, and cheatgrass.

Methods

The fire restoration study examines the post-fire treatment of fires from 1999-2019. Treatment scenario groups were used to lump similar treatments into like categories. Treatment scenario groups describe the different combinations of treatment that occurred in the study area. For example, a treatment scenario is an area that received a single aerial seeding and chaining event following a wildfire.

We used the Rangeland Analysis Platform (RAP; Allred et al. 2021) to quantify vegetation before the wildfire (3 years) and every subsequent year after the wildfire post-wildfire mitigation. We used functional when analyzing vegetation cover. The groups included annual forbs and grasses, perennial forbs and grasses, and shrubs (Bryan 2022). We performed an effect size analysis to compare treatment outcomes across treatment types across time to determine changes in vegetation post-wildfire management.

When evaluating restoration species to determine which species and varieties best persist through drought, wildfire, and cheatgrass invasion, we examined the responses of 52 species and varieties. The plant materials used in this study are listed in Table 1. The study was conducted on an agricultural research farm operated by the Utah Division of Wildlife Resources' Great Basin Research Center in Ephraim, UT, USA. Seedling establishment was quantified by estimating frequency in June 2016 using a frequency grid (Vogel and Masters 2001). In the fall of 2020, an experimental burn on the research plots unintentionally burned the entire site. Persistence was measured in June 2021, and we collected the frequency of cheatgrass, annual grasses, and weeds. Our study assessed the ability of the various species and varieties to establish, persist, and resist cheatgrass invasion through drought and fire. To determine which species or variety resisted invasion and persisted through drought and grazing, we used a dimensional scaling (NMS) analysis to cluster the species that performed the best (Clifford 2022).

Results

The overall effect of the functional groups on treatments showed modest increases in annual grasses and forbs 0.31 (0.14,0.48), and perennial grass and fobs had a slightly more significant effect 0.46 (0.37,0.054). At the same time, shrubs declined -0.17 (-0.27,0.06) due to wildfires even after post-fire management (Bryan 2022). The method of postfire (aerial seeding, drill seeding, and chaining) mitigation showed little consistency in our analysis.

The NMS ordination of the responses of the 52 varieties of restoration grasses showed that varieties were clustered into four discrete groups using a hierarchical cluster analysis, accounting for 59.4% of the information Table 1.). Pairwise comparisons for the interactions showed that group 2 had a significantly higher frequency of restoration species and lower frequency of cheatgrass than all other groups for all years studied (Table 1; Clifford 2022).

Discussion

The outcomes from the different post-fire restoration methods used in West Box Elder County are variable. Our analysis did not prove that one treatment method was superior in all cases. Mild successes in perennial establishment occurred across all treatment types. Annual cover increased and appeared to depend more on pretreatment levels than treatment type. The results also indicate that the needed recovery time after fire may be longer than 15 years, especially when evaluating shrub response to post-fire treatments. The analysis reemphasized that annual, perennial, and shrub responses to treatments are highly variable and depend on many factors besides the treatment method. Factors influencing treatment success include the site's pretreatment abiotic and biotic conditions, including plant composition, soil type, health, aspect, and elevation (Boyd et al. 2012, Knutson 2014, Miller 2012). Considering these factors and acknowledging variations in treatment outcomes emphasizes the importance of avoiding extrapolating results from one successful treatment to other potential treatments. The success or failures of a handful of individual projects should not become the basis for future management decisions. Instead, examining several occurrences of a particular treatment can provide a more complete picture of the range of expected outcomes. Our research can be used to inform managers better when developing strategies for future treatments, especially when considering the treatment type that should be used and the various abiotic and biotic conditions of the proposed restoration sites. Planning restoration methods to suit individual projects best will require high levels of collaboration between stakeholders to decide where and how best treatment practices should occur.

We attempted to determine which varieties of restoration grasses could establish, persist, and resist cheatgrass over seven years, including multiple years of below-average precipitation and a fire that burned all treatments in 2020. Climate projections show increasing temperatures and periods of drought throughout the Great Basin in the future (Snyder et al. 2019). Similarly, the continued spread and dominance of cheatgrass will increase wildfire across the Great Basin (DiTomaso et al. 2010). Therefore, finding species and varieties that can establish and persist through drought and fire is critical for maintaining intact stands of perennial grasses and resisting invasion by cheatgrass. Our results suggest that the varieties found in group 2 possess some functional traits that enable them to establish, persist, and resist cheatgrass through drought and fire. Given the diversity in species found in group 2 and the variation across varieties of the same species, we recommend that restoration seed selection be based on the functional traits that allow varieties to establish, persist, and resist cheatgrass through drought and fire.

In the future, range managers must maintain rangeland integrity and function. Our study shows that our best efforts can return rangelands to the pre-disturbance condition. If the rangelands have already lost some function before the disturbance, it becomes the new ceiling for ecological conditions. Future rehabilitation will require careful study of the disturbed sites, and cautious evaluation of the plant species chosen for restoration efforts focused on plant functional traits rather than classifications. Rehabilitating rangelands needs to be more of an adaptive process rather than a recipe to ensure we maintain rangeland integrity,

Table 1. List of species sorted by NMS group designation from the hierarchical cluster analysis. Species abbreviations include bluebunch wheatgrass (BBWG), bluegrass (BG), basin wildrye (BWR), crested wheatgrass (CWG), intermediate wheatgrass (IWG), fine fescue (FF), slender wheatgrass (SLWG), Snake River wheatgrass (SRWG) and thickspike wheatgrass (TSWG).

Group			
1	2	3	4
BBWG, Boardman	BBWG, Anatone	BG, Mountain Home	FF, R1574
BBWG, P-7	BBWG, Columbia	BG, Opportunity	Junegrass, KomaL
BBWG, P-33	BBWG, Goldar	BWR, Magnar	Salina Wildrye, KBJ_4x
BBWG, Wahluke	BBWG, P-45	FF, Boreal	Sideoats Grama, Vaughn
BBWG, Whitmar	BWR, Continental	TSWG, Bannock II	SLWG, First Strike
BG, Canbar	BWR, Int. Tetra		SLWG, Pryor
BG, High Plains	BWR, L_57X		SLWG, SanLuis
BG, UP_Sandburg	BWR, L_66X		
BWR, L_72X	BWR, Trailhead		
FF, Covar	BWR, Trailhead II		
FF, Durar	CWG, HxB28		
FF, R4S22	CWG, Hycrest		
Salina Wildrye, 9053601	CWG, Hycrest II		
SRWG, E_64X	IWG, AI		
TSWG, Bannock	IWG, Luna		
	IWG, Oahe		
	IWG, Rush		
	Salina Wildrye, LS_4		
	Siberian Wheatgrass, Stabilizer		
	Siberian Wheatgrass, Vavilov II		
	SRWG, Discovery		
	SRWG, dryland		
	SRWG, Secar		
	SRWG, Secar78		
	TSWG, Critana		

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Fire for vegetation management in grazed rangelands

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Char height on fence posts as a practical proxy of flame length and fire intensity in grass fires

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Key words: Wildfires; Fireline intensity; South Africa; Grasslands; Fire behaviour

Abstract

Wildfire behavioural parameters are assessed through metrics that can be expensive to measure with sufficient resolution in real time, such as rate of spread, intensity, and severity. Wildfire researchers and practitioners are thus in need of accurate, cost-effective, and user-friendly methods to estimate these metrics. Flame length is one such established proxy metric widely used to estimate fireline intensity, however direct measurements can be challenging. Char height on tree trunks has been proposed as a cost-effective proxy for flame length, and thus fireline intensity, but its accuracy has not been widely tested.

Based on research by Williams et al. (1998) in Australian eucalypt savannas, this study explores the relationship between char height on fence posts and flame length in a South African grassland fire context. Data were collected at 143 monitoring plots within 7 landscape-scale prescribed fires in Eastern Cape mesic montane grassland. Flame length was recorded in real time using installed wooden fence posts of known height as visual aids, and grouped by fire type (head, back, flank). Char height measurements were later recorded from the soil surface to the maximum height of charring on the fence posts.

Across all fire types, the flame length (y) could be accurately estimated from char height ($y = 1.42x + 0.971$; $R^2 = 0.609$), but there were some differences between fire types. For head fires, char height yielded a strong rank correlation ($r_{s(37)} = 0.807$; $p < 0.001$) with flame length, while char height in flank fires had a moderate rank correlation ($r_{s(25)} = 0.532$; $p < 0.005$). Back fires did not show a significant rank correlation between char height and flame length ($r_{s(15)} < 0.15$; $p > 0.567$). Pragmatically, the simple doubling of *post-hoc* char height serves as a direct estimate of flame length.

This research confirms that in mesic montane grasslands of southern Africa, char height is a reliable *post-hoc* indicator of flame length, particularly for head fires, and could have wide practical application as a rule-of-thumb in these grassland ecosystems.

Introduction
Wildfires are a common occurrence in many landscapes and present significant challenges for fire management in rural or remote areas. Understanding fire behaviour, particularly the intensity of fires, is critical for both prediction and post-fire analysis, which contributes, *inter alia*, to planning suppression efforts, and protecting human and ecological assets.

Wildfire behaviour is typically assessed through various parameters, such as rate of spread, intensity, and severity, however, these metrics can be challenging to measure. Among these, measuring fire intensity directly can be a particularly tedious and time-consuming process, and as a result, empirical evaluations of intensity are not often conducted (Van Wilgen 1986; Schwilk 2003; Scott et al. 2014). There is, therefore, a demand from both researchers and practitioners for accurate, cost-effective, and user-friendly methods for measuring fire intensity in the field.

It has long been established that direct correlations exist between flame length and fireline intensity (Byram 1959; Brown & Davis 1973; Rothermel & Deeming 1980; Van Wilgen et. al. 1985; Van Wilgen 1986; Cochrane & Ryan 2009; Scott et. al. 2014), however, direct measurements of flame length during fire progression can be challenging and impractical due to the dynamic nature of fires.

In response, charring and leaf scorch height on trees have been proposed as useful and practical post-fire proxies of flame length and thus fire intensity (Van Wagner 1973; Williams 1998), offering an accessible alternative for both researchers and land managers (Williams et. al. 2003). Based on data collected from a series of fire experiments conducted between 1990 and 1994 in eucalypt savannas at the Kapalga research site, Australia, Williams et. al. (1998) showed that the height of char and scorch on savanna trees were both associated with fireline intensity. These relationships between flame length, height of char (and scorch), and fireline intensity have been corroborated in literature (Byram 1959; Van Wilgen et. al. 1985; Van Wilgen 1986; Cochrane & Ryan 2009), but their accuracy and applicability have not been widely tested in different systems.

Previous research has explored the relationship between fire intensity and various fuel and weather conditions, however, little attention has been given to the potential for physical markers, like char height, to provide post-fire, accessible data for fire behaviour assessment. This study explores the relationship between char height on fence posts and flame length in mesic montane grasslands of the Eastern Cape, South Africa.

Fence posts are commonly found in many rural and wildland-urban interface areas, where they could provide a simple and immediate reference for fire behaviour. By examining char height in relation to flame length measurements under different fire conditions, we aimed to establish a field-based method for estimating fire intensity that could complement traditional fire behaviour prediction models.

Methods
The study was conducted on seven landscape-scale controlled burn sites across the Eastern Cape province of South Africa from early September to mid November 2019. These burn sites were comprised mostly of mesic montane grassland and occasional savanna vegetation. The prescribed burns were conducted as planned management burns to remove moribund and unpalatable material, as well as control woody encroachment (Figure 1).

Figure 1. Example of prescribed management burn, conducted for the purposes of removing cured, unpalatable material.

Dry, untreated wooden fence posts (>3m) were planted prior to burn treatments, at 143 monitoring plots situated within the seven landscape-scale burn sites.

Flame length and fire spread type (head, back, or flank) were recorded observationally at each monitoring plot (n = 143). Objects of known height (planted fence posts) in the fire's path, were used as visual aids when measuring flame length (Van Wilgen 1986). Weather conditions (wind speed and direction, relative humidity, and temperature) were recorded at one-minute intervals, in the vicinity of the fire, using a portable weather station (Campbell Scientific; R.M. Young Company). Fuel load and degree of curing were also recorded.

Where charring occurred, it was recorded on the planted fence posts. Height of char was measured in centimetres, from the base of the post, at the soil surface, to the maximum height of charring, following the methods proposed by Williams et. al. (1998) (Figure 2).

The entire dataset met the assumptions for normality, so linear regression analysis was used to test the relationship between char height and double (2x) char height (dependent variables) and real-time flame length (independent variable). For the individual fire types, non-parametric tests were required, so Spearman's rank correlation was performed to validate associations between char height and flame length.

Results

The approximate mean weather conditions prevailing for the duration of each prescribed burn are summarised in Table 1. In terms of the formal Fire Danger Rating System (Lowveld) for the Republic of South Africa (Government Gazette Notice 1099 of 2013), weather conditions recorded for each monitoring plot, translate to Fire Danger Indices (FDIs) ranging between 30 and 72, in the mid "Green" and upper "Orange" zones, respectively. The total mean FDI for all monitoring plots was 43.44 ± 6.69. The total mean fuel load and curing percentage for all monitoring plots were 6.76 ± 1.72 ton/ha and 72.6% ± 6.97%, respectively.

Figure 2. Example of charring on pre-planted fence post. Charring occurred higher on the leeward side of the pole.

Table 3: Summary of approximate mean weather conditions and Lowveld Fire Danger Index (FDI) scores with standard deviations (SD), for duration of prescribed burns at each site in the Eastern Cape, South Africa. Lowveld FDI scores were calculated according to the methods stipulated in Government Gazette Notice 1099 of 2013 for the Republic of South Africa.

Site	Date	Air Temperature ± SD (ºC)	Wind Speed (km/h)	Relative Humidity ± SD (%)	Lowveld FDI Score ± SD
1	11 Sept 2019	24 ± 0.78	4–14	60 ± 0.47	39 ± 2.7
2	17 Sept 2019	23 ± 0.71	7–14	57 ± 0.23	46 ± 3.5
3	15 Oct 2019	17 ± 1.34	2–15	55 ± 0.41	37 ± 2.7
4	16 Oct 2019	26 ± 1.2	5–14	55 ± 0.3	44 ± 3.4
5	4 Nov 2019	19 ± 0.39	8–16	49 ± 0.21	42 ± 1.1
6	8 Nov 2019	18 ± 0.54	7–21	49 ± 0.54	40 ± 2.5
7	12 Nov 2019	24 ± 0.89	13–42	51 ± 0.25	54 ± 7.2

Charring occurred on 83 of the 143 planted fence posts (~58%). Across all fire types, the flame length (y) could be accurately predicted from char height ($y = 1.42x + 0.971$; adjusted $R^2 = 0.609$), but there were differences between fire types (Figure 3). In head fires, char height showed a strong positive correlation ($r_{s(37)} = 0.807$; $P < 0.001$) with flame length. Char height in flank fires had a moderate correlation ($r_{s(25)} = 0.532$; $p < 0.005$). In contrast, char height from back fires did not show significant correlation with flame length ($r_{s(15)} < 0.15$; $p > 0.567$).

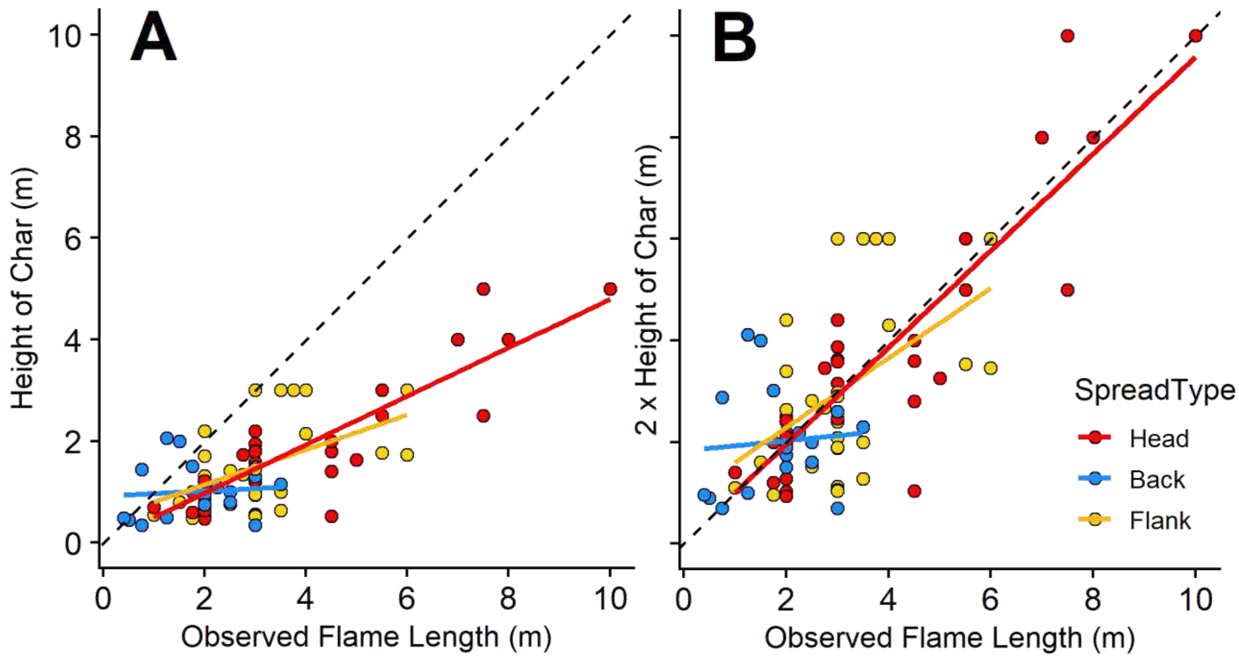

Figure 3. Observed flame lengths versus height of charring (A) & double (2x) the height of charring (B) measured on pre-planted fence posts, separated by fire spread type (head, back, or flank), for 83 monitoring plots in 7 landscape-scale fires in mesic montane grassland. Dashed lines indicate perfect agreement between observed flame lengths and char height values. Solid lines are linear regressions for each fire spread type (head, back, or flank). The regression for 2x height of charring is presented, given the pragmatic potential of this simple proxy. Linear regression for all observations in scatterplot B: $y = 0.71x + 0.971$; adjusted $R^2 = 0.609$, where y is double (2x) char height and x is the observed flame length.

Discussion and Conclusion

The results reveal a significant correlation between char height and flame length, suggesting that char height can serve as a reliable field-based indicator of fire intensity. Serendipitously, for the pragmatic application of this proxy, doubling the charring height provides a simple direct estimate of flame length in head and flank fires. The repeatability of the proxy across multiple sites and varied weather conditions suggests that the proxy may be applicable across a broad range of grassland wildfire conditions.

Williams et al. (1998) previously identified char height on pole-type fuels as a useful *post-hoc* indicator of flame length in eucalypt savannas at the Kapalga research site in Australia. Our study extends this finding to mesic montane grasslands in the Eastern Cape, South Africa, demonstrating a similar relationship (Figure 3).

It is important to note that approximately 40% of fence posts were not charred, which can be attributed to the absence of fuel within the immediate vicinity of the posts, low fire intensities, or short residence times. When applying char height as a post-fire indicator of flame length or fireline intensity, one should be cognizant of the likelihood of the absence of charring and, where possible, identify the fire type in the area.

Despite this limitation, this simple relationship has wide practical applications in southern Africa and other subtropical grassland and savanna systems. Char height provides a useful rule of thumb as a field-based method for estimating fire intensity without the need for specialized equipment. We conclude that char height on fence posts can serve as an effective *post-hoc* measure of fire behaviour, especially in areas where other fire behaviour metrics are expensive and challenging to obtain.

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Mesquite (*Prosopis*) seedling responses to fire and grass production in the southern Great Plains, USA

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Key Words: canopy cover; prescribed burning; shrub-grass competition; woody plant encroachment

Abstract

Prescribed fire is an economical land management practice used to mitigate the global increase in woody plant encroachment (WPE) on rangelands. For woody plants that resprout following fire, the seedling stage may be vulnerable to fire. However, we know little about long-term growth of mesquite seedlings that survive fires. We measured seedling survival and post-fire gains in canopy cover of two cohorts (seeds planted in two different years) of honey mesquite (*Prosopis glandulosa*) seedlings in response to winter or summer fires in mixed-grass (~2,000 kg/ha) or tallgrass (~7,000 kg/ha) fuel types in the Southern Great Plains, USA. Post-fire seedling survival was highest to lowest in no fire, winter fire and summer fire, respectively, in both grass types and seedling cohorts. Canopy cover in all fire treatments and both cohorts increased to a greater level in mixed-grass than tallgrass over a 20-year period. Fire treatment had little effect on post-fire canopy cover gains. Rate of cover gain in mixed-grass (3.4 percentage units per year: PU/yr) was greater than a previously reported rate of 2.2 PU/yr for mature mesquite over 20 years at the same site. Lower mesquite seedling growth in tallgrass plots was likely due to a combination of greater pre-fire mortality, greater mortality from more intense fires, and greater post-fire grass competition for resources. Results suggest that mixed-grass, which is the dominant grass type in the region, may not be sufficiently competitive to slow the rate of mesquite seedling growth even after summer fire.

Introduction

Fire was an integral part of pre-settlement grasslands and rangelands in the southern Great Plains (SGP), USA and likely suppressed the expansion of woody plants (Briggs et al. 2005, Guyette et al. 2012). After European settlement, many woody species, including the fire-resistant native woody legume, honey mesquite (*Prosopis glandulosa* Torr.), expanded in density and distribution; due in part to the reduction of fire frequency that limited mesquite seedling establishment (Archer et al. 1995, 2017). In addition, cattle consumption and fecal deposition of viable mesquite seeds enhanced distribution (Brown and Archer 1987, Ansley et al. 2017).

Adult mesquite plants resprout following top-kill and very few are root-killed by fire (Ansley et al. 2021). However, seedlings are vulnerable to fire for a brief period of time (Wright et al. 1976). Productive stands of grass can reduce growth rate of young mesquite (Brown and Archer 1989, Van Auken and Bush 1990). However, we know little about long-term growth of mesquite seedlings that survive fires. Ansley et al. (2015) quantified mortality of mesquite seedlings when burned with summer or winter fires in mixed-grass and tallgrass fuel types and found that summer fires in both grass types and winter fires in tallgrass increased seedling mortality compared to no fire. Our objective here was to quantify long-term (20-year) growth of those seedlings that survived the fire treatments.

Methods

We conducted the study within a fenced pasture on a private ranch in north Texas. We included two patches of native mixed-grass and two patches of tallgrass. Each patch was 2.7 ha in size. The mixed-grass patches were mostly comprised of Texas wintergrass (*Nassella leucotricha*) and buffalograss (*Buchloe dactyloides*), with a small proportion of C_4 mid-grasses such as sideoats grama (*Bouteloua curtipendula*) (average standing biomass ~2,000 kg/ha). The tallgrass patches consisted of introduced kleingrass (*Panicum coloratum*) planted in the 1970's (~7,000 kg/ha). All grass patches occurred on the same Tillman clay loan soil type (Ansley et al. 2015).

We hand-planted 924 mesquite seeds in each of twelve 0.125 ha plots in one mixed-grass and one tallgrass patch in April 1997 (hereafter Cohort-97), and repeated the procedure in the second of each patch in April 1998 (Cohort-98). We established three treatments (no fire, winter fire and summer fire) in each grass patch with four replicate plots per treatment. Seedlings were 17 months old during summer fires and 10 (Cohort-97) or 22 (Cohort-98) months old during winter fires. We did not apply winter fire to 10-month-old Cohort-98 seedlings due to drought and insufficient grass fuel and instead winter burned the following year. No further fires occurred after the year 2000. We excluded livestock grazing during the study period. More details are in Ansley et al. (2015).

We obtained aerial images of the plots in the years 2000, 2002, 2012 and 2019 that provided excellent contrast between mesquite and grass cover and visually estimated mesquite canopy cover in each plot each year. We analyzed canopy cover responses to fire treatments within each grass patch using the PROC MIXED procedure in SAS with fire treatment and time post-fire as main effects with four replicate plots per treatment (SAS 2013). We separated means using LSD at $P \leq 0.05$.

Results

Percent seedling survival and number of live seedlings per plot at 1 year after all fire treatments were highest in no fire, mixed-grass for both cohorts and lowest in the summer fire treatment within each cohort and grass type (Table 1).

Mesquite canopy cover of Cohort-97 in mixed-grass increased at similar rates in the three treatments and reached 65-75% by 2019 (Figure 1A). Cohort-97 cover in tallgrass increased at similar rates among the three treatments but only reached 25-33% canopy cover by 2019. Similar responses were found with Cohort-98 seedlings except that canopy cover gain in mixed-grass was slightly lower in the summer fire than the winter fire treatment by 2019, with no fire intermediate (Figure 1B).

Table 1. Mesquite seedling cohort, land patch, grass type, fire treatment season and year, seedling age at the time of fire treatment, and average percent seedling survival and number of live seedlings the first growing season after all fires were completed.

Seedling Cohort	Land Patch	Grass Type	Fire Season and Year[1]	Age when Burned (Months)	Post-fire Percent Seedling Survival	Live Seedlings Per Plot Post-Fire
Cohort-97	1	Mixed	No Fire	---	7.2	67
Cohort-97	1	Mixed	w-1998	10	5.5	51
Cohort-97	1	Mixed	s-1998	17	2.0	19
Cohort-97	2	Tallgrass	No Fire	---	1.9	17
Cohort-97	2	Tallgrass	w-1998	10	2.1	19
Cohort-97	2	Tallgrass	s-1998	17	0.8	8
Cohort-98	3	Mixed	No Fire	---	7.3	67
Cohort-98	3	Mixed	s-1999	17	3.1	28
Cohort-98	3	Mixed	w-2000	22	5.4	50
Cohort-98	4	Tallgrass	No Fire	---	5.4	50
Cohort-98	4	Tallgrass	s-1999	17	2.3	22
Cohort-98	4	Tallgrass	w-2000	22	3.8	35

1/ w = winter fire; s = summer fire

Discussion

Even though the fire treatments reduced the starting number of live mesquite seedlings compared to no fire, this had minimal effect on post-fire gains in canopy cover. The only exception occurred in the Cohort-98 mixed-grass patch where summer fire reduced canopy cover gain over time compared to winter fire. A spike in growth in all treatments between 2000 and 2002 was more pronounced with Cohort-97 than the 1-year younger Cohort-98 seedlings and this may have affected differences seen in 2019. Growing season precipitation was well above normal in 2002 (Ansley et al. 2021) and Cohort-97, being 1 year older, may have been able to exploit the enhanced soil moisture across all fire treatments more effectively than Cohort-98.

Largest gains in canopy cover came from Cohort-97 in the mixed-grass type. Averaged over the 3 treatments, canopy cover reached 68% over 20 years, or a rate of cover increase of 3.4 percentage units per year: PU/yr). Rate of gain for Cohort-98 in mixed-grass was similar to Cohort-97; 60% over 19 years (2000 to 2019), or 3.2 PU/yr. These rates of cover gain are greater than a previously reported rate of 2.2 PU/yr for mature mesquite over 20 years at the same site (Ansley et al. 2001). A lower rate of cover gain with mature mesquite suggests that the growth rate slows with age, but results from the current study show this decline in growth rate may not occur within the first 20 years of growth.

Slower mesquite growth in tallgrass was likely due to a combination of greater pre-fire seedling mortality due to tall grass competition (Van Auken and Bush 1990), greater mortality from more intense fires (Ansley et al. 2015), and greater post-fire grass competition for resources. Results suggest that mixed-grass stands that have degraded to lower producing species such as Texas wintergrass and buffalograss may not be sufficiently competitive to slow the rate of mesquite seedling growth even after summer fire and (in this study) under no livestock grazing pressure. However, results from the tallgrass patches suggest that mixed-grass stands that have a greater proportion of more productive C_4 mid-grass species than found in our mixed-grass stands might provide greater long-term resistance to mesquite seedling recruitment and growth.

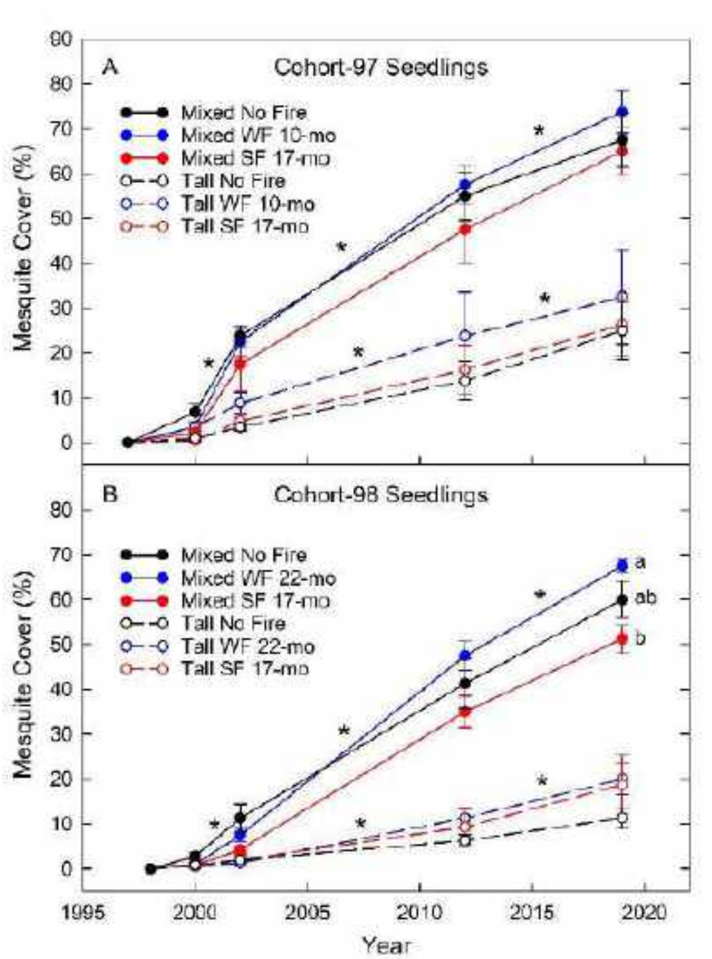

Figure 1. Change in mesquite cover from seedlings of Cohort-97 (A) or Cohort-98 (B) in mixed-grass (Mixed) and tallgrass (Tall) when exposed to no fire, winter fire (WF) at 10-months (Cohort-97) or 22-months (Cohort-98) of age, or summer fire (SF) at 17 months of age. Vertical lines are ±1 standard error. Means with similar letters within each grass type and year are not significantly different ($P \leq 0.05$). An asterisk indicates a significant ($P \leq 0.05$) difference from one time period to the next when averaged over the 3 treatments in each grass type. There were no significant differences among fire treatments within each grass type in any year.

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Lessons from a 30 year burning experiment in northern Australian grazed tropical savannas

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Key words: savannas; fire; frequency; season; grazing

Abstract
Like all savannas, the semi-arid tropical savannas of northern Australia have evolved with fire. However, the presence of fire in the landscape has changed significantly with the reduction of traditional Aboriginal burning and increased control of wildfires. The incidence of fire is now greatly reduced on most land used for grazing by livestock. To address concerns about how reduced fire might influence vegetation structure and productivity, a long term fire experiment at Victoria River Research Station, also known as Kidman Springs, 400km south of Darwin in the Northern Territory began in 1993. Treatments (each with two replicates) include: season of burning (early in the dry season in June, or late in the dry season in October); fire interval (two, four and six–yearly); and four unburnt controls. The treatments are applied on a calcarosol Eucalypt woodland and on a vertosol grassland. The three decades have seen unanticipated climate driven shifts in pasture composition, and increases in woody cover in all but the most intense fire regimes and subsequent declines during a recent run of drier years. Fire prevented woody cover increases since 2009 on the grassland. On the woodland woody cover fluctuated more through time, but was at similar or lower levels in 2023 to 2009, even on unburnt controls due to drought related dieback. The herbaceous understorey is resilient to fire with perennial grasses relatively unaffected and greater diversity post fire due to increases in ephemerals. Understorey herbaceous dry matter was only negatively correlated with woody cover on the grassland. Hence, concerns about increasing woody cover leading to reduced pasture productivity may be unfounded in the woodland, but without fire native woody encroachment into the productive grasslands can change the structure from a grassland to an open woodland and may negatively impact carrying capacity for livestock. Since 2013 wet season spelling has been implemented post fire. This has improved the pasture composition on the grassland and suggests the minimum required fire interval for effective management of woody cover could be increased from four to six yearly, provided fuel loads are adequate for an effective fire. Other research at the site has investigated biocrust, mite, faunal and above and below ground carbon storage response to long term fire regimes. This is the only long term grazed fire experiment in Australia's tropical savannas. It continues to provide new insights and is open to the global research community.

Introduction
Australian savannas are well adapted to fire but not grazing, having evolved with regular fire, but only very low levels of native herbivore pressure. The incidence of fire had greatly declined on grazed pastoral land

compared to under Indigenous ownership and management due to cessation of traditional burning, reduced fuel loads due to grazing by introduced herbivores, and deliberate exclusion of fire by pastoralists to protect infrastructure and forage for livestock. There was evidence of woody encroachment into the most productive vertosol grasslands and concerns that continued lack of fire would lead to further woody encroachment and loss of carrying capacity for livestock due to competition between the woody and pasture layers. The Kidman Springs fire experiment started in 1993 and for thirty years has provided insights into the long-term impacts of regular fire regimes, and how fire can be managed in the grazed context. Combined with insights from long term grazing exclosures at the site (Bastin et al. 2003) the experiment can provide insights into the broader potential drivers of vegetation change (fire, rainfall, grazing, CO_2) in the region, answering questions that were not anticipated at its inception. This review aims to update the findings emerging from the site in the context of its beginnings.

Methods

The fire experiment is on Victoria River Research Station (VRRS) 400km south of Darwin in the Northern Territory on a calcarosol Eucalypt woodland and a vertosol grassland. 90% of the rain falls during the 'wet season' between November and March with distinct seasonally dry periods between June and October. On each site the following fire treatments (each with two replicates) include: season of burning (E-early in the dry season in June, or L-late in the dry season in October); fire interval (two, four and six–yearly); and four unburnt controls to give 16 160m x 160m plots separated by firebreaks. See Cowley et al. (2014) for full experimental design and methods. Since 2013, all plots have been rested from grazing post fire after the late dry season fires until the end of the following wet season, effectively providing a wet season spell every second year. In 2019 all two, four and six–yearly burn treatments were implemented. Tree basal area (TBA) and canopy cover were assessed using a bitterlich gauge at 19m intervals along 4 x 100m transects per 2.4 ha plot in 2009, 2017, 2019, 2021 and 2023. Total standing dry matter and species composition of the herbaceous understorey has been assessed annually from 1994 to 2001 and every two years thereafter. A linear mixed effects model in R was used to test the effect of burn interval and season of fire and for significant differences between burn treatments within year, and between years within treatments. The experiment-wise error rate was set at 0.05.

Results

The fire experiment began after an extended dry period with six of the seven years between 1986 and 1992 with below median rainfall (762mm). More recently four of the five years between 2018 and 2022 had below median rainfall (Fig. 1).

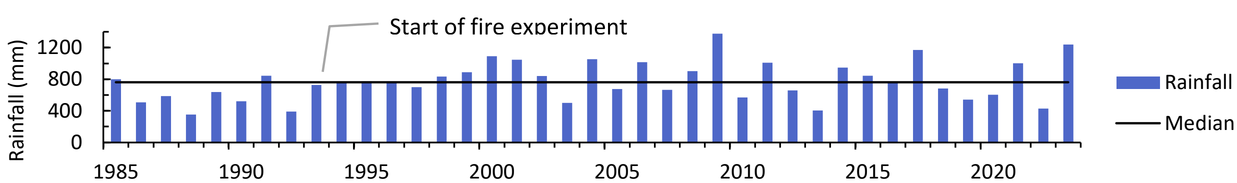

Figure 1. July to June rainfall and median rainfall (1970 - 2024) at VRRS

Pasture composition shifts in unburnt plots

Pasture composition varied through time even on unburnt controls, signalling grazing and rainfall responses. On the grassland *Iseilema* spp. declined from 19% in 1994 to 2% in 2023, while *Ophiurus exaltatus* increased from 0% to an average 18% of total yield since 2013 on the grassland control plots (Fig. 2). The proportion of *Aristida latifolia* increased at the expense of *Chrysopogon fallax* between 2003 and

2013 until the introduction of wet season spelling post burns. On the woodland the pasture shifted from arid shortgrass dominated to *Heteropogon contortus* dominated by 2001, although this subsequently declined following dry years between 2019 and 2021 (Fig. 2).

Woody cover

TBA significantly varied with year and burn interval on both the grassland (Fig. 3a) and woodland (Fig. 3b), while late dry season fires had significantly lower TBA than unburnt on the woodland, but not the grassland. The impact of 15 years of fire treatments had already influenced TBA when it was first measured in 2009, although differences were not significant. However, since then woody cover has further diverged between fire treatments, particularly on the grassland (Fig. 3a). TBA in 2023 on unburnt grassland plots was more than double 2009 levels, while TBA on the more severe fire regimes, early or late burnt every two or four years has stayed relatively stable since 2009. Late 2 had significantly lower TBA than unburnt in 2019 and 2023, and late 6 was lower than unburnt in 2023. On the woodland TBA peaked in 2019, except for the two most severe burn treatments late 2 and 4 yearly which did not vary through time. On the other woodland treatments TBA declined more with the dry years between 2019 and 2021 than on the grassland. Although by 2023 TBA was often comparable with levels in 2009, treatments had diverged enough that the unburnt woodland plots had higher TBA than all the late burnt plots and the 2 yearly early burnt treatment. The late 6 yearly burnt treatment went from having similar TBA to all other treatments in 2009 to having the lowest TBA by 2023.

In contrast to TBA, canopy cover varied significantly with treatment in all years on both the grassland and woodland. All late burnt plots and early 2 (except for the woodland in 2009) always had lower canopy cover than the unburnt plots in the woodland and grassland (Fig. 3c and 3d). Canopy cover was relatively stable on the grassland through time, except on the unburnt plots where it increased after 2009, while on the most severe burn treatment (late 2 yearly) canopy cover was lowest in 2023. Canopy cover peaked on the woodland in 2019 and was lowest in 2021.

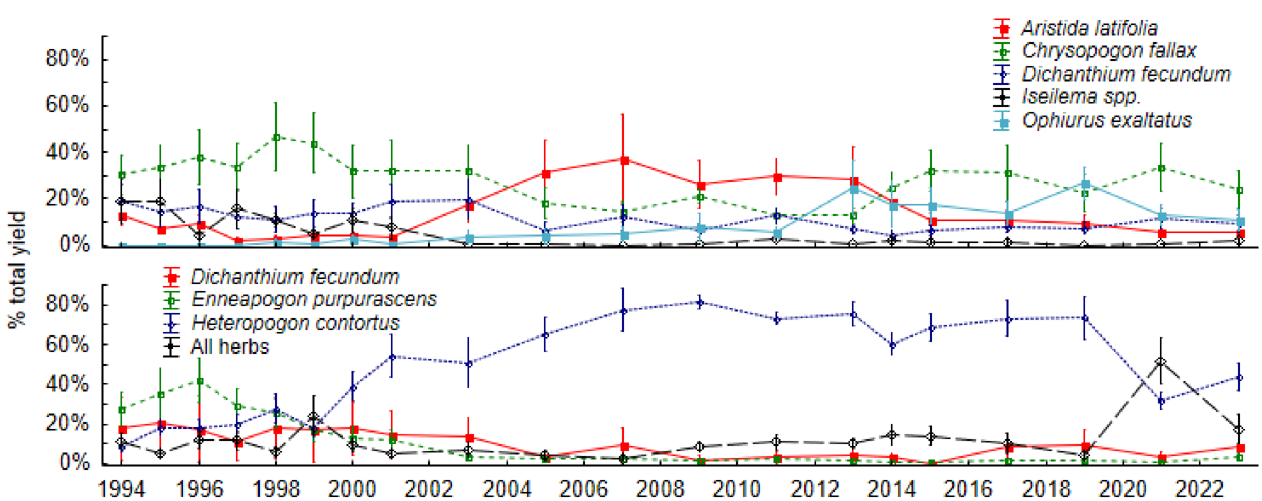

Figure 2. Change in species composition on unburnt control plots on the grassland (top) and woodland (bottom) savanna at VRRS. Mean +- the standard error

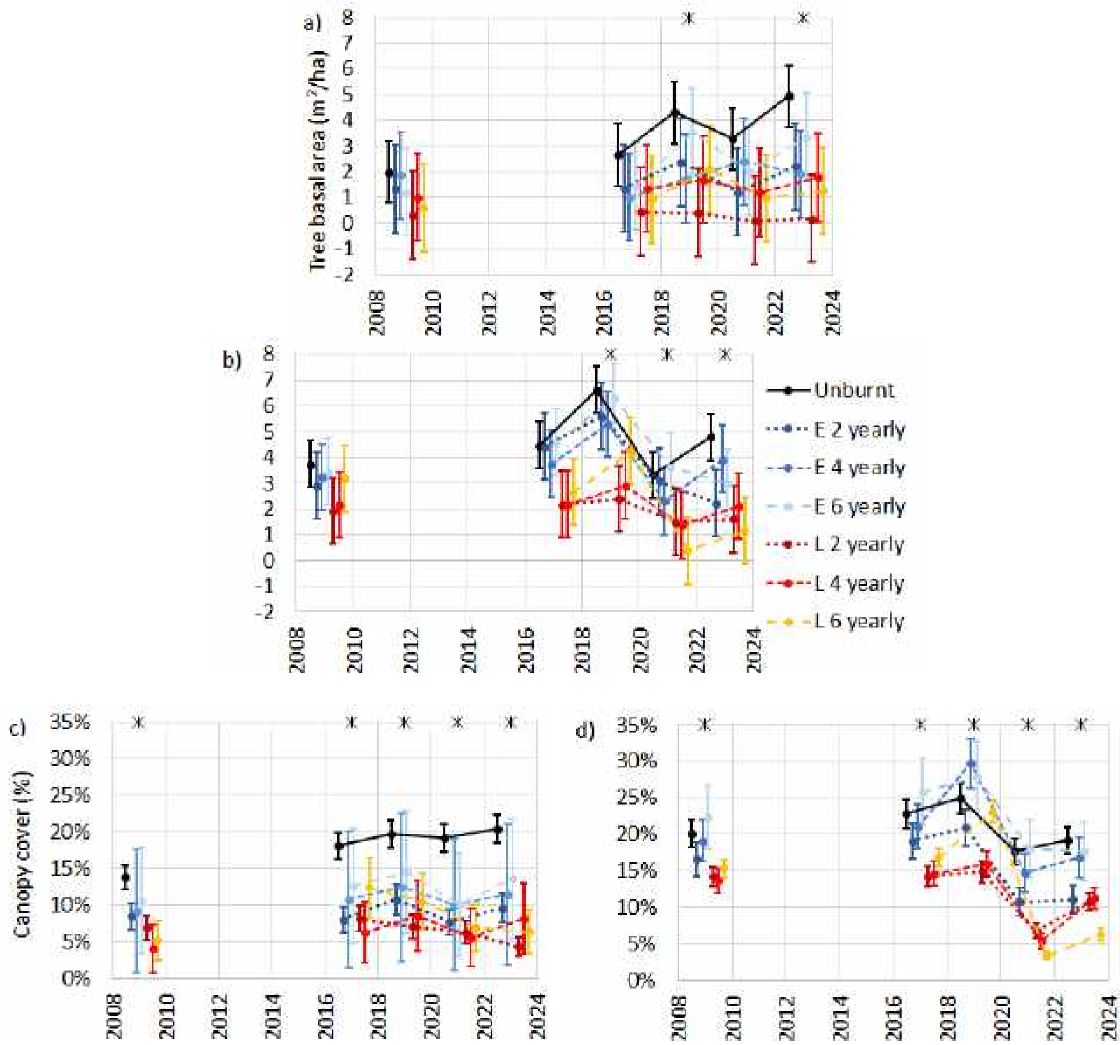

Figure 3. Tree basal area on a) grassland and b) woodland and canopy cover on a c) grassland and d) woodland through time for different fire treatments savanna at VRRS. Mean +- the 95% CI. * significant difference between treatments

Discussion

Cowley et al. (2014) hypothesized that the shift in composition of the woodland from arid short grass to *Heterogon contortus* was likely a response to multidecadal shifts in rainfall from drier prior to the fire experiment to wetter through the first two decades of the fire experiment. Similar increases had also been observed in grazed and ungrazed areas on the research station (Bastin et al. 2003). The subsequent decline in *H. contortus* during the recent drier years supports this. Similarly on the grassland, the replacement of the more arid adapted *Iseilema* spp with *Ophiurus exaltatus* which prefers damp conditions may also be in response to long term fluctuations in rainfall. A study of the full vegetation composition and diversity at the site in 2016 found the perennial grasses were unaffected by fire treatment, and vegetation diversity increased post fire with flushes in ephemerals (Lebbink et al. 2018).

Post fire spelling was introduced by fencing the fire experimental plots from the broader paddock in October 2013 to prevent high post fire grazing on the fire site which was contributing to a decline in pasture condition on more frequently burnt plots, particularly the early burnt plots (Cowley et al. 2014). Wet season spelling of the fire experimental plots for around six months every two years effectively reduces the average stocking rate by one quarter, compared to if continuously grazed at the same stocking rate. It also allows palatable species to establish and recover over the wet season in the absence of grazing. Within two years of wet season spelling, *Chrysopogon fallax* had recovered and *Aristida latifolia* declined to levels at the start of the experiment, although the recovery of *Dichanthium fecundum* has been much slower and has still not reached the same proportions as it was at the beginning the study on either soil type.

The impact of fire treatments on the woodland woody cover has also shifted since the introduction of post burning spelling. Before 2013 the 6 yearly and early burnt plots tended to have higher woody cover and lower fuel loads driving less effective fires. Cowley et al. (2014) concluded that fires need to be 4 yearly to manage woody cover. However, since 2013 even in dry years higher yields and more effective fires have contributed to declines in woody cover, particularly on the woodland 6 yearly late burnt plots. This suggests that provided fuel loads are suitable for effective fires, six yearly late fire may be sufficient to the manage the tree-grass balance on the woodland. On the grassland early and late 4 yearly fires were equally effective.

Although grassland woody plants were observed to be almost completely defoliated at times during the dry years, as of 2023 they had recovered to at least 2019 levels. Woody cover has remained relatively unchanged on the burnt grassland treatments, but may still be increasing on unburnt sites. This contrasts with the woodland site where declines in both TBA and canopy cover were greater and no treatments had recovered to 2019 levels by 2023. Following three dry years between 2018 and 2020 the combined impact of fire and dry years lead to the lowest canopy cover observed for the late and early 2 burn woodland treatments. Changes in canopy cover are more responsive to fluctuations in soil water deficits than tree basal area, because many of these species are semi-deciduous and regularly shed leaves in the dry season each year. Fire is more likely to cause topkill than mortality of these fire adapted species (Dyer 2001), which are exceptional resprouters. Loss of tree basal area represents woody plant death, whereas canopy cover can fluctuate rapidly without tree death. On the grassland burnt plots there are many small supressed shrubs of *Terminlia volucrens* and *Bauhinia lysiphyllum* which are vulnerable to top kill with fire. On the unburnt plots without regular fire, they have grown to trees > 2m in height, and exert competition with the understorey pasture layer (Cowley et al. 2021). In contrast there was less evidence of competition between the pasture and woody layers on the woodland, and drought led to significant tree deaths regardless of fire, as has been found previously in north eastern Australia (Fensham et al. 2019), suggesting fire could be prioritised to the more productive grasslands.

The fire experiment at VRRS continues to provide unique insights into the impacts of fire in the grazed context on the savanna vegetation, but also the less anticipated impacts of multidecadal shifts in rainfall on vegetation composition and structure. The site not only contributes to our understanding of savanna ecosystems, but also provides a visual demonstration of fire management for local land managers and has been used to determine the impact of fire on carbon storage, biodiversity and biocrusts.

Acknowledgements
Thanks to the many people who have assisted with data collection and site management. The research has been funded by Meat and Livestock Australia until 2001 and the NT Department of Agriculture and Fisheries.

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Multi-species grazing, mob grazing, and fire effects on cool-season grass invaded rangelands of the northern great plains of north America

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Keywords
Livestock management, prescribed fire, Long term, alternative management, invasive species

Abstract
Grasslands in the northern Great Plains of North America sustain abundant plants, wildlife, and livestock but are threatened by invasive plant species. Predicted shifts toward more variable weather will challenge sustainable management of these grasslands. Effective and feasible management options need to be developed in collaboration with, and for, land managers. As part of the Long-Term Agroecosystem Research (LTAR) network, a nationwide network with 19 research sites focused on developing strategies to address current agricultural needs, we initiated an experiment in 2019 to answer whether applying fire and/or grazing can reduce the dominance of invasive Kentucky bluegrass (*Poa pratensis*) in North America's northern Great Plains ecosystems. We contrast a prevailing practice (season-long grazing at a moderate stocking rate) with four alternative practices at a half-hectare plot scale: (1) mob grazing (high intensity, short duration) by cattle, (2) multi-species grazing (mob grazing by cattle, with goats foraging at key times of the year), (3) prescribed fire, and (4) prescribed fire followed by cattle grazing. A stakeholder group was engaged in making decisions to determine alternative practices and how to apply them. Every five years, the treatment with the best overall outcomes is applied at a field scale (15 ha). We found that prescribed fire and mob grazing reduced the cover of Kentucky bluegrass and increased the cover of some native plant species. When combined, prescribed fire and grazing had the most reductions in Kentucky bluegrass and increases in native plant species. However, there are trade-offs associated with each treatment related to plant production and nutritive values, livestock weight gain, and soil compaction and infiltration. We discuss results in the context of optimizing land management based on land manager goals and current and future economic and ecosystem benefits.

Introduction
Naturally occurring fire, indigenous fire management, grazing, and soils shaped the vegetative communities on the Great Plains (Epstein et al. 1997, Fuhlendorf and Engle 2001, Lake and Christianson 2020). However, since European settlement, fire and grazing regimes on the Great Plains have been severely altered. These changes have resulted in increased abundance of invasive perennial cool-season grasses severely altering the species composition in the primarily cool-season dominated plant communities in the northern Great Plains.

Fire suppression in fire-adapted rangelands generally results in cascading ecosystem changes that not only affect the local area in which fires occur but influences the delivery of ecosystem services at landscape and watershed scales. From an ecological perspective, suppressing fire in fire-adapted ecosystems inhibits natural regulating processes and, consequently, promotes ecosystem degradation (Backer et al. 2004). From an economic perspective, ecosystem changes associated with fire suppression have led to reduced grazing land resilience, lower land productivity, changes in livestock carrying capacity, and increased risk of loss of property and life to catastrophic fires resulting from fuel load accumulation (Pyne 1984; Teague et al. 2001, Toledo et al. 2014).

Mob grazing is increasingly popular with producers, but the impacts of the practice, especially on soil and vegetative composition, are unclear. This is also true of other alternative animal practices such as multi-species grazing (Walker 1997). There is a need to evaluate and compare the impacts of alternative grazing management practices and prescribed burning on vegetation and soils.

Methods
The experiment was located on native rangeland at the Northern Great Plains Research Laboratory, USDA-ARS, which has been invaded by the perennial cool-season grass, Kentucky bluegrass. Five different land management treatments were replicated four times each in a randomized complete block design. The five treatments were (1) grazing with cattle only at a moderate stocking rate until 50% of the palatable vegetation was removed (Control); (2) use of a mob grazing technique (high intensity, short duration) for cattle only (MOBC), (3) grazing by goats and mob grazing by cattle (MOBCSR); (4) a fall prescribed fire(Fire); and (5) a fall prescribed fire that was grazed by cattle in the following spring (FireC). Each treatment was randomly assigned to a 0.5 ha plot within each block. We implemented a staggered start design, meaning that 2 experimental blocks were started in 2019, and the remaining 2 experimental blocks were started in 2020. To minimize the impact of plot size, treatment blocks were selected with care to represent the landscape and reduce potential sources of variability. Treatments were located on Loamy Ecological Sites (USDA 2024).

Vegetation sampling on each plot was conducted using the Modified Whittaker technique (Stohlgren et al. 1995; Stohlgren 2007) and the line intercept method (Herrick et al. 2005). Rangeland health assessments were performed using the Integrated Grazingland Health Assessment protocol (Toledo et al. 2016).

Soil attributes were measured in all treatments prior to treatment deployment, throughout the study, and at the end of the study. Samples were collected from depth increments of 0-0.05, 0.05-0.1, 0.1-0.2, 0.2-0.3, and 0.3-0.6 m using a hydraulic sampler and analyzed for physical, chemical, and biological attributes. Attributes included soil bulk density, water-stable aggregation (physical), soil pH, electrical conductivity, exchangeable cations, available N and P, micronutrients, total C and N, and particulate organic matter C and N, (chemical), and C mineralization, potentially mineralizable N, and phospholipid fatty acid profiles (biological). Field measurements of sorptivity, penetration resistance, and soil water content were conducted annually before and after grazing, while saturated hydraulic conductivity was measured after grazing.

Results

We found that prescribed fire and mob grazing reduced the cover of the invasive Kentucky bluegrass (Figure 1). When combined, prescribed fire and grazing had the most reductions in bluegrass. However, there were trade-offs associated with each treatment related to plant cover and livestock weight gain.

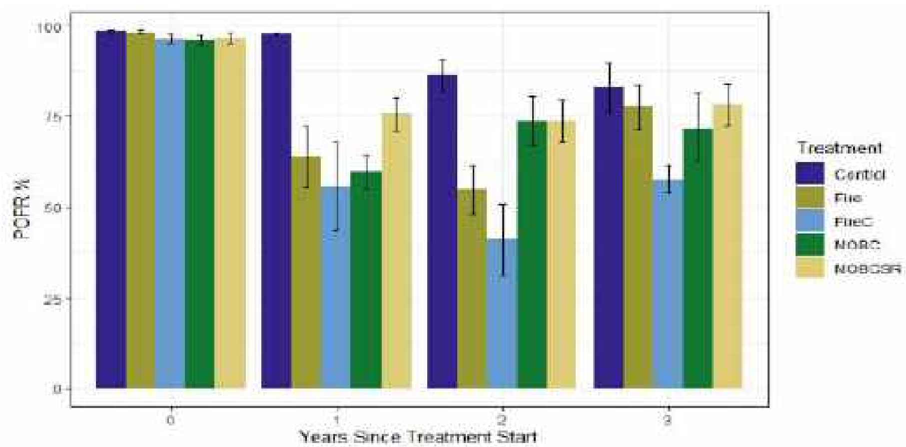

Figure 1. Percentage cover of Kentucky bluegrass (*Poa pratensis*; POPR) in treatment plots before the start of treatments and each year since treatment started. Error bars were constructed using one standard error from the mean.

Livestock weight gain differences between the control and mob grazing treatments were not significantly different in 2021 or 2023 and were only significantly different in 2022. However, there was a trend of slightly higher weight gains per hectare in the mob treatments (Figure 2). Qualitative rangeland health data (visible platy structure near the soil surface) suggest plots that were mob grazed were more compacted than plots that were grazed season-long, and the ease with which pores of a saturated soil-transmitted water was greater in the control and fire treatments than in the mob treatments but results vary by year (Figure 3).

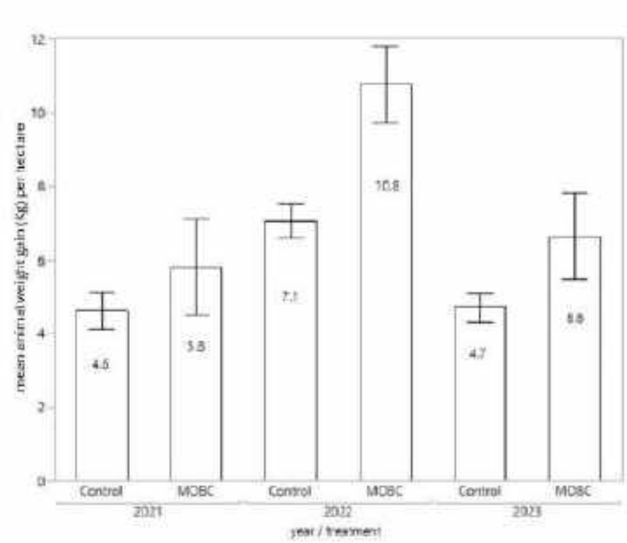

Figure 2. Twenty-eight-day mean animal weight gain (Kg) per hectare on season-long grazing (Control) and mob grazing (MOBC, alternative practice) by year. Error bar constructed using one standard error from the mean. Livestock did not graze fire treatments long enough to produce reliable weight data.

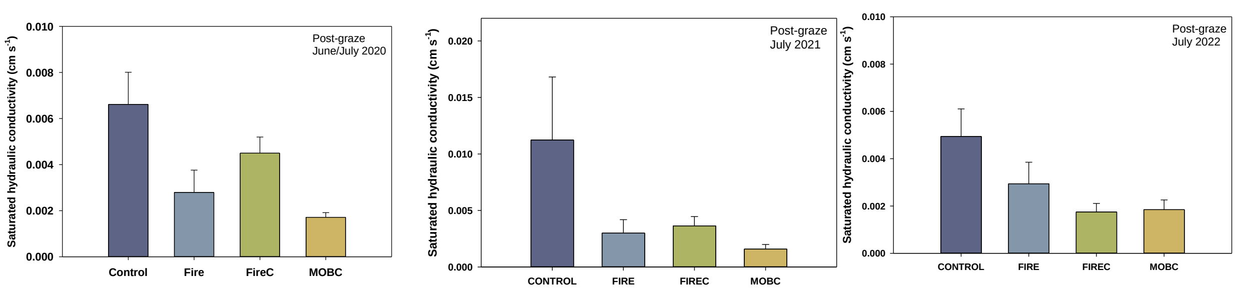

Figure 3. 2020, 2021, and 2022 post-graze saturated hydraulic conductivity of season-long grazing control (prevailing practice), fire treatment (Fire), fire treatment that was grazed by cattle (FireC), and mob grazing treatment (MOBC).

Discussion [Conclusions/Implications]

Fire treatments were more effective at reducing cover of Kentucky bluegrass than the other treatments. Mob grazing showed reductions in bluegrass and increases in weight gain per hectare compared to the control, but results were not consistently significant and were also associated with negative changes in soil physical condition. We were unable to compare weight gains of livestock in grazed fire treatments because they spent too little time on the treatments to produce reliable weight data.

Although Kentucky bluegrass is a palatable and productive grass (Toledo et al. 2014), no treatment is not an option if the goal is to maintain healthy and productive rangelands in the northern Great Plains. The combination of fire and grazing provided the most positive results in terms of Kentucky bluegrass reductions. In a region where prescribed fire is not always seen as positive, it was important for landowners who were part of the stakeholder group to see these results first-hand. Land managers need to evaluate their goals for their land and the current and future economic and ecosystem benefits and constraints of applying any of these treatments.

Acknowledgements
We acknowledge the contributions of our project-specific customer focus group, the many landowners and agency personnel who have contributed comments and ideas throughout the experiment, and Chris Gordon at The Nature Conservancy Cross Ranch Preserve for prescribed fire training and help during burning days. We would also like to acknowledge the contributions of the small army of technicians who keep this experiment running and ensure that all measurements are taken precisely and consistently. A special thanks to Daniel Asplin, Justin Feld, Shawn Miller, Michael DeGreef, Clay Erickson, Rebecca Knutson, Nicole Davidson, Allison Bargmann, Jenny Hanson, Raina Hanley, and Olivia Avery for their help with running this experiment and data collection. This publication is a contribution from the Long-Term Agroecosystem Research (LTAR) network. LTAR is supported by USDA. This work is also being supported by funds from a Conservation Effects Assessment Project jointly funded by the USDA NRCS and USDA ARS.

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Understanding the system – rangeland dynamics and ecology

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Effects of orientation on soil moisture, temperature, biomass production, and nutritional composition of natural grassland in the central Chile

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Key words: grassland; quality; pasture; dryland

Abstract

The natural dryland grassland of Central Chile serves as the nutritional base for sheep production systems. The orientation of a hill influences solar exposure, potentially affecting soil temperature and moisture, consequently impacting the growth cycle and nutritional quality of the grassland. Therefore, this study aimed to assess the orientation's effect on biomass production and the nutritional quality of the grassland. To achieve this goal, a farm with slopes facing the four cardinal directions (N, S, E, W) was selected for the trial. Three exclusion plots were established for each orientation. Grass samples were collected monthly to measure availability (kg DM/ha), Dry Matter (DM, %), Crude Protein (CP,%), Neutral Detergent Fiber (NDF,%), and Acid Detergent Fiber (ADF,%). Soil moisture and temperature were monitored at depths of 7.5 and 12 cm using a portable TDR 350 moisture sensor, expressed as Volumetric Water Content (VWC, %) and Celsius degrees (°C), respectively. Simple and multifactorial ANOVA were employed for data analysis. Results revealed that the average soil moisture at both depths was highest on the S slope, with 9.6±7.8% at 7.5 cm and 12.2±10.1% at 12 cm. The W slope exhibited the lowest moisture; however, it was not statistically different from the N and E slopes. The higher soil moisture on the S slope corresponded with lower temperatures (24.8±6.6°C), approximately 4°C lower than other orientations. This soil moisture/temperature combination resulted in no significant differences ($p<0.05$) in biomass production between orientations until after senescence (November). Regarding nutritional quality, no orientation effect was observed on DM (%), but differences were noted in ADF, NDF, and CP. The E orientation exhibited the lowest NDF value (52.6±5.0%), the S orientation had the lowest ADF value (37.3±2.7%), and the N orientation showed the lowest CP value (9.2±1.6%). These variations suggest the potential for utilizing orientation differences to accommodate animal categories with varying nutritional requirements.

Introduction

The natural dryland grassland of Central Chile serves as the nutritional base for sheep production systems. However, changes in precipitation and temperature patterns due to global warming have altered the grasslands' growing season, affecting the availability and nutritional quality of the forage throughout the year (Liu et al. 2019). Accurate information about forage availability is essential for efficient and precise grassland management and feed planning in extensive livestock systems (Serrano et al., 2016). Unfortunately, much of the available information regarding the nutritional value and its temporal pattern is outdated, with data spanning several decades (Ruiz, 1996). In Central Chile, the effects of climate change have manifested as reduced precipitation and increased temperatures, highlighting the importance of topographical features that influence soil moisture availability. For example, the orientation of a slope affects solar exposure, which can influence soil temperature and moisture, thereby impacting the growth cycle and nutritional quality of the grassland (Cui et al. 2023). The objective of the study was to evaluate the effect of slope orientation on biomass production and the nutritional quality of the grassland, while also updating the existing information on the production and nutritional quality of natural dryland grasslands in Central Chile.

Methods

The study was conducted on a livestock farm located in the interior dryland of the Las Cabras commune, O'Higgins Region. According to the modified Köppen classification, the area has a warm temperate climate with winter rainfall (Santibañez 2017).

For the research, 12 exclusion plots, each of 100 m² (10 x 10 m), were established and distributed across the four cardinal orientations (N, S, E and W, three plot per slope). The study spanned the grassland growth period, from July to December. Samples were collected monthly using a ring with a surface area of 0.09 m². In each exclusion plot, once the grass reached a minimum height of approximately 5 cm, three grass samples were collected. Grass was clipped at ground level to ensure sampling during the early growth stages using electric hand shears. The samples were placed in plastic bags, stored in a cooler, and transported to the Animal Feed and Food Quality Laboratory at the O'Higgins University for further processing. Fresh weights were recorded, and the dry matter percentage was determined to estimate biomass availability per hectare. Nutritional composition of the samples was analyzed using a FOSS NIR DS2500, measuring the following parameters: Dry Matter (DM, %), Crude Protein (CP, %), Neutral Detergent Fiber (NDF, %), and Acid Detergent Fiber (ADF, %). Soil moisture and temperature were monitored at depths of 7.5 and 12 cm using a portable TDR 350 moisture sensor. Moisture content was expressed as Volumetric Water Content (VWC, %) and temperature as degrees Celsius (°C). In each exclusion plot, 12 measurements were taken—six per depth. Data analysis was performed using simple and multifactorial ANOVA, with month, orientation, and depth considered as factors.

Results

Grassland growth began in July; however, due to the limited grass height, sampling was not feasible. Consequently, 324 samples were collected from August to December. Although an effect of orientation and month on biomass availability was observed ($p<0.05$), significant differences were only detected in December. On the N- and W-facing slopes, maximum biomass availability was observed in October (Figure 1). In contrast, on the S- and E- facing slopes, peak biomass availability occurred in November. Subsequently, plant senescence began, resulting in a slight decrease in biomass availability.

Orientation and month also had a significant effect on the dry matter, crude protein, acid detergent fiber (ADF), and neutral detergent fiber (NDF) contents. The N-facing slope exhibited lower nutritional quality during most of the evaluated months, characterized by lower crude protein concentrations and higher NDF and ADF concentrations (Figure 2).

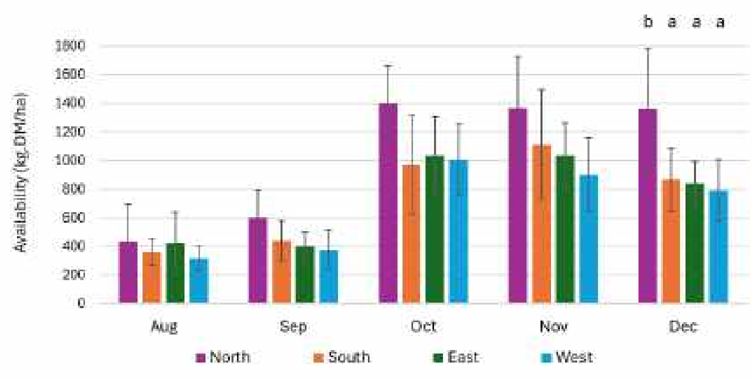

Figure 1. Effect of month and orientation on average biomass availability

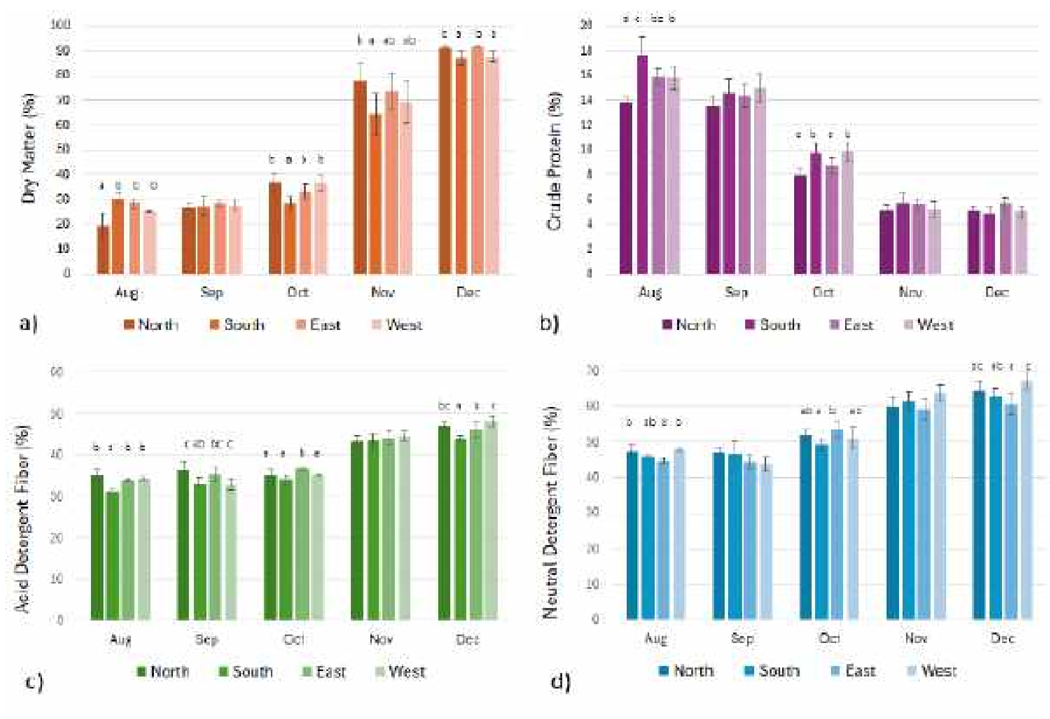

Figure 2. Monthly variation in Dry Matter content (a), Crude Protein (b), Acid Detergent Fiber (c), and Neutral Detergent Fiber (d) of the grassland.

Soil temperature and moisture variables were recorded from July to December (Figure 3). Both month and orientation significantly affected these variables at both depths (7.5 cm and 12 cm) ($p<0.05$). Depth significantly influenced soil moisture but had no effect on temperature. Soil moisture decreased rapidly from July to October, with the rate of decline slowing from October to December. From August to December, the S-facing slope consistently exhibited significantly higher soil moisture content compared to the other orientations ($p < 0.05$). At 12 cm depth, soil moisture was lower on the S- and W-facing slopes compared to measurements taken at 7.5 cm in all evaluated months. Soil temperature trends were similar across the N-, E- and W-facing slopes. On the S-facing slope, however, the temperature increase exhibited a lag of approximately two months compared to the other orientations.

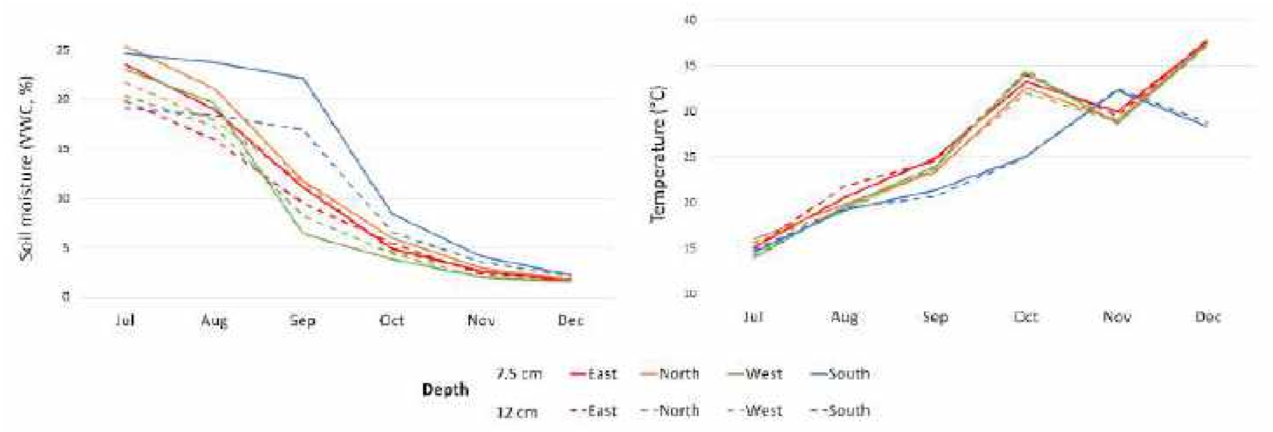

Figure 3. Effect of month, orientation, and depth on soil moisture and temperature

Discussion

Topographic factors such as slope and orientation influence the range of microclimatic conditions, including solar radiation, temperature, and soil moisture (Bennie et al.2008). These variables, which are critical for the growth of the grassland species, determine their productivity, and nutritional composition, demonstrating the potential for utilizing orientation differences to accommodate animal categories with varying nutritional requirements. In the southern hemisphere, S-facing slopes receive the least solar exposure throughout the day, resulting in lower soil temperatures (Figure 3). These lower temperatures reduce evapotranspiration, helping to maintain higher soil moisture levels and creating a greater moisture differential between the 7.5 and 12 cm depths during the wet months (Figure 3). The lower temperatures on the S-facing slopes likely delayed the onset of growth, resulting in shorter growth cycles and lower biomass availability. This growth delay contributed to lower fiber levels and higher protein content in August and September. However, as the microclimates generated by slope orientation can influence species composition, further studies are needed to identify the species present on each orientation (Zhang et al., 2022).

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Structure and phenology of herbaceous forage plants in the Sahelian rangelands of Senegal during the rainy season

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Key words: Grazing; rainy season; pastoralism; phenology; Sénégal;

Abstract

This study describes the structure and phenology of Sahelian rangelands during the rainy season. It was undertaken in thorny steppe on a grazed plot and a nearby fenced plot with otherwise similar site characteristics. Measurements were taken every 10 days over two rainy seasons between July and October 2022 and between August and October 2023. The measurements included the phenological stage, the vegetative and flowering height, the foliage cover, and the phytomass. The results showed that phytomass did not systematically differ between grazed and fenced plots. Flowering started as early as mid-July, but most of the plants flowered in early October. Flowering and fruiting occurred earlier (based on the number of days after the first rain) in the late rainy season (2023) than in the early one (2022). These stages reached their peak in October; senescence began in October. Vegetative height, reproductive height, and coverage were similar between the two years. Height peaks were similar, but they were reached earlier (based on the number of days after the first rain) in the late rainy season than in the early one. Coverage peaks were similar (59.8% in the early rainy season vs. 65.8% in the late one). Vegetative height (around 30 cm), reproductive height (around 36 cm), and coverage (around 60%) reached their maximum in October, but reproductive height was greater than vegetative height. These parameters were lower at the grazed, and flowering started earlier at the grazed site. Grazing reduced cover and height, and delayed flowering. Structure and phenology were more sensitive to changes in rainfall between years. Knowing phenology helps determine the best time to harvest the phytomass, because the nutritional quality of the forage is known to decrease after fruiting.

Introduction

In the Sahelian rangelands, the main economic activity is pastoral livestock farming, which is mainly based on ephemeral vegetation. These rangelands comprises a stratum of annual herbaceous plants, mainly grasses, and a stratum of scattered woody plants dominated by the genus *Acacia* (Diawara et al., 2018). In the Sahel, the quantity of grass produced is largely determined by rainfall, which varies between years. Low rainfall caused low biomass which leads to pastoral crises.

It is therefore important to know the dynamics of the herbaceous stratum so as to adapt pastoral livestock farming to climatic constraints. However, most studies on phytomass production in the herbaceous stratum have mainly focused on variations between years and between zones, with sampling often taking place at the end of the rainy season; few studies have looked at dynamics during the season, and herbaceous plants grow very quickly during the rainy season (from June or July to October) due to the availability of soil moisture (due to rainfall) and nutrients and the impact of grazing (Habibou et al., 2018). Most studies have focused solely on biomass. However, studying other vegetation parameters over the entire life cycle of plants can provide a great deal of useful information for understanding vegetation dynamics, especially in relation to animal production.

The goal of this study was to measure the structure and phenology of the herbaceous stratum over a rainy season and to examine whether grazing had any effect on the measured parameters. Thus, phytomass, vegetative height and phenology were monitored at ten-day intervals during the rainy season, for two years, in thorny steppe at a grazed site and nearby a fenced site. These sites had otherwise similar site characteristics. The gazed site was grazed by cattle, horses, donkeys, sheep and goats at high intensity. The fenced sites excluded all herbivores from grazing. This study is innovative in that it measures parameters that are not always measured (height of inflorescences) and that were measured much more frequently than usual.

Materials and Methods

Study area

The study was conducted in the Sahelian part of Senegal named Ferlo (Fig. 1). The Ferlo, also known as the sylvopastoral zone, is the largest of Senegal's six agroecological zones. It is located between 15°21′ north and 15°28′ west. It covers an area of 54,380 km2 or 27.6% of the national territory. The physiognomy of the vegetation in Ferlo has changed from a wooded savannah to a shrubby savannah in the 1960s to a thorny steppe today (Habibou et al., 2018).

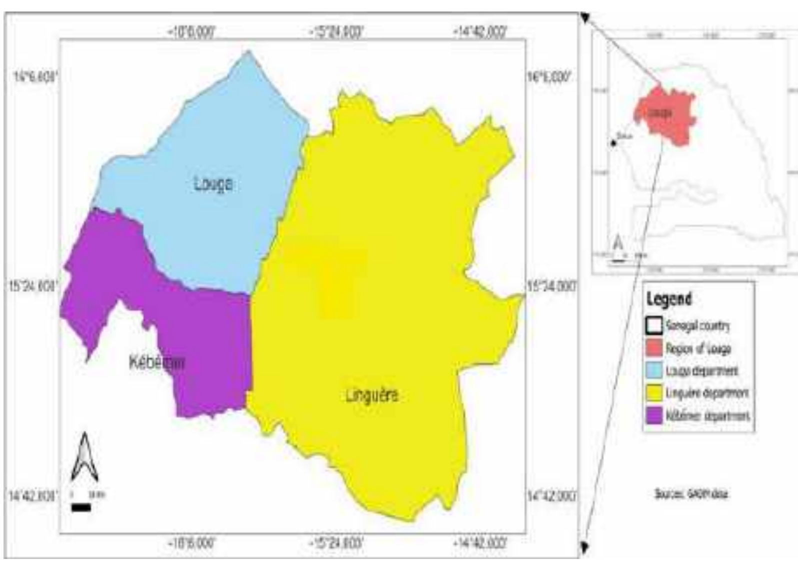

Figure 1: Study site

Data collection

Similar measurements were taken at a grazed site (g) and a fenced site (f) in the rainy season for two years to see if there were any differences between the rainy seasons and whether grazing had any effect on the parameters monitored. The measurements were carried out between July and October 2022 and between August and October 2023. Annual rainfall was 356 mm accumulated over 21 different events in 2022 and 336 mm over 20 different rainfall events in 2023. The 2022 rainy season was about 30 days earlier but was marked by long dry spells at the beginning of the season. Measurements started ten days after the first rainfall of at least 0.1 mm and were taken every ten days up to the end of the rainy season. Twenty-eight points were measured on each measurement date at each site. At each collection point, the following parameters were measured:

- Herbaceous phytomass, harvested at ground level on an area of 1 m2 was weighed fresh and placed in an oven at 65 ◦C until a constant weight was obtained before being weighed again to obtain the dry weight.
- Phenological stages: leafing, flowering, fruiting, and senescence. When a stage was present in the quadrat, the percentage of plants at that stage was estimated visually.
- Vegetative height was measured from the soil to the highest leaf.

Statistical Analysis

Student's test was used to compare parameter values across sites on each measurement date and between monitoring years.

Results

Phytomass

In contrast to 2022, where there was little variation in production between the two sites, overall phytomass production was lower at the grazed site in 2023. Maximum phytomass was reached on the same date (early October), but the peak at the grazed site (1800 kg·ha^{-1}) was less than that of the fenced site (2357 kg·ha^{-1}).

Vegetative Height

In 2018, vegetative height was equal at both sites at the beginning of the rainy season, i.e., 40 days after the first rainfall (up to early August) (Fig. 2). For the rest of the rainy season (mid-August to the end of October), it remained lower at the grazed site. This height reached a maximum of 42 cm at the fenced site and 31.3 cm at the grazed site. However, the maximums were reached on the same date, i.e., in mid-October (the 110th day after the first rainfall). In 2023, vegetative height was lower at the grazed site during the rainy season. This height reached its maximum of 48.09 cm at the fenced site slightly earlier than at the grazed site (27.4 cm) in August. This maximum height was therefore lower at the grazed site.

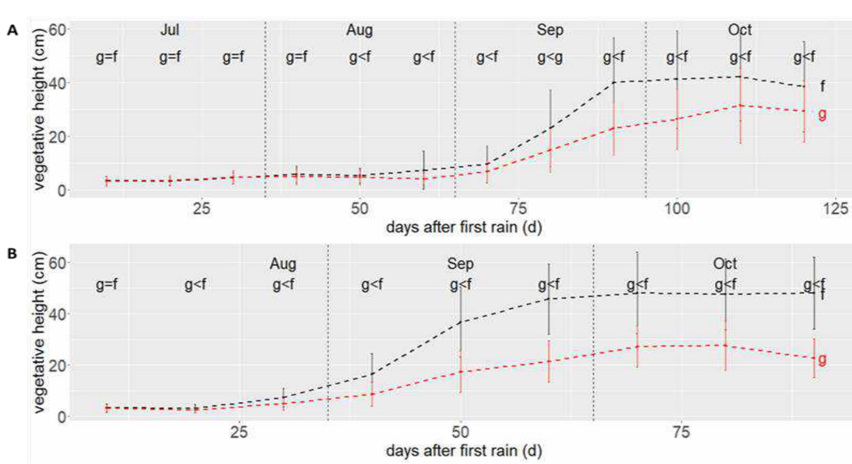

Figure 2: Vegetative height of grazed (g, red) and fenced (f, black) sites in 2022 (A) and 2023 (B).

Phenology
In 2022, the difference in phenology between the fenced site and the grazed site concerned the date flowering first appeared (Fig. 3). It occurred on the 20th day after the first rain (second ten days of July) at the grazed site and on the 30th day after the first rain (third ten days of July) at the fenced site. In 2023, flowering began 10 days after the first rain at the grazed site and 20 days after the first rain at the fenced site. In contrast, fruiting occurred earlier (40 days after the first rain) at the fenced site compared to the grazed site (50 days after the first rain). Senescence started at both sites on the same date, i.e., 80 days after the first rainfall (August). Each of the different phenological stages appeared in the same month at both sites and both years.

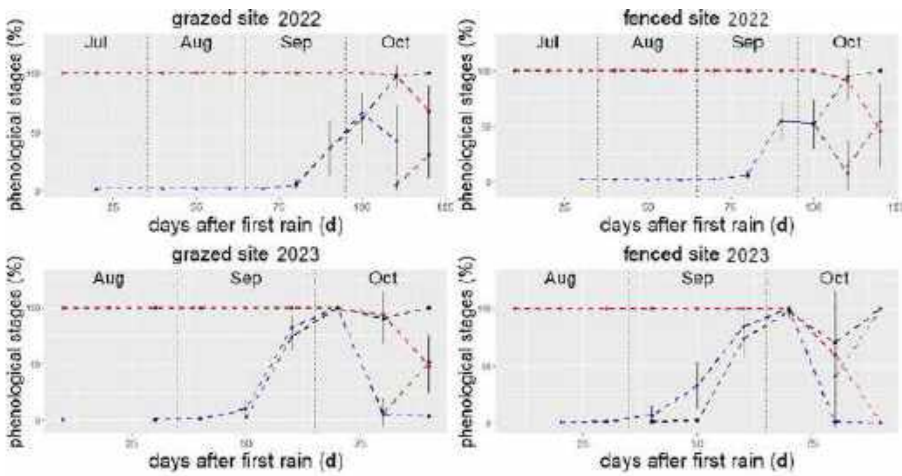

Figure 3: Phenology of grazed and fenced sites in 2022 and 2023. Red: leafing; blue: flowering; black: fruiting; brown: senescence

Discussion
The amount of phytomass was lower at the grazed site than at the fenced site, though the differences were small in 2022 throughout the season. Nevertheless, this result supports the hypothesis that grazing decreases phytomass production, which is similar to previous results in a steppe formation, even in a savanna (Diatta et al., 2023) .

Animal husbandry can cause overgrazing that reduces productivity. On the other hand, trials testing protection from cultivation, forest removal, fire, and grazing carried out in Niger (Sadoré reserve), Burkina Faso, and Senegal resulted in slightly lower herbaceous production than in the grazed control, mainly because of the greater relative importance of broadleaf weeds (Diawara et al., 2018).

Flowering and fruiting occurred earlier in a late rainy season year compared to an early rainy season year. These two stages reached their peak in October, while foliage cover started to drop. Seeding began in October for both years. The onset of flowering in mid-July indicates the existence of early-flowering species at the site. Earlier flowering was noted on pastures in Burkina Faso (Sanou et al., 2021).

Peaks in vegetative height (31 cm) and reproductive height (36 cm) were reached in October, but the reproductive height was slightly higher than the vegetative height. These figures ranged from 0.5 to 1 m (Pontanier et al., 2003) for the height at maximum vegetation and from 40 to 60 cm (Ngom, 2013) for the Ferlo area. These ranges align with other evidence that the herbaceous stratum in the typical Sahel can reach 50 cm in height on sandy dunes (Diatta et al., 2023). It is explained that even though some species continue a vegetative growth after flowering, the majority of grasses stop doing so. Grasses were the major family of the pastures studied, but most annual grasses, under the influence of the photoperiod, flower between the end of August and the beginning of September. This means that almost all species reach their maximum size and stop growing at that time.

Conclusions and Implications

The vegetative height, reproductive height, and flowering of herbaceous plants were sensitive to grazing.

The presence of early-flowering species in the area is consistent with species adaptation to the Sahelian climatic conditions, in particular to the short duration of the rainy season.

The dates of appearance of the phenological stages and the height of the herbaceous layer do not seem to depend on the date of the start of the rainy season.

When measuring the height of the canopy in grassy rangelands, it is best to measure reproductive height so as not to underestimate it.

Acknowledgements

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The photodegradation effect of plant litter in typical temperate steppe varies by the litter state and age

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Key words: Photodegradation; Nutrients turnover; C loss; Litter types

Abstract

We established two field decomposition experiments using *Leymus chinensis* and *Stipa grandis* litter, to quantify the effect of different decomposition drivers (including microbial decomposition, abiotic photodegradation and photoacceleration) on the decomposition of different litter types (surface litter and standing dead) and age (young and old). In experiment I, the presence of photodegradation greatly enhanced the effect of microorganisms. For surface litter, microbial decomposition, abiotic photodegradation and photoacceleration reduced mass 64.4%, 18.9% and 16.7% respectively. For standing dead, microbial decomposition, abiotic photodegradation and photoacceleration reduced mass by 51.6%, 21.5% and 26.9% respectively. Solar radiation affected the decomposition of carbon only; it had no effect on nitrogen. Cellulose was less susceptible to the effect of solar radiation than lignin and hemicellulose. In experiment II, we assessed the effects of prior solar radiation on the subsequent decomposition of plant litter, and found that microbial decomposition and abiotic photodegradation decreased the mass of young litter more than that of old litter, while photoacceleration decreased the mass of young litter less than that of old litter. In conclusion, our results indicated that the impact of abiotic photodegradation tended to decrease over time, and that photoacceleration contributed more to the mass loss than the direct photo-mineralization. Our results suggest that although young and dead standing plant biomass can accelerate decomposition process, which potentially increases the carbon loss of ecosystem and decreases the accumulation of organic carbon; this may indicate a new challenge for grassland sustainability.

Introduction

Traditional models underestimate the decomposition rate in arid environments, and this is largely due to the neglect of photodegradation phenomenon. That has been studied in different ecosystems (King 2012; Wang et al. 2021). However, most of these studies evaluating the effect of solar radiation on decomposition are based on a simple comparison between blocking radiation and allowing radiation to access the litter. Furthermore, it is often difficult to separate the relative contributions of abiotic litter loss and loss due to photofacilitation. Such studies are very limited for assessing the impacts of photodegradation compared with microbial decomposition in different environments and conditions. For example, whether decomposition positions with different decomposition microenvironment (Lin and King 2014; Jacobson et al. 2015; Wang et al. 2017) will influence the contribution of photodegradation to the decomposition of litter, and whether the contribution of abiotic photodegradation and photoaccelerate on litter degradation changes with time or litter type? These questions require quantitative experiments to answer. In this study, we explore whether decomposition processes differ between different litter types, and how the different types of litter affect the contributions of microbial decomposition, photodegradation and photofacilitation to litter degradation. In addition, we also examined how our treatments influenced litter chemistry, to provide clues as to what compounds might be involved in photodegradation.

Methods

The study was carried out in an experimental grassland at the Grassland Ecosystem Research Station of Inner Mongolia University. The experiment materials were the litter of two dominant plants (*Leymus chinensis* and *Stipa grandis*). We conducted two small experiments that used a two-by-two factorial design and the same decomposition treatments, including two sunlight treatments (sun and shade) and two microbial treatments (sterilization and non-sterilization). The decomposition time both was about one year.

Experiment I: This involved litterbags (5 g litter materials). Half were laid flat on the ground (surface litter); the other half were laid upright and suspended 0.1 m above the ground to simulate the dead standing plant biomass (standing dead). Experiment II: Standing dead materials of *L. chinensis* and *S. grandis* were collected and divided into two parts; half were brought back to lab and stored in refrigerator at a low temperature (young litter), the rest were exposed to sun outside for 7 months (old litter).

Treatment implementation: (1) Sun treatment: 15 cm × 20 cm nylon net bags with a mesh size of 1 mm which passes 90% of UV radiation and photosynthetically active radiation (PAR). (2) Shade treatment: the same nylon net bags covered with two layers of black sunshade net which block 95% of UV radiation and PAR. (3) Sun+sterilization treatment: 12 cm × 17 cm solar-transparent polyethylene ziplock bags (0.08 mm, DengBi, Anhui) which passes 85% of UV radiation and PAR. (4) Shade+sterilization treatment: the same ziplock bags covered with two layers of black sunshade net. For sterilization treatment, before putting into ziplock bags, the air-dry decomposition materials entailed placing in an oven at 121℃ for 20 min (Day et al., 2015). These ziplock bags were changed regularly every two months to ensure their transmission and integrity during the experiment period.

Calculation method: where the X_0 is the initial litter mass, and X_t is the litter mass at a specific time t within the experimental duration. Litter nutrients remaining (carbon, nitrogen, hemicellulose, cellulose and lignin remaining) within a specific time-frame from 0 to t were also computed, where the C_0 and C_t respectively is the litter chemical content of at initial time point (t=0) and sampling time point (t), respectively. The formulae are:

$$Mass\ remaining = X_t / X_0 \times 100\%$$

$$Nutrients\ remaining = C_t / C_0 \times 100\%$$

$$Relative\ contribution\ to\ mass\ change_{microbial\ decomposition/abiotic\ photodegradation} = \frac{Mass\ remaining_{shade+sterilization} - Mass\ remaining_{shade/sun+sterilization}}{Mass\ remaining_{shade+sterilization} - Mass\ remaining_{sun}}$$

$$Relative\ contribution\ to\ mass\ change_{photoaccelerate} = 100 - relative\ contribution_{microbial\ decomposition} - relative\ contribution_{abiotic\ photodegradation}$$

Results

Experiment 1

Litter C loss and the contributions of different decomposition pathways

During 405-day decomposition, mass remaining gradually decreased with time (Fig. 1) and mass remaining under the four treatments were significantly different across from four kinds of decomposition materials. At the end of the experiment 1, the relative contribution of microbial decomposition, abiotic photodegradation and photoaccelerate to cumulative mass loss of *L. chinensis* and *S. grandis* surface litter is 64.4%, 18.9% and 16.7% respectively, and 51.6%, 21.5% and 26.9% respectively for their standing dead.

Litter chemistry

More N remained under the non-sterilization treatment than under the sterilization treatment. N remaining in the litter exposed to sun was usually more than that of litter under shade, while less N remained under the sun+sterilization treatment than under shade+sterilization (Fig. 2a~d). Without sterilization, N remaining in surface litter was higher than that of standing dead without enrichment process. By contrast, for both surface litter and standing dead, C remaining in litter exposed to sun was less than that of litter under shade (Fig. 2e~h).

Sunlight and sterilization treatments both significantly affected the amount of hemicellulose and lignin remaining for both *L. chinensis* and *S. grandis*, but did not significantly affect cellulose remaining (Fig. 2i~n). Only for *L. chinensis* did the litter state significantly effect lignin remaining. Sunlight significantly decreased the amount of hemicellulose and lignin remaining. Hemicellulose and cellulose remaining were slightly lower for non-sterilized surface litter, while the lignin remaining was higher.

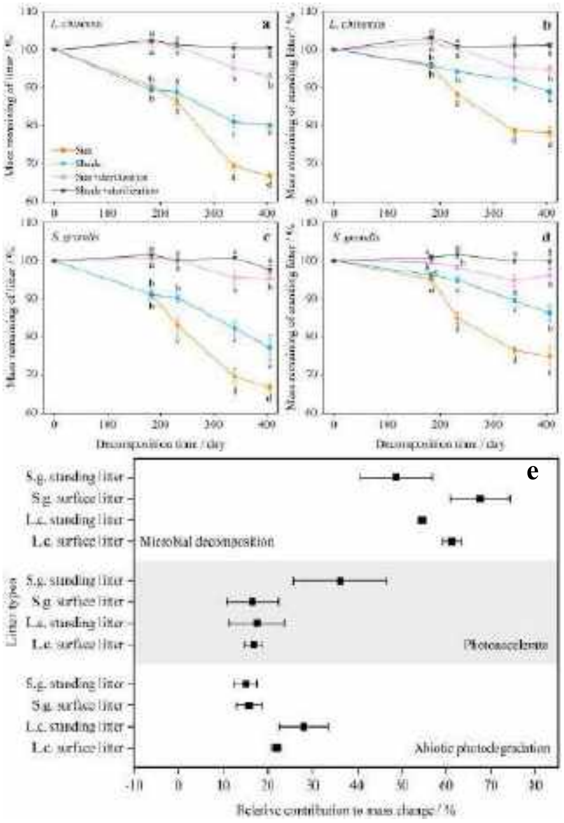

Figure 1 Mass remaining dynamics of litter at different treatment (a~d) and relative contribution of different decomposition pathway to mass change (e) over Experiment 1.

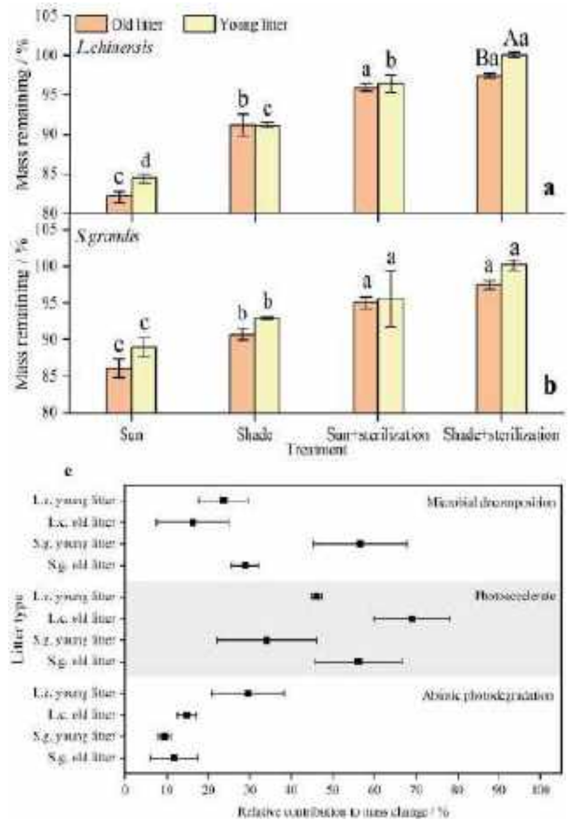

Figure 3 Mass remaining of litter at different treatment (a, b) and relative contribution of different decomposition pathway to mass change (c) over the experiment 2.

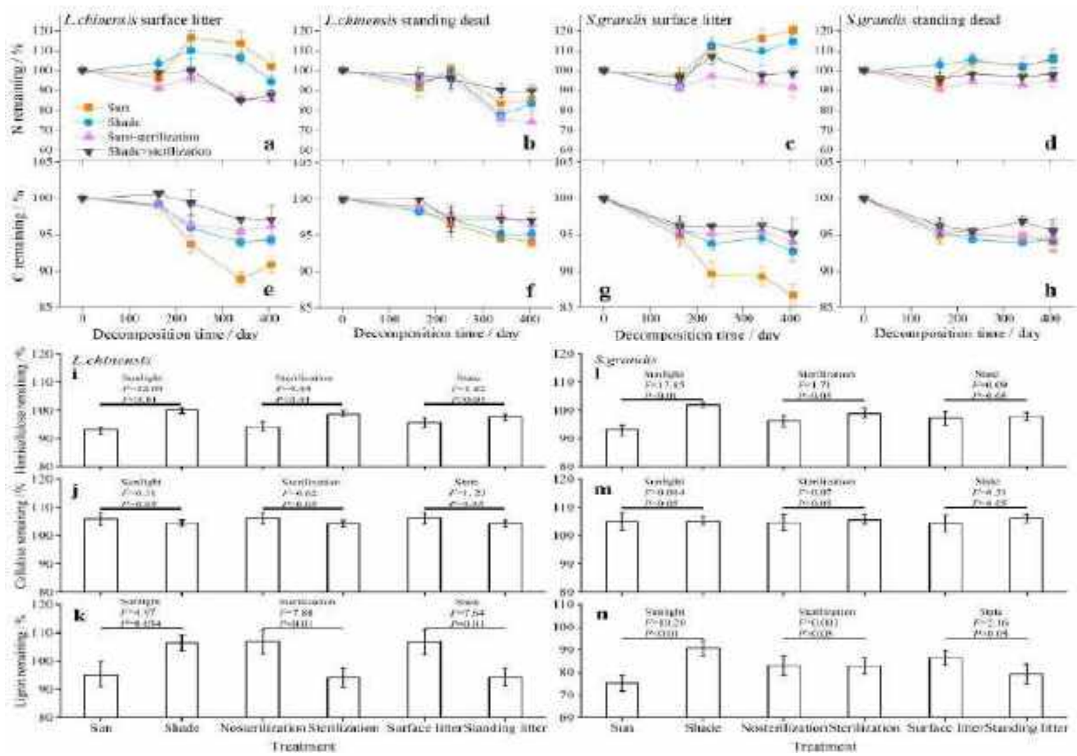

Figure 2 Dynamics of N and C remaining of different litters (*L. chinensis* surface litter (a, e), standing dead (b, f), *S. grandis* surface litter (c, g), standing dead (d, h) under all treatments, and effects of main treatment effect (sun or shade, nonsterilization or sterilization, surface litter or standing dead) on hemicellulose, cellulose and lignin remaining of *L. chinensis* (i, j, k) *and S. grandis* (l, m, n) over the Experiment 1.

Experiment 2

Litter mass remaining and the contributions of different decomposition pathways

The different treatments had significant impacts on both old and young litter. At sun treatment, mass remaining of old litter was lower than that of young litter. Moreover, for young litter, the relative contributions of microbial decomposition, photoacceleration and abiotic photodegradation were 40.1%, 40.0% and 19.5% respectively, while for old litter the relative contributions were 22.5%, 62.6% and 13.2% respectively (Fig. 3).

Discussion

Our results show that solar radiation significantly increased litter decomposition rate. This, solar radiation is a driver of litter decomposition in grassland ecosystem. Solar radiation enhances decomposition by more than 60% on average. However, the promotion effect varies between litter state types. Sunlight increases mass loss of surface litter and standing litter by 56.3% and 88.4% respectively. That means photodegadation promotes decomposition of standing litter more than surface litter. The different drivers of litter decomposition differ between litter state. photoacceleration and abiotic photodegradation have a greater effect on standing litter than on surface litter. Furthermore, there was more N remaining in surface litter, while standing litter has none, which limits microbial mineralization of carbon-based compounds. On the other hand, compared with young litter, old litter decomposed faster, perhaps because of its exposure to sun for 7 months (Angst et al. 2017). That suggests keeping litter standing and this subject to insolation will lead to faster decomposition when on the soil. Compared with the new litter, the microbial decomposition and abiotic photodegradation of the old litter is less, while photopromotion increases degradation.

Synthesizing two experiments, we conclude that the order of contribution of different decomposition pathway was: microbial decomposition (44.7%) > photoaccelerate (36.6%) > abiotic photodegradation (18.3%). No matter the litter types, microbial decomposition was always the leading pathway in the decomposition process, photoacceleration has a much larger impact photodegradation.

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Exploiting polyploidy in *Pennisetum Purpureum* to increase forage yield, feed value and tolerance to diseases

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Keywords: napiergrass, colchicine, induced mutation, polyploidy, genotype improvement

ABSTRACT

Napier grass (Pennisetum purpureum) is a key forage crop in Kenya. However, its yield and quality are often hindered by headsmut and stunt disease. Genetic improvement through mutation breeding, particularly using colchicine to induce polyploidy, offers a potential solution for improving Napier grass.The experiments were carried out as a factorial experiment in a complete random design (CRD). This study aimed to evaluate the response of embryogenic calli to different colchicine concentrations (0, 0.05, 0.1, and 0.2%) over 24, 48, and 72 hours duration to induce polyploidy in *South african* and *Bana* napier grass germplasms. The most suitable media for shoot regeneration was Murashige and Skoog (MS) medium supplemented with 0.2 mgL-1 Benzyl Adenine (BAP), 0.1mgL-1 dichlorophenoxyacetic acid (2, 4-D) and 0.1mgL-1 Indole-3-Butyric Acid (IBA) while media with 1mgL-1IBA, 1mgL-1 2, 4-D and 0.5mgL-1 BAP was more suitable in inducing embryogenic calli in all genotypes. Chromosome doubling was confirmed through chromosome counting and stomatal size, and number. Notably, we recommend use of flow cytometry to confirm ploidy level. Results showed that a 0.1% colchicine concentration with a 48-hour treatment was most effective for producing mutant plantlets, while higher concentrations were toxic. Significant genetic and agronomic variations were observed between the mutants and controls, indicating that the selected mutants are valuable genetic resources and recommended for characterization across representative agro-ecologies for large-scale production and used in *Penniseturm purpureum* breeding programs.

Introduction

Livestock plays a crucial role in food security, income, and employment, with global meat and milk demand expected to double by 2050(Herrero et al., 2013). In Kenya, smallholder farmers are key contributors to beef and dairy production, Napier grass (*Pennisetum purpureum*) is the primary livestock feed in Kenya, particularly in zero-grazing and semi-intensive systems (Muyekho et al., 2003; Lukuyu et al., 2011). However, continued contribution of napier grass to the livelihoods of the small-scale farmers is threatened by low growth vigor, low biomass and low feed value due to inferior germplasm (Jones et al., 2004).

Therefore, there is a need to enhance genetic diversity of pasture and forage to meet growing demand, and this is a key strategy for improving food crops resulting to enhanced plant performance (Ardabili and Zakaria, 2015). In light of the above background, this study aimed to investigate the response of embryogenic calli to different colchicine concentrations in inducing polyploidy for regeneration and selection of novel napier grass mutants.

Materials and methods

Experimental site and Plant materials

The experiment was conducted as a factorial with three factors: four levels of colchicine concentration (C0(0%), C1(0.05%), C3(0.2%) and C3(0.2%)), three levels of exposure period (T1 24, T2 48 and T3 72) and two napier grass germplasm (V1 *South africa* and V2 *Bana grass* resulting to 24 treatment combinations, that were replicated thrice using a factorial completely randomized design (CRD) resulting to 96 experimental unit. However, a pre-experiment needed to be conducted to carryout somatic embryogenesis to come up with explants to be used in the next stage of study which is colchicine treatment and acclimatization in the greenhouse. This pre-experiment was conducted as a factorial experiment in a completely randomized design(CRD) having three factors; 3 growth hormone for callus induction, 3 growth hormone for shoot regeneration and rooting and 2 germplasms of napier grass. This resulted to 18 treatment combination that were replicated six times. This resulted to 108 experimental units where the best explant that formed embryogenic calli were selected for the next stage of study. The following callus induction medium was used; GM0 as a comparative control in a hormone free media, GM1 (MS media supplemented with 0.3mg/L-1 BAP, 0.5mg/L-1 2,4-D and 0.5mg/L-1 IBA) and GM2 (MS media supplemented with 0.5mg/L-1 BAP, 1.0mg/L-1 2,4-D and 1.0mg/L-1 IBA). For Shoot regeneration, the following medium was used; SRM0 as a comparative control in a hormone free medium, SRM1 (MS media supplemented with 1mg/L-1 BAP, 0.25mg/L-1 2,4-D and 0.25mg/L-1 IBA and SRM2 (MS media supplemented with 2mg/L-1 BAP, 0.5mg/L-1 2,4-D and 0.5mg/L-1 IBA.

Embryogenic calli formation and shoot regeneration

Shoot tips from the two Napier grass genotypes were surface sterilized and prepared for tissue culture. Callus induction and shoot regeneration were achieved using Murashige and Skoog (MS) medium with specific plant growth hormones, while rooting involved transferring shoots to a medium supplemented with NAA, 2,4-D, and ascorbic acid.

Treatment with Colchicine

The impact of colchicine concentrations and treatment duration on explants survival and polyploidy induction was examined as a factorial experiment in a CRD with three replications. Explants were exposed to treatment after 134 days of culture by immersing them in filtered- sterilized colchicine solution for the designated times as stated earlier, then rinsed three times with sterile distilled water. Explants were then cultured on shoot regeneration media Ms supplemented with various concentrations of BAP (0, 1, 2 mg/L), 2, 4-D (0, 0.25, 0.05 mg/L), and IBA (0, 0.25, 0.05 mg/L). For rooting plantlets, elongated shoots were transferred to rooting medium as stated earlier.

Evaluation of induced mutants to determine ploidy level

Two months after transferring them to the greenhouse after treatment with colchicine, plants that regenerated were subjected to screening for confirmation of polyploid by measuring stomata number and size, chromosome counting and genomic DNA of mutant plants *viz* their progenitors.

Chromosome number by Karyotyping

Chromosome counting was done through karyotyping by treating leaf samples with 3% chromic acid, 20%formaldehyde, and 6% aceto-carmine, before observing them under a light microscope at X80 and X100 magnification

Stomata size and Number

Stomatal density and size were measured by applying nail polish on 35 day old leaves measuring $0.2cm^2$ and counting stomata under a microscope at X20 and X40 (Yu et at., 2009)

Phenotypic evaluations of induced mutants

Phenotypic evaluations of the induced mutants included weekly counting of tiller number and measuring plant height, and stem diameter, with stem diameter measured 10 cm from the base and height recorded from the ground to the highest point.

Results

Response of genotypes to tissue culture

The analysis revealed significant genotype effect on callus formation, necrosis, and embryogenic callus formation. After 4 weeks, all genotypes formed 97.5% calli, with no significant differences in germplasm, and no embryogenic callus formed. After week 7 and 8, The percentage of embryogenic callI after 8weeks was 68.9% and 66.2% on germplasm V1 and V2 on media with 1.0mgL-1 IBA, 1.0mgL-1 2,4-D and 0.5mgL-1 BAP while genotypes V1 and V2 on media with 0.5mgL-1 IBA, 0.5mgL-1 2,4-D and 0.3mgL-1 BAP formed 31.1% and 33.8% calli . Explants cultured on hormonal free media did not produce any sign of growth of callus or embryogenic callus, they were also 100% necrotic. V1 had the highest necrosis after 4 weeks 14.9% and 8 weeks 12.2% while V2 had the lowest case after 4 weeks 9% and 8 weeks 4% necrosis. (Table.1)

Table 1. Effects of different growth hormone combination on embryogenic calli induction.

Growth Media	Genotype	No.of Calli formed/% (4weeks)	No. of Necrosis formed/% (4weeks)	No. of embryogenic calli formed/% (4Weeks)	No. of embryogenic calli formed/% (8weeks)	No. of Necrosis formed/% (8weeks)
GM0	V1	0(0)	96(100)^a	0(0)	0(0)	0(0)
	V2	0(0)	74(100) ^{ab}	0(0)	0(0)	0(0)
GM1	V1	65(87.83)^c	11(14.86)^b	0(0)	25(33.783)^c	9(12.162)^a
	V2	63(85.13)^d	9(12.16)^d	0(0)	23(31.081)^d	4(5.405)^d
GM2	V1	68(91.89)^b	9(12.162)^d	0(0)	51(68.919)^a	6(8.108)^c
	V2	69(93.24)^a	10(13.514^c	0(0)	49(66.216)^{ab}	8(6.757)^b

Mean levels with ^{abcd} different numbers following each value within a column demonstrate significant differences by Tukeys Test ($p \leq 0.05$)

Shoot and Root regeneration
Growth of shoot was initiated after 134 days in most media, with regeneration significantly influenced by different hormone combinations. Hormone- free media resulted in no growth and 100% necrosis. The most effective media for shoot regeneration was Ms supplemented with 0.05mg/L IBA, 0.05mg/L 2,4-D, and 2mg/L BAP, achieved 43 and 40% shooting (Table 2). After 14 days, the putative mutants were transferred to the greenhouse, where rooting was successfully induced using MS medium with 1mg/L NAA and 150mg/L ascorbic acid (Table 2, Fig 1)

Table 2. Growth hormone combination effects on shoot induction derived from shoot tillers of two genotypes of *Penniseturm purpureum*

Growth Media	Genotype	No. of regenerated clumps (%)	No. of regenerated shoots (%)
SRM0	VI	0(0)^{ns}	0(0)^{ns}
	V2	0(0)^{ns}	0(0)^{ns}
SRM1	V1	16(21.6)^{c}	15(20.27)^{c}
	V2	14(19)^{d}	11(14.86)^{d}
SRM2	V1	37(50)^{a}	32(43.24)^{b}
	V2	32(43)^{b}	30(40.54)^{a}

Mean levels with ^{abc} different numbers following each value within a column demonstrate significant differences (p≤0.05). SRM0 is explants established in hormone free media. SRM1 is MS media supplemented with 1.0mg/L-1 BAP, 0.25MG/L-1 2,4-D and 0.25mg/L-1 IBA. SRM2 is MS media supplemented with 2.0mg/L-1 BAP, 1.0mg/L-1 2,4-D and 1.0mg/L-1 IBA

a b c d

Fig.1 Regeneration of two genotypes of penniseturm purpureum through somatic embryogenesis. a) Embryogenic callus in MS media supplemented with 0.5mg/L-1 BAP, 1.0MG/L-1 2,4-D and 1.0mg/L-1 IBA . b) Sprouting embryos in different growth stage in calli treated with colchicine. c) Shoot regeneration and root induction with MS medium supplemented with 0.05mgL-1 IBA, 0.05mgL-1 2,4-D and 2mgL-1 BAP and transferred to media supplemented with NAA 1mgL-1 and 150mgL-1 Ascorbic acidl. d) Regenerated synthetic induced mutants with their progenitors after being potted and transferred in the greenhouse

Effect of different colchicine concentrations on survival of explants and ploidy induction
Explants from two germplasm were treated with different colchicine concentrations on solid media. The percentage (%) survival rate differed depending on colchicine concentration, exposure duration and

temperature. Higher concentrations and longer exposure time led to severe toxicity and reduce callus survival, however, it increased octoploidy induction. The optimal condition for inducing polyploidy was 0.1% colchicine with a 48 hours exposure, resulting to 48% polyploidy. Putative mutants exhibited shorter height, increased tillering, and reduced stem diameter compared to their progenitors. Chromosome counting and stomata size and number confirmed successful polyploidy induction (Fig 2)

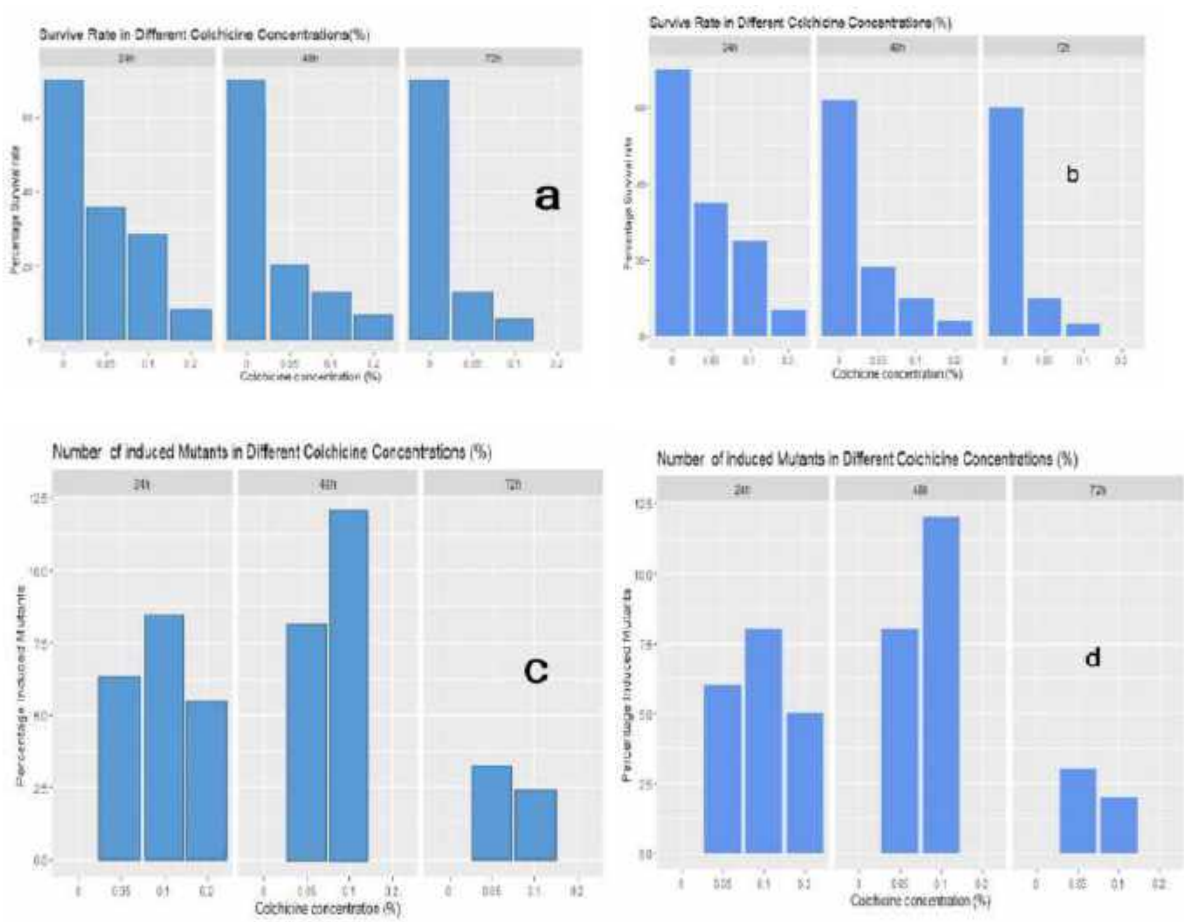

Fig 2 Different letters shows differences at ($p \leq 0.05$)
ns Non significance

(a) Colchicine concentrations; C0=0,C1=0.05, C2=0.1 and C2=0.2%
(b) Scores as 1-3 shows variation in survival rate after treatment where 1=5-25%, 2=26-45% and 3=46-70%

Score as abc shows variation in No. of induced mutant where a=2-5 %, b=6-8% and c=12%

Phenotypic effect on leaf characteristics

Induced mutants stomata size and number was significantly different from their progenitors. Mutants exhibited larger stomata with stomatal length of 20 or more (>120um) than their progenitors, however, they had lower stomatals density (Table 3, Fig 3). Similarly, analysis of variance detected high significance in tillering ability after 6 weeks of establishment in the greenhouse where induced mutants were the first to produce tillers but after 8 weeks, there was a high significance in number of tillers between induced mutants with their progenitors (Table 3,Fig. 4). Induced plants had slow growth rate as a result of chromosome abbreviation (deletion, duplication, inversion and translocation), physiological and toxic effect which presumably reduced cell survival (Table 3, Fig. 4). The mean stem diameter of synthetic induced mutants was slightly smaller compared to their progenitors (Table 3, Fig 4)

Table 3. Quantitative and qualitative characteristics in *Penniseturm purpureum* induced mutant's.

Germplasm	stomata number (per mm^2)	Stomata size (mm^2)	Plant height (cm)	No. of Tillers after 6 weeks	No. of Tillers after 8 weeks	Stem diameter after 8 weeks (cm)
C0T0V1	21^{a}	122.54^{c}	190.23^{a}	0^{c}	2^{cd}	5.2^{a}
C0T0V2	19^{ab}	120.65^{cd}	145.31^{c}	0^{c}	5^{b}	4.7^{ab}
C2T2V1	11^{c}	162.44^{a}	123.86^{d}	^{2ab}	3^{c}	4.6^{bc}
C3TIV2	12^{d}	158.45^{b}	170.18^{b}	3^{a}	6^{a}	4.5^{bc}

t-tests were performed between compiled mean from two control lines and those from synthetic induced mutants of each germplasm. Mean levels with ^{abcd} different letters following each value within a column shows significant differences (p≤0.05).

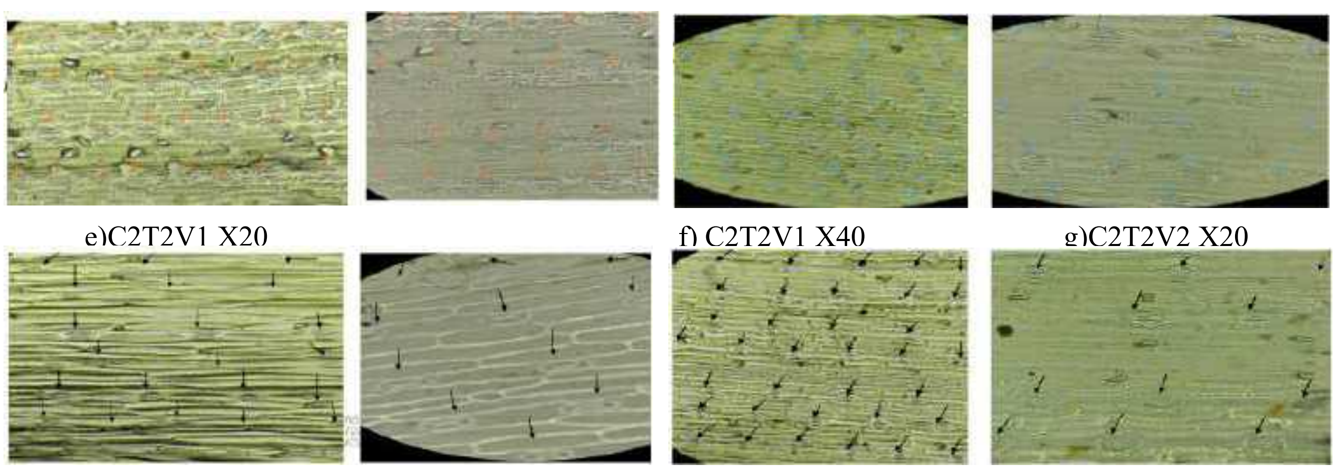

Fig 3 Difference in stomata size and number between synthetic induced mutant and their progenitors at x20 and x40 magnification. Blue and orange arrow points at progenitors stomata while Black arrow points at putative induced mutants.

Fig.6 Chromosome number of Penniseturm purpureum visualized under a light maicroscope at X100

(a) COTOV1 progenitor(2n=4x=28).
(b) C2T2V1 synthetic induced mutant (2n=8x=56
(c) COTOV2 progenitor (2n=4x=28)
(d) C2T2V2 synthetic induced mutant (2n=8x=56
    * Measurements of Some chromosomes number were diverse among counts, possibly due to overlaying chromosomes

Fig.4 Abnormalities shown by synthetic polyploidy after treatment with colchicine. A,B and C shows albino plants and leaf chlorosis abnormalities two weeks after treatment with 0.1% colchicine concentration and 48h duration, and 0.2% with 24h and 48h duration of exposure. E, F G and H shows abnormalities several weeks after establishment. E shows chromosome incompatibility that result to death of plants. F and D shows leaf chlorosis of new leaf whole that is dying off. G and H shows new leaf whole emerging with vigor immediately former dying off.

Discussion

This study reports the first successful creation of octoploids plants from selected tetraploid *Pennisetum purpureum* germplasms through in vitro polyploidy induction using colchicine.Two germplasms, *South africa* and *Bana grass*, were used to produce synthetic mutants. The process involved optimizing a tissue culture method where shoot tillers were cultured on Murashige and Skoog (MS) media with varying concentrations of plant growth hormones (Unami et al., 2012). The most effective media for inducing embryogenic calli and subsequent shoot regeneration was MS supplemented with low levels of BAP, IBA, and 2,4-D (Unami et al, 2012). The study also highlighted the challenges of colchicine use, such as toxicity at higher concentrations, which reduced calli survival and resulted in deformed plants. However, a concentration of 0.1% colchicine over two days proved optimal for inducing polyploidy (Mba et al., 2009) The study observed significant morphological and genetic changes in the induced mutants, such as increased stomatal size, decreased stomatal density, and variations in plant height, tillering, and chlorophyll expression (Queensenberry et al., 2010). These traits are crucial for selecting superior mutants for breeding programs.

In conclusion, this study successfully advanced napier grass breeding by regenerating polyploidy mutant plantlets through chromosome doubling and somatic embryogenesis, with confirmation of polyploidy via chromosome counting, stomata size and number, Genomic DNA and other morphological characteristics. However, flow cytometry is recommended for further ploidy level confirmation. The superior mutant plantlets can be selected and recommended for characterization across representative agro-ecologies for large-scale production and used in *Penniseturm purpureum* breeding program in Kenya and its environs.

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Seasonal variation in litter decomposition rates: a comparison of spring- and autumn-detached litter in a steppe grassland ecosystem

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Key words: carbon concentration; lignin; photodegradation; standing litter

Abstract

In grassland ecosystems, many plants gradually senesce in autumn, forming standing dead material (standing litter) that remains through the winter rather than immediately falling to the ground as litter. However, limited research has focused on the decomposition of standing litter during winter and its subsequent effects on decomposition after being shed in the following spring. We conducted a one-year experiment in the typical steppe of Inner Mongolia, China, to investigate the decomposition processes of litter from the dominant plant *Leymus chinensis* and *Stipa grandis* litter in autumn and spring. During the experiment, autumn-shed litter was placed directly on the soil surface, while spring-shed litter remained suspended above the soil surface for the first seven months of winter until it detached and fell to the ground. The results showed that throughout the study, the decomposition rate of spring-shed litter was consistently faster than that of autumn-shed litter. Notably, the lignin content in spring litter decreased significantly during the winter standing period, while no such change was observed in autumn litter. This suggests that photodegradation played a crucial role in lignin decomposition during the winter, facilitating the subsequent breakdown of plant litter. These findings highlight the significant differences in decomposition rates between litter shed in autumn and spring.

Introduction

Litter decomposition is crucial for nutrient cycling, soil fertility, and carbon dynamics, with decomposition rates largely determined by litter quality and microbial communities (Bradford et al. 2016). The state of plant material, whether standing dead or detached on the soil surface, significantly influences decomposition (Lin and King 2014). In grasslands, plants often retain dead material as standing dead for extended periods, exposing it to harsh environmental conditions that inhibit microbial activity (Wang et al. 2017). However, the role of the standing-dead phase in decomposition, especially processes like lignin photodegradation, remains underexplored. Understanding these dynamics is critical for comprehending nutrient cycling, particularly in grazed grasslands, where management practices influence the standing-dead phase.

Microorganisms in soil and vegetation are vital to litter decomposition, but those attached to litter often face drier conditions and greater temperature fluctuations, which reduce their activity and slow decomposition (Lin and King, 2014; Wang et al. 2017). In addition to microbial decomposition, abiotic processes such as leaching, physical fragmentation, and lignin photodegradation also play important roles (Rahman et al. 2013; Yanni et al. 2015). Solar radiation promotes photodegradation, making lignin more accessible to microbes for further decomposition (Lin et al. 2015; Austin et al. 2016). In sunlit areas, photodegradation dominates, while microbial decomposition is more significant in shaded regions (Lin and King 2014). For example, in semi-arid grasslands and alpine meadows, suspended litter decomposes faster than litter on the soil surface (Wang et al. 2021; Lin and King 2014). Although photodegradation is not the only factor, its contribution to litter decomposition is significant.

The natural grasslands of northern China, covering 2.82 million square kilometers, play a crucial role in supporting pastoral activities and maintaining ecological stability (Li et al. 2019). These grasslands are predominantly dominated by species like *Leymus chinensis* and *Stipa grandis*, which have tall, erect stems that persist long after senescence in autumn (Giese et al. 2009; Peng et al. 2014). The region's land use practices include grazing, mowing, and fencing, with grazing, especially rotational and continuous grazing, being the most common management strategy (Li 1989; Baoyin et al. 2014; Zhang et al. 2020). During the non-growing season, grazing and trampling accelerate litter accumulation and shorten the standing-dead phase (Mor-Mussery et al. 2021). Consequently, in grazed grasslands, dead plants bypass the standing-dead phase and fall directly to the soil surface. In contrast, ungrazed grasslands may see dead plants remain standing through the winter and fall in the spring or summer when grazed. This highlights the significant role of trampling in litter decomposition, as it accelerates litter burial and promotes the formation of a soil-litter interface (Liu et al. 2018; Wei et al. 2021).

To explore the effects of the standing-dead phase on litter decomposition, we conducted a one-year experiment in central Inner Mongolia, comparing the decomposition of litter from *Leymus chinensis* and *Stipa grandis* shed in autumn and spring. We hypothesized that: (1) plant residues that undergo the standing-dead phase decompose more slowly during this period than those that fall directly to the soil surface after senescence; and (2) residues that experience the standing-dead phase, due to changes in lignin content, are more readily degradable and decompose more rapidly than fresh litter.

Methods

The study was conducted at the Grassland Ecosystem Research Station of Inner Mongolia University, located 60 km northeast of Xilinhot, Inner Mongolia, China (116°31′E, 44°15′N, elevation 1146 m). The region has a temperate semi-arid climate, with an average annual temperature of 2.8°C and precipitation ranging from 280 to 350 mm, mostly occurring from May to September. The native steppe is dominated by *L. chinensis* and *S.* grandis.

The experiment was conducted in a 50 m × 50 m grassland plot, which had been used for grazing but had remained ungrazed for six years prior to the study in 2018. In November 2017, we collected senescent leaves and stems from two dominant grass species, *L. chinensis* and *S. grandis*. The collected litter was air-dried at room temperature, then portioned into 10 g samples and placed in nylon mesh bags (15 cm × 20 cm, with a 1 mm mesh size). The bags were divided into two groups to simulate the decomposition processes of autumn and spring litter. The first group, termed "surface litter" consisted of material placed directly on the soil surface, representing the decomposition of autumn litter. The second group, referred to as "standing litter," was initially suspended 0.1 meters above the ground for seven months over the winter before being placed on the soil surface to simulate the spring decomposition process, following the standing-dead phase. Litter samples were collected at the 7th and 12th months of decomposition. This study involved placing both autumn and spring litter from all species in five replicates, using a fully random design. This resulted in a total of 40 litterbags, calculated as: 2 plant species (*L. chinensis* and *S. grandis*) × 2 litter types (autumn *vs.* spring) × 2 sampling points（7months and 12 months） × 5 replicates. The concentrations of nitrogen (N%) were quantified using an elemental analyzer (Vario MACRO cube, Elementar, Germany). Neutral detergent fiber content (NDF%) and acid detergent fiber content (ADF%) were measured using an ANKOM 2000 Automated Fiber Analyzer (A2000i, Fiber Analyzer, American). The digestion of acid detergent lignin (ADL%) in 72% H_2SO_4 solution, obtained by the lignin sulfate method, was used to analyze the lignin content of ADF fractions (Trofymow et al. 2002).

Results

Changes in plant litter mass

For both species (*L. chinensis* and *S. grandis*), the mass of both spring and autumn litter decreased significantly during decomposition. In the first 7 months, the remaining mass of spring litter from *L. chinensis* was significantly higher than that of autumn litter (P<0.05), while no significant difference was observed between spring and autumn litter for *S. grandis* (P>0.05). By the 12th month, the remaining mass of spring litter from *L. chinensis* was significantly lower than that of autumn litter, while no significant difference was observed between the spring and autumn litter of *S. grandis* (P>0.05).

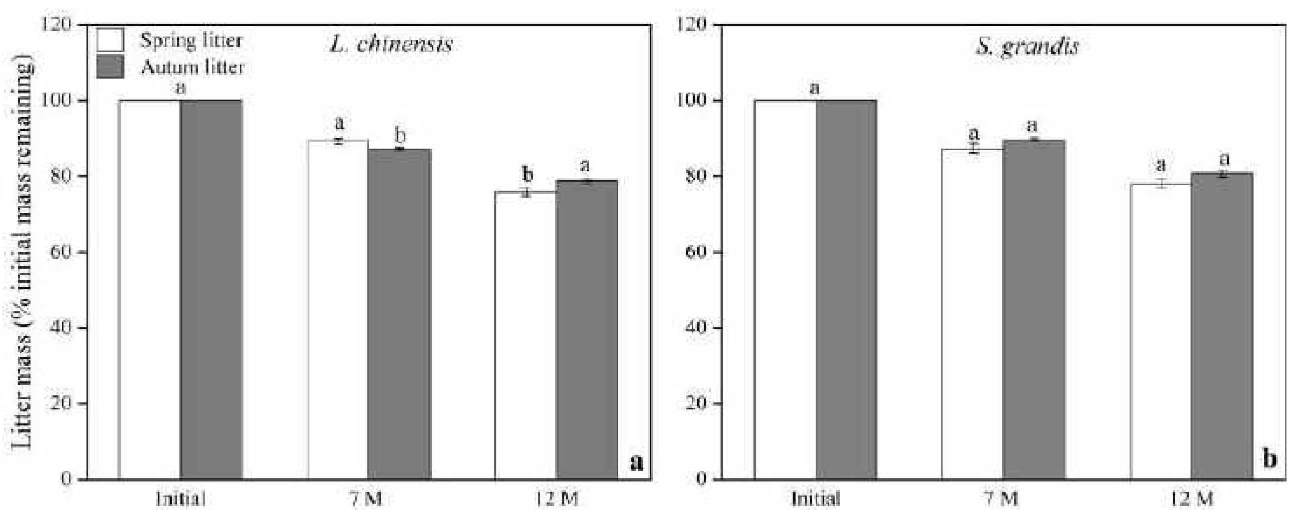

Fig. 1. Remaining litter mass (RM) of *L. chinensis* (a) and *S. grandis* (b) over the one-year experimental period. Bars represent means, and error bars indicate standard error. The spring litter was suspended as standing dead for the first 7 months (winter) under ambient conditions (7M) before being placed on the soil surface for the remainder of the one-year period, whereas the autumn litter was directly placed on the soil surface for the entire decomposition period. Different lowercase letters indicate significant differences between spring and autumn litter within the same period at P < 0.05.

Changes in litter quality

In the first 7 months, nitrogen content in spring litter of *L. chinensis* and *S. grandis* significantly decreased (P<0.05), while nitrogen content in autumn litter showed an increasing trend. After one year of decomposition, nitrogen content in all litter types significantly increased (P<0.05) (Table 1). Meanwhile, hemicellulose and cellulose contents in both spring and autumn litter continuously declined over the course of decomposition. Additionally, during the first 7 months of the standing-dead phase and the subsequent surface litter phase, lignin content in spring litter of both *L. chinensis* and *S. grandi*s significantly decreased (P<0.05). In contrast, lignin content in autumn litter of *L. chinensis* significantly increased throughout the decomposition period. After one year of decomposition, lignin content in spring litter was significantly lower than that in autumn litter (P<0.05) (Table 1).

Discussion [Conclusions/Implications]

The decomposition rate of litter varies significantly across different ecosystems, influenced by litter quality, decomposer communities, and environmental conditions (Bradford et al. 2016). Numerous studies have highlighted the impact of lignin content on the decomposition rate of litter (Liao et al. 2022). Our results show a significant positive correlation between litter decomposition rates and the contents of hemicellulose, cellulose, and lignin, which is consistent with previous studies (Duan et al. 2018; Wang et al. 2022).

Table 1 Nitrogen (N) content, hemicellulose, cellulose, and lignin content in initial litter (Initial) and subsequent treatments of *L. chinensis* and *S. grandis*. Values are means ± standard error. Different letters within a row indicate significant differences (P < 0.05).

	L. chinensis		*S. grandis*	
	Spring	Autumn	Spring	Autumn
N				
Initial	1.16	1.16	1.05	1.05
7 M	1.00±0.40b	1.17±0.42a	0.72±0.03b	1.19±0.01a
12 M	1.32±0.04a	1.16±0.04b	1.00±0.05b	1.23±0.04a
Hemicellulose				
Initial	31.48	31.48	33.7	33.7
7 M	34.68±0.29a	29.05±0.33b	32.63±0.56a	29.67±0.49b
12 M	28.22±1.54a	27.46±0.88a	31.83±0.67a	28.68±0.53b
Cellulose				
Initial	30.15	30.15	28.62	28.62
7 M	29.42±0.21a	27.00±0.89b	24.61±0.80b	30.61±0.48a
12 M	25.59±0.83a	22.63±0.45b	26.9±0.79b	29.08±1.76a
Lignin				
Initial	7.64	7.64	8.00	8.00
7 M	5.26±0.17b	8.44±0.37a	7.61±0.31a	7.18±0.21a
12 M	4.77±0.18b	8.46±0.22a	5.13±0.29b	7.41±0.55a

Relationships of litter decomposition rate with litter quality

The remaining mass of litter showed significantly positively correlated with the contents of hemicellulose, cellulose and lignin (P<0.05), but it was no significant correlation with nitrogen content (P>0.05) (Fig. 2).

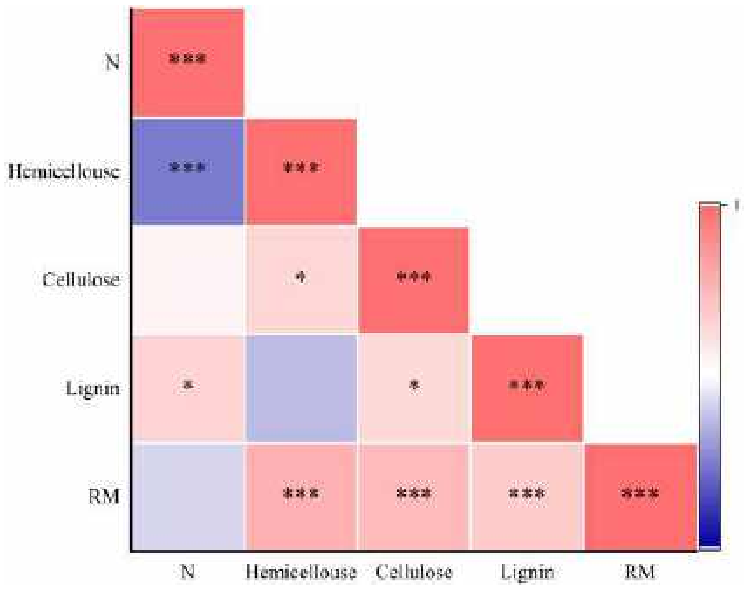

Fig. 2. Heatmap of the correlation between litter mass remaining and litter quality

In addition to soil microbial communities, solar radiation also plays a significant role in litter decomposition (Wang et al. 2021; Jiang et al. 2022). We found that after 7 months of exposure, spring litter experienced greater mass loss than autumn litter, both at the 12th and 17th months. This indicates that spring litter, having undergone the standing-dead phase, decomposed faster than autumn litter, which had not. This result is in line with previous studies, which suggest that the retention of standing-dead biomass promotes subsequent decomposition in the soil surface (Day et al. 2015; Angst et al. 2017). Moreover, after 7 months of winter exposure to sunlight, spring litter decomposed more rapidly than autumn litter, likely due to photodegradation. Lignin, a key component of plant cell walls, is difficult to biodegrade (Huang et al. 2022), but it is highly susceptible to photodegradation when exposed to UV and blue-green light, promoting subsequent microbial decomposition (King et al. 2012; Austin et al. 2016). Our data show that after 7 months of exposure, the lignin concentration in spring litter decreased, whereas in autumn litter, lignin concentration increased. A similar trend was observed in the decomposition of *S. grandis* litter. This suggests that the significant breakdown of lignin enhances microbial decomposition, leading to a faster decomposition rate in spring litter than in autumn litter.

Our study suggests that the enhanced photodegradation of refractory structures in standing litter, compared to that in litter lying on the ground, likely explains why the standing-dead phase contributes to overall faster decomposition. Our findings highlight the importance of considering litter status (standing dead or lying on the soil surface) and factors like grazing that alter this status when modelling or calculating litter decomposition in semi-arid grassland ecosystems.

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Grazing and ecohydration for ecological health

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Restoration techniques of rangelands in the hyper-arid area of central Saudi Arabia

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Key words: Reintroduction; assisted regeneration; rainwater harvesting; tilling

Abstract
Restoration efforts are influenced by previous human use and management actions which have contributed to different levels of habitat degradation and biodiversity loss. We discuss the monitoring and evaluation of restoration activities tailored to study sites in two adjacent Royal Reserves located in the hyper-arid desert area of central Saudi Arabia. One reserve has been fenced for over 40 years with limited public use. The other was open to life stock grazing until recently and has over one million visitors each year in the winter. Ecological assessments in both reserves identified the extent and scale of degradation which informed restoration priorities. Planned restoration techniques were based on nature-based solutions suitable for these areas. In the more ecological intact reserve, restoring the ecological dynamics was the main focus through the reintroduction of native grazers, i.e. gazelles and oryx. Restoration activities of native flora included rainwater harvesting on an experimental scale. In the open reserve, restoration primarily focuses on restoring the floristic composition. Here we implemented a pilot study to assess if tilling the compacted top crust facilitated germination and establishment of plants. Monitoring the impacts of restoration efforts is crucial to be able to evaluate if targets are met. We implemented various monitoring techniques to assess changes in vegetation structure and composition, and spatial abundance and presence of newborns of reintroduced animals. Results were used to evaluate if reintroduced animals established themselves and if assisted regeneration led to the germination and growth of plants in the pilot studies. This paper highlights the preliminary empirical assessments of these different restoration techniques for rangelands in hyper-arid areas.

Introduction
In the current Anthropocene era, unsustainable use, habitat destruction, introduction of invasive species and overexploitation has led to the alarming loss of biodiversity and reduced ecosystem services (Díaz et al., 2019). Safeguarding habitats is one of the most effective conservation strategies for combatting this biodiversity crisis and desertification (Barth, 1999). Typically, habitat restoration efforts focus on the re-establishment of plant communities. Restoration efforts should, however, integrate the restoration of both key plant and animal groups, especially those animals that change habitat directly, such as herbivores, and

indirectly, such as carnivores (Suraci et al., 2016). Re-establishing plant-animal interaction and trophic complexity is crucial to achieving all the ecosystem services nature provides, including nutrient cycling, soil formation, pollination, and seed dispersal that rely on the plant-animal dynamics.

Hyper-arid, arid, and semi-arid lands form about one third of the Earth's terrestrial surface. These lands contain unique biological and cultural diversity, and biodiversity loss can have a disproportionate impact on these ecosystems due to low redundancy and a high risk of trophic cascades (Zhang et al., 2023). The Kingdom of Saudi Arabia hosts 32.5% of the global hyper-arid areas and hence plays a significant role in the conservation of biodiversity in these ecosystems (Keith et al., 2022). In recent years, contributing to global commitments, large areas have been established as protected areas in Saudi Arabia with the aim to have 30% of its terrestrial area protected by 2030. Two adjacent protected areas established in 2018 are the King Khalid Royal Reserve (KKRR) and the Imam Abdulaziz bin Mohammed Royal Reserve (IARR). They are located in central Saudi Arabia, and the area is characterised by low rainfall, high diurnal and seasonal fluctuating temperatures with predominantly sandy, gravelly soil and low levels of nutrients. Rangeland vegetations consist of slow growing perennials and ephemeral plants with long-lived soil seed banks. Understanding the full complexity and integrity of the ecosystem as well as the sources of degradation (prior land use) and implemented restoration practices will enhance the success of habitat restoration efforts (Atkinson et al., 2022). An ecological assessment using the Recovery Wheel and a 5-star scale assessment approach (Mcdonald et al., 2016), is a widely used tool and was implemented in each reserve to assess the integrity of the ecosystem and to prioritize restoration efforts (IARDA internal report).

In this study, we highlight different restoration strategies in the two reserves. In KKRR we discuss the reintroducing of key herbivores and in both reserves we conducted a pilot study to increase the native plant community through assisted regeneration (McDonald et al., 2019). Specifically, in KKRR we assessed if the reintroduced ungulates remained close to the release site and if they produced offspring, two indicators for establishment success. Additionally, we assessed if rainwater harvesting pits increased the germination of annuals from the seed bank. In IARR, we assessed if tilling the compacted top crust resulted in the initial growth of annuals and the subsequent establishment of perennials.

Methods

The study areas are within KKRR and IARR, approximately 100 km northeast of Riyadh. KKRR is 1,160 km^2 and has four main habitats, the pediplain, plateau, wadi (valley) and catchment. The pediplain is about 250 km^2 and contains numerous catchment areas. It is bordered by the escarpment of the Urumah Mountain plateau to the east and at all other sides by roads and has been fenced for over 40 years. This area was used to reintroduce 242 native ungulates between 2021 and December 2024. The rainwater harvesting (RWH) pilot study of 4.35 ha was also located in this pediplain, on a slightly sloping surface at the foothills of the escarpment with pits of ~ 1 x 1.5 m and 10-15 cm deep. IARR is 11,300 km^2 and has six main habitats, the pediplain, plateau, wadi, catchment, sand plain, and sand dune. This reserve harbours 13 catchment areas with Rawdhat Khuraym being the largest with eight main wadis draining into it and is a very popular destination for people in the winter. Adjacent to Rawdhat Khuraym, was the experimental tilling area of 680 ha.

In total nine Arabian oryx, one sand gazelle and two Arabian gazelles were deployed with satellite-based GPS collars to assess site fidelity. The collars were programmed to drop off after one year. Camera traps were positioned at 53 locations in the pediplain next to water sources, burrows, and on wildlife trails to estimate newborn animals and relative occupancy. Relative occupancy was calculated as the number of locations with species-specific observations divided by the total number of camera locations. Since water is a limiting resource, locations next to water sources likely attract animals and are therefore not representative of capture rates and were excluded from the relative occupancy calculations. Newborn individuals were identified by the distinctive brown collar for oryx and absence of horns for gazelles. The monthly maximum number of newborns at each location was recorded.

The succession of plants in the RWH pits was monitored by recording the percentage cover and species abundance every two months at 60 randomly selected pits and adjacent control sites from November 2023 to July 2024. For the tilling experiment in IARR, we collected data using the line-intercept method along a 100-m transect placed in the furrows at five sample sites in each of the three experimental plots (tilling to 5, 10 and 15 cm in plot A, B, and C resp.) and three sample sites in a nearby control plot. The first transect location was randomly selected as being the 10th furrow from the eastern edge. The following four sample sites were approximately five furrows to the west. All germinated plants were recorded under and to 10 cm left and right of the transect line from January 2023 to June 2024. Observed species in both pilot studies were classified to the highest taxon possible and into their life span as annual or perennial.

Results

Establishment of reintroduced ungulates in KKRR

Based on the GPS data from the collars, the three gazelles predominantly stayed in the catchment areas of approximately 60 km^2 close to the release site with the one sand gazelle travelling a maximum distance of 10 km and the male Arabian gazelle moving in and out of KKRR to the adjacent IARR but staying within a few km from the border of KKRR. Of the nine tracked Arabian oryx, four individuals climbed up the escarpment and left KKRR, they followed the wadi into IARR, three of them died in IARR. Three other individuals also climbed up the escarpment but stayed in the wadis on the plateau of KKRR, and one died. The other two individuals predominantly stayed within 50 km^2 along the escarpment just north of the release site (Fig 1).

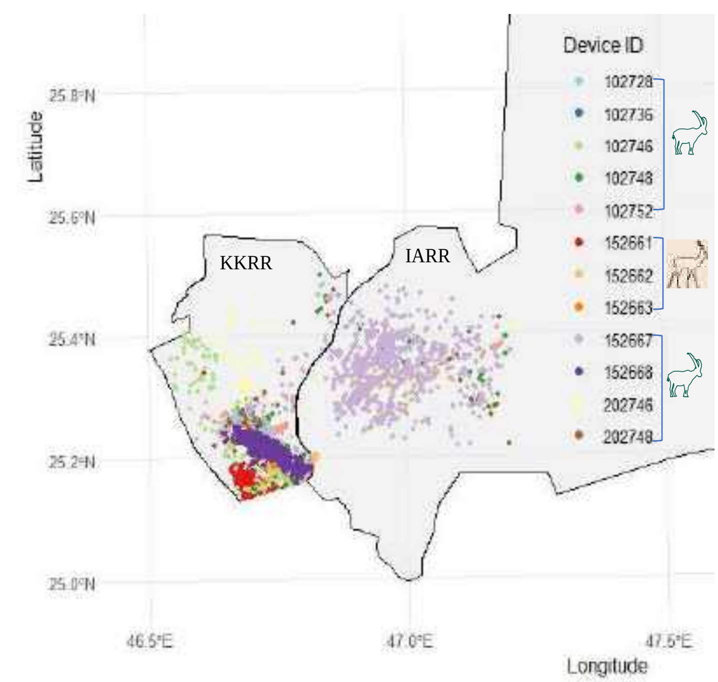

Figure 1. Movement patterns derived from GPS data of 12 tracked individuals for one year. Device ID 15661 is a sand gazelle, 152662 and 15663 is Arabian gazelle and the other nine are Arabian oryx.

Spatial occupancy data from the camera trap data showed that oryx and sand gazelles roamed widely but the Arabian gazelle was most restricted in its relative occupancy (Table 1). Camera trap data showed newborns of all species.

Table 1. Relative occupancy (rel. occ.) and demographics per species for the period 2021-2024

Characteristic	Arabian oryx	Sand gazelle	Arabian gazelle
Reintroduced	45	120	11
No of cameras with observations (rel, occ.)	19 (56%)	17 (50%)	3 (9%)
No of newborn	9-14	40-48	1
No of mortalities	4	11	5*

*4 assumed, 1 confirmed

Rainwater harvesting in KKRR

Creating a shallow pit to collect rainwater had a positive effect on the germination of predominantly annuals (Fig. 2). The mean cover of plants increased from approximately 3% at the start of the experiment in November 2023 to 21% in the following four months, then slightly decreased to 19% in May and then decreased sharply to 6% in July when most remaining plants were dry. The control area never showed more than 1% cover. The abundance had a slightly different pattern as it steeply increased from 5 plants to 40.6 plants in January but only 8% were perennials. Afterwards, abundance steadily decreased to 32.4 plants in March, 17.0 in May, and finally dropped to 4.5 in July of which 100% were perennials predominantly *Zygophyllum indicum*.

Figure 2. Succession of plants in the rainwater harvesting pits

Tilling in IARR

Tilling the top crust led to germination and growth of various species of plants including perennial plants. The number of unique species recorded was 39, about three times higher compared to the control with just 12 species. The great majority of the observed species (84%) were herbaceous plants, 10% were shrubs and 6% grasses. No seedlings of trees were observed. The vegetation was dominated by annual plants of which *Malva neglecta* was most represented both in abundance and cover (Fig. 3). The perennial shrub *Zilla spinosa* was the second most represented. Tilling to a depth of 15 cm (plot C) resulted in the highest cover and abundance. The species *Erucaria hispanica* and *Zilla spinosa* were responsible for the high cover in May. Both species were still present in June but had partially died off in plot B resulting in the subsequent decline in cover. However, in plot C they did establish and flourished to at least double their cover in June (Fig.2). A year later, the same trend in cover is still present with C having the highest cover and abundance, but the composition has changed to only perennials in all plots.

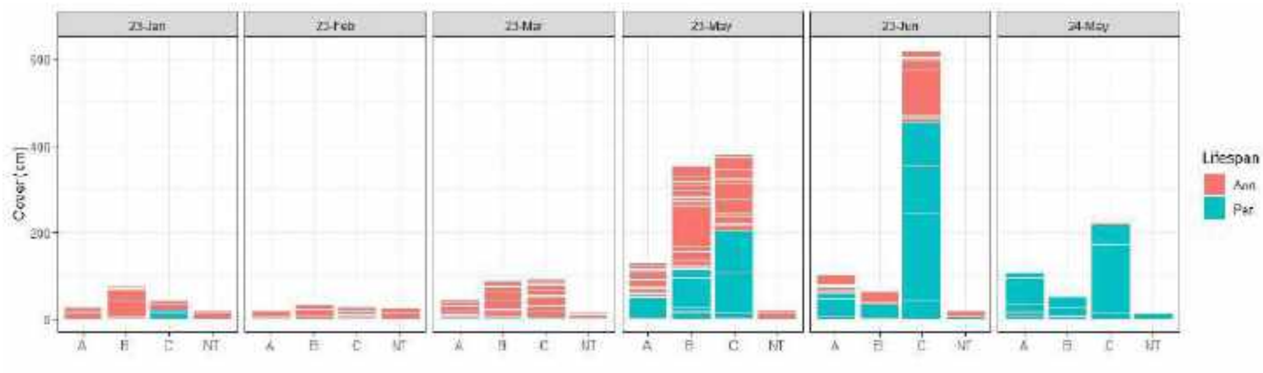

Figure 3. Trend in vegetation cover by lifespan and per treated plot (NT=No Treatment and is the control area)

Discussion

Monitoring and evaluation are essential to determine whether restoration projects are successful so that we achieve the intended benefits (Otiendo, 2019). These assessments also help to ensure that project and program resources are used efficiently and effectively. Using complementary monitoring techniques can provide a more comprehensive evaluation as the GPS tracking devices in combination with the camera traps demonstrated for the assessment of indicators of establishment of reintroduced animals in this study. The data showed newborn of all reintroduced species indicating that KKRR can sustain pregnancies. Additionally, results showed the high site fidelity of gazelles but less so for oryx as they did move out of the pediplain. These roaming oryxes either established them on the plateau of KKRR or followed the wadi to the adjacent IARR, underscoring the importance of safe wildlife corridors between the reserves. This roaming behaviour could indicate that space was a limiting factor in retaining animals at release sites since food resources were plentiful (IARDA Carrying Capacity internal report). With the many reintroduction programs currently on-going in the Kingdom of Saudi Arabia (Alatawi, 2022), we believe these results can inform other programs of the benefits of monitoring using different techniques to evaluate success.

Natural generation is a preferred restoration method as it mimics nature and leads to a sustainable establishment of plants following the natural succession processes after external threats (grazing, logging, off-roading) are removed. However, natural generation is only possible when the ecosystem is intact and fully functional. In our study sites, assisted regeneration was implemented and monitored for 6 months to 1 year. Both pilot studies showed rapid germination of annuals after rainfall with the establishment of some perennials indicating the presence of viable seeds in the seedbank and the outset of restoring native vegetation. Other factors could also have contributed to this success, such as the closeness to surrounding vegetation and topography. Also, the rougher surface that resulted from the tilling and the creation of shallow pits could have trapped more windblown seeds which could explain the higher germination in both pilot studies. Conducting pilot studies to evaluate the appropriateness of the used technique is an important step before implementing it on a large scale.

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Ecological regeneration in a low rainfall environment using long-rest grazing management

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Key words: Drought; resilience; sustainability

Abstract
In 2020, after 3 years of severe drought which heavily impacted the productivity of Buckleboo Station, we commissioned the design of a detailed 5-year Ecologically Sustainable Rangelands Management (ESRM) Environment Plan.

Buckleboo Station has fast-tracked the ESRM Environment Plan, with the added benefits of producing more lamb in a shorter timeframe and championing innovative and industry-leading regenerative grazing practices. The station has changed from set stocking to long-rest grazing. The dorper ewes are now running in one mob. The station is sub-divided into 6 grazing areas of approximately 40,000 acres, each area being grazed for 3 months followed by 15 months complete rest. Every watering point has a trap yard around it. More watering points are being prepared to ensure even grazing of each area.

Badly degraded and scalded country has been treated with a crocodile seeder, to divot the surface, aiming to slow down the flow of water and re-hydrate the soil. These areas will be closely monitored to determine if the native grasses return.

New technology has been adopted for key project outcomes: Ceres satellite tags for livestock movement monitoring, NDVI satellite monitoring, satellite monitoring of water storage tanks, and soil probes to measure moisture available to plants in a range of different soil types. Twelve monitoring sites are being constructed across the station to monitor the changes in vegetation.

In October 2021, the Emissions Reduction Fund (ERF) approved a large carbon project (over a million tonnes of carbon sequestered) for Buckleboo Station. This project is managed by Australian Integrated Carbon. More fencing will be constructed in the future to control the grazing of livestock. Our key action is managing the carbon project with long-rest grazing and not destocking the carbon project areas.

Introduction
Buckleboo Station endured a severe three-year drought 2018 – 2020, that heavily impacted the station's ability to efficiently and sustainably produce dorper lambs. In early 2019, management decided to urgently

address these issues by improving long term sustainability through regenerative grazing, improved water management, improved monitoring and drought resilience activities. Buckleboo Station commissioned the design of a detailed 5-year Ecologically Sustainable Rangelands Management (ESRM) Environment Plan through Contour Environmental and Agricultural Consulting. The Buckleboo Station ESRM Environment Plan is based on the ESRM project tool that follows the principles of regenerative grazing to maximise the restoration of biodiversity, water and nutrient cycling and energy efficiency within the local ecosystem. The ESRM methodology was selected for the following reasons:

• Involvement of a rangeland ecologist to build a better understanding of how different actions would impact the environment.

• The process aligns the goals for the property and the business with the capability of the land.

• Proven track record of success in Western Australia with pastoralists and mining companies.

In 2020, Buckleboo Station engaged the services of Contour Consulting to prepare a detailed ESRM Environment Plan in conjunction with the existing business plan. This is a new way of planning as far as the pastoral industry is concerned. Contour Consulting has used satellite imagery and GPS mapping to locate key problem areas across the station and develop strategies to address them. Additionally, as part of the initial commencement of the ESRM Environment Plan, we used an innovative mapping process to locate deep underground water using electromagnetic data sets. The concept of long-rest grazing on a pastoral property is quite innovative in South Australia.

Sustainability improvements on Buckleboo will be achieved through activities that will:

• Increase ground cover from 20% to 70%. Ground cover of 70% will reduce water and wind erosion to almost nil. The increased ground cover also has significant production advantages due to increased water infiltration, good microbial activity, improved soil structure and buffering from extreme temperatures. We anticipate that it will take several years to reach such levels of groundcover in an arid environment.

• Regenerate the grasslands which have been badly degraded due to overstocking and under grazing by sheep and kangaroos. These grasslands are essential in the dietary mix for our sheep so once the higher quality and more palatable native grasses return this will provide better quality feed. Sheep require the correct amount of protein and energy in their diet to maximise production. The chenopod shrubland is very high in protein and the grasses provide the energy component. Historically the grasses have been overgrazed leaving an imbalance in the diet which has caused low production.

• Re-generate the Chenopod shrublands. The rest period (approx. 15 months) will allow these bushes to re-foliate and recover much more quickly. The areas around watering points require close monitoring as they have been badly affected due to the long-term effects of heavy grazing pressure. It is important to keep the chenopod shrublands healthy as these plants are a tremendous feed reserve through dry times and also help protect the landscape from wind erosion in dry periods.

• Introduce and install more watering points so that a much larger area of land can be grazed, allowing the flock to grow by a predicted 60%, and ensuring the grazing areas will be grazed more evenly.

• Provide opportunities for Carbon Farming. Vegetation assists the retention or accumulation of soil carbon. There is significant interest in the potential for soil carbon projects across the Australian rangelands. While sequestration rates are generally low, there is a large area available, providing the opportunity for substantial abatement. Unfortunately, at this time, the significant cost of establishing projects, undertaking the required soil sampling at a suitable scale and monitoring project delivery and change require further developments before a methodology can be adopted in pastoral or rangeland areas. We will be in a good position to immediately apply this methodology once it has been established.

Methods

The ESRM process works closely with pastoralists to develop an ecologically sustainable, profitable and respected pastoral community. It enables land lessees to receive support to develop whole of property plans that include mechanisms for reporting on rangeland condition, implementing rehabilitation works, managing threats, and coordinating landscape and catchment approaches to maintain and improve vegetation cover. ESRM planning at Buckleboo Station incorporated grazing and fire management with erosion mapping and erosion control works to improve the rangeland condition of the property. A desktop analysis of Buckleboo was carried out using data from the South Australian Government, Australian Government, Trove and the Rainman Streamflow software package. Available information was used to undertake a preliminary landscape function assessment, characterise the flora, fauna and vegetation present, and to understand the context of management history and previous work carried out on Buckleboo and in the surrounding area. Maps of infrastructure, land systems and satellite imagery were prepared for use in discussions during a station visit which occurred between the 24th – 27th October 2020. It was attended by James Kerr and James Wright (Paroo Pastoral) and facilitated by Richard Marver (Contour Consulting). During the visit, detailed discussions around the prepared maps provided the framework for the infrastructure development plan. A preliminary assessment of the condition of Buckleboo Station and areas of interest was made based on discussions with the property owner. Participants were asked to identify these areas on a map, and to document their own knowledge and observations regarding the environmental condition of the station. Targeted on-ground and aerial surveys (using an Unmanned Aerial Vehicle or drone) of areas of interest and proposed areas of infrastructure development were then conducted.

The proposed grazing strategy for Buckleboo is to have six secure paddocks with reliable (12 month) water supply that encompass the entire station area. To achieve this, dams will be supplemented with tanks and troughs supplied by several bores and a pipeline. The paddocks are created by subdividing the current infrastructure to create paddocks that encompass similar land types. The paddocks will be grazed under a rest-based system giving each paddock approximately 3 months grazing with 15 months rest. A more intensive rotation may be implemented in the future dependent on the success of the proposed 6-paddock rotation in encouraging pasture regeneration, and how well it fits into the management schedule for the station.

Two grassland regeneration paddocks will be created which will exclude kangaroos and wallabies and which, after being rested for a season, will be grazed conservatively during lambing (May/June). The existing paddocks near the homestead will be strategically grazed with sale/young stock that will provide them with a short graze, followed by a longer rest period. Any mechanical regeneration works that are carried out within the paddocks will have a greater chance of success if they are rested from grazing until vegetation has colonised the area. Resting these historically heavily utilised areas will speed their recovery. A rest-based grazing system will provide the most amount of benefit to the highly productive grassland areas of the lease. A short, heavy graze period applies the same level of grazing pressure to an area as a long, light graze period, while maximising the length of the rest period. This will result in a healthier root system, and a more resilient tussock that has a better chance of surviving long dry spells.

As part of the ongoing project, we will be using the following new technology:

- NDVI satellite monitoring; we have engaged CIBO Labs to monitor the increase in biomass using NDVI technology.
- Ceres satellite tags: These tags are the world's first real time satellite tracking ear tags for livestock. The tags not only indicate the location of animals and allow lifetime traceability but also provide health information such as temperature and elevated heart rate. Livestock movement data will help us understand the movement/concentration of sheep in a grazing cell in line with our objective to encourage more even utilisation of the available grasslands and Chenopod shrublands by provision of additional water points.
- Satellite water monitoring of storage tanks: These monitors are designed to improve productivity and efficiency on pastoral stations. The daily reporting enables the station manager to monitor the amount of water stored and to identify issues such as major leaks in the system very quickly. Monitors also increase productivity as there is no need to drive around watering points every day.
- Soil probes: Soil probes inserted 1 m into the ground enable us to understand the amount of moisture that is available to the plants in a range of different soil types.

Results

The changes to the landscape biomass are observed with satellite images from Cibo Labs (Figure 1). These images are acquired in January each year. 2020 was the end of a three-year drought, 2021 was an average rainfall year, however, the recovery was slow due to low levels of biomass, 2022 was a higher-than-average rainfall year with 485mm, 2023 was another average rainfall year, however, the good rainfall in 2022 is reflected in the satellite image, 2024 was a very dry year with 175mm recorded. The biomass continued to improve and the image for January 2025 is the evidence of the significant increase in biomass since 2020.

Evidence of the success of the program to date is provided by the following observations on landscape changes by James Thiessen and Kylie Moritz (Australian Integrated Carbon) and Richard Marver (Contour Consulting) in 2022.

James Thiessen and Kylie Moritz:

- Traditionally, trees and shrubs that are not observed regenerating on pastoral stations were observed - notably
  - Western myall *(Acacia apyrocarpa)* estimated to only regenerate 5 times per century – after massive rainfall. Readily grazed by sheep and rabbits. Young recruits were observed
  - Pin bush (*Acacia burkittii*) – in the book Acacia's of South Australia (D.J.E Whibley & D.E Symon 1980) the authors predicted that within a century A. burkittii will be close to extinction where both rabbits and sheep occur together. So, it was great to see this species regenerating at multiple sites across the station
  - Bullock Bush *(Alectryon oleifolius)* – new growth shoots observed suckering off old established trees – Bullock Bush is a favoured plant by all herbivores
  - Other notable species regenerating at various sites were the native apricot (*Pittosporum angustifolium*), Black Oak *(Casuarina pauper),* Sheep Bush *(Geijera linearifolia)*, Sugarwood (*Myoporum platycarpum*)

- Buckleboo's road to recovery after being heavily grazed last century is looking very promising. Planned and well executed rotational grazing is enabling the regeneration of many trees and shrubs. This was observed alongside a very healthy ground cover full of grasses, forbs and an amazing-looking soil crust.

Figure 1. Increase in biomass using CIBO Lab, NDVI technology

Richard Marver:
"Since my first visit to Buckleboo I have been privileged to be able to witness the amazing recovery and transformation of the landscape through the implementation of a regenerative management plan. The plan has allowed the station to capitalise on the recent good seasons. The aspects of the improvement that I have been most pleased to see are the recruitment and establishment of the palatable saltbush species within the lake country, and the universal improvement in groundcover due to increased abundance of perennial grasses, particularly in the naturally Spear Grass dominated vegetation areas. With continued regenerative management I expect this recovery to result in a far improved landscape resilience through the next dry season".

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Ecohydrological resilience of sagebrush rangelands following tree encroachment

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Key words: Erosion; Juniper; Pinyon; Runoff; Woody Plant Encroachment.

Abstract

The expansion and contraction of pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) woodlands in the western US is a broadly occurring phenomenon. The sagebrush (*Artemisia* spp.) vegetation type is vulnerable to woodland encroachment and much of the western US sagebrush domain has transitioned to PJ woodlands. These ecological state changes alter plant community structure and function and delivery of ecosystem services. This study applied a set of vegetation, soil, and rainfall simulation experiments over a range of scales (point to hillslope) to evaluate the ecohydrologic and erosion impacts of a shrubland-to-woodland ecological state transition on sagebrush rangelands on coarse-textured soils. The transition shifted the plant community from a fine to coarse structure and increased the connections between bare areas. Declines in shrub and herbaceous covers associated with pinyon and juniper woodland-encroachment increased the connectivity of runoff and sediment sources. Bare patches in the woodland contributed ample runoff and sediment at the fine spatial scale (0.5 m^2) that facilitated flow paths and erosion over the hillslope scale. Overall, the shrubland-to-woodland transition marked substantive declines in cover and enhanced connectivity of runoff and sediment sources.

Introduction

Pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) [PJ] woodlands substantially increased in density and distribution throughout much of the western US after European settlement, and continue to expand into rangeland plant communities due to intensive land use, historic fire exclusion, and atmospheric CO_2 enrichment. The encroachment of sagebrush shrublands by pinyon and juniper is commonly associated with degradation of understory vegetation and groundcover (Miller et al., 2000), impaired hydrologic function

(Williams et al., 2014, 2022), and amplified soil loss (Pierson et al., 2007, 2010; Roundy et al., 2017). The extensive conversion of sagebrush rangelands to PJ woodlands throughout the western US merits a fundamental understanding of key ecological processes regulating these ecosystems. A primary tenant in pinyon and juniper removal to restore sagebrush vegetation is to implement treatments in the early stages of woodland encroachment, while sagebrush and native perennials remain the dominant vegetation (Miller et al., 2014; Roundy et al., 2014). Further, treatment implementation should target sites where specific objectives such as sagebrush and perennial grass retention/recruitment and reduced runoff and erosion risks are plausible. Decisions on implementing sagebrush restoration treatments to reduce pinyon and juniper require baseline data and understanding on the structure and function of these communities across the diverse landscapes in which they occur.

The purpose of this study was to evaluate the ecohydrologic and erosion impacts of shrubland-to-woodland plant community transitions on sagebrush rangelands on coarse-textured soils. The primary objectives were to quantify (1) vegetation and ground cover conditions at the hillslope scale (990 m^2 plots) and (2) vegetation and ground cover, soil properties, runoff rates, and sediment delivery at the fine spatial scale (0.5 m^2 plots) at a site dominated by sagebrush shrubs (Fig. 1a) and at an immediately adjacent site dominated by pinyon and juniper trees (Fig. 1b). The study sites represent different ecological states (sagebrush shrubland and PJ woodland) of the same ecological site.

Methods

Study area and experimental design

Experiments were conducted at a sagebrush shrubland (Sagebrush Site) and a PJ woodland (Woodland Site) located (~39.8227°N latitude, -114.014°W longitude) at 1850 m elevation approximately 40 km northeast of Kanab, UT, USA. The sites are immediately adjacent to one another on an Upland Loam (Mountain Big Sagebrush) Ecological Site (Site id: R035XY308UT; NRCS, 2024). The sites receive approximately 400 mm of precipitation annually and have an average annual air temperature of 9.9°C. The sites are on S to SE facing aspects with gentle sloping terrain (6-8% slope). Hillslope-scale vegetation and ground cover at each site were measured on three 33 m × 30 m rectangular site characterization plots. Fine-scale plots were randomly located to occur on interspace (areas between shrub and tree canopies), shrub, and tree microsites (Pierson et al., 2010; Williams et al., 2014). Eight interspace and nine shrub fine-scale plots were installed and sampled at the Sagebrush Site. Twelve interspace, six shrub, and six tree fine-scale plots were installed and sampled at the Woodland Site.

Vegetation and ground surface measurements

Hillslope-scale overstory tree cover and understory vegetation and ground cover at each site were sampled on the aforementioned 990 m^2 site characterization plots using a set of tree measures and line-point intercept methods consistent with hillslope-scale methods in Williams et al. (2020a). Foliar and ground cover on each site characterization plot were recorded for 60 points with 50 cm spacing along each of five line–point transects 30 m in length and spaced 5-8 m apart, for a total of 300 sample points per plot. Foliar cover and ground cover were measured on fine-scale plots using point frame methods described by Williams et al. (2020a). Foliar and ground cover on each fine-scale plot were recorded at 7 points with 10 cm spacing along each of 15 evenly spaced (5 cm apart) transects oriented perpendicular (downslope) to the hillslope contour, for a total of 105 points per plot. Litter depth on each plot was measured to the nearest 1 mm at four evenly spaced points (~15-cm spacing) along the outside edge of each of the two plot borders located perpendicular to the hillslope contour.

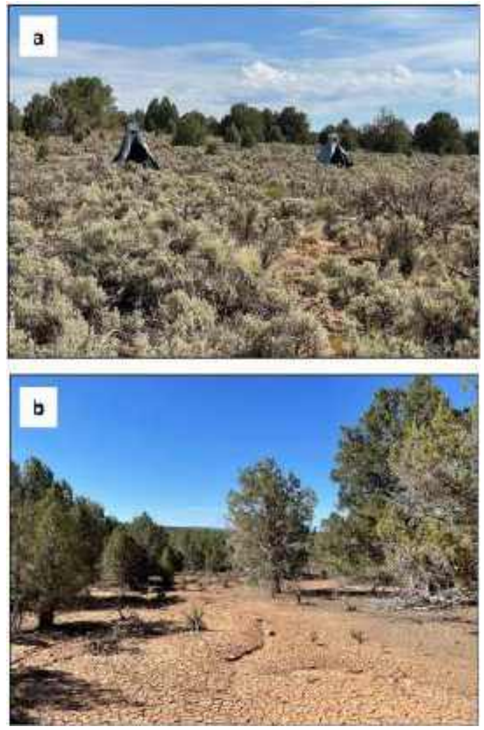

Fig. 1. Photographs of (a) the Sagebrush (*Artemisia* spp.) Site showing rainfall simulators, minimal tree cover, ample understory vegetation, and limited erosion features and (b) the Woodland Site showing an extensive bare intercanopy between tree islands and with visible overland flow paths and erosion features.

Soil characterization and soil property measurements
Soils for each fine-scale plot were characterized using a suite of sampling methods. Three surface soil grab samples (with litter, duff, and biological soil crust removed) were obtained adjacent to each fine-scale plot and transported to the lab in sealed bags for subsequent soil texture analyses. Soil bulk density was sampled immediately adjacent (≈ 15 cm distance) to each fine-scale plot using a 4.8 cm diameter metal core inserted 5 cm into the soil (litter and duff removed). Bulk density for each soil core sample was calculated in the lab as the oven dried (105˚C) soil mass divided by the core cylinder volume (90.5 cm^3). The persistence of soil water repellency (SWR) was quantified immediately adjacent to each fine-scale plot under dry antecedent soil moisture conditions using the water drop penetration time (WDPT) test as described by Williams et al. (2020b). Soils were classified as wettable where WDPT < 5 s, slightly water repellent when WDPT ranged 5 s to 60 s, and strongly water repellent when WDPT > 60 s.

Rainfall simulations
Rainfall simulations were conducted to quantify fine-scale runoff and erosion processes using methods and simulators described by Williams et al. (2020a). Two separate, but sequential 45-min rainfall simulation experimental runs were conducted on each fine-scale plot. The Dry Run applied rainfall at an intensity of 64 mm h^{-1} on dry antecedent soil moisture conditions. The Wet Run applied rainfall at an intensity of 100 mm h^{-1} on wet soil conditions approximately 15 min following the Dry Run. The mean rainfall intensity and cumulative rainfall applied by run type were similar ($P > 0.05$) across all plots. Actual rainfall applied for 45 min simulations averaged 48 mm and 75 mm for the Dry and Wet Runs, respectively. Timed samples of runoff were collected over 1-min to 5-min intervals throughout each 45-min rainfall simulation and were analyzed in the laboratory for runoff volume and sediment concentration as described by Williams et al. (2020a).

Statistical analyses
Data comparisons for hillslope-scale experiments were conducted using two-sample *t* tests. Assumptions of normality and homogeneity of variance were assessed, and transformations were applied where necessary to address deviances. The Mann-Whitney U test was used for comparisons where transformations were ineffective. Comparisons for fine-scale data were conducted via one-way analysis of variance. Post hoc pairwise comparisons were made using Tukey's honestly significant difference test. Assumptions of normality and homogeneity of variance between groups were assessed and addressed through data transformations. The Kruskal-Wallis method was applied for fine-scale comparisons in cases where normality was not achieved through data transformation. All significant effects were assessed at the $P < 0.05$ level.

Results
Vegetation cover assessed in summer 2022 quantified the contrasting cover conditions for the two sites. The Sagebrush Site had minimal tree cover (Fig. 1a) and understory foliar cover of 29% shrub, 9% herbaceous (grasses and forbs), and 8% standing dead covers. Litter (45%) and moss (13%) were the dominant ground covers and bare soil was 36%. The Woodland Site had approximately 32% overstory tree canopy cover and about 68% of the area as sparsely-vegetated intercanopy between trees (Fig. 1b). Total understory foliar cover at the Woodland site was 6% and consisted of minor amounts of shrub (2%), grass (1%), and standing dead (2%) covers. Litter cover and bare soil both approached 40%. Most of the litter occurred underneath tree canopies. Incised flow paths and erosion features were common throughout the intercanopy at the Woodland Site (Fig. 1b).

For the fine-scale, shrub microsites at the Sagebrush Site averaged about two-folder greater shrub foliar (64%) cover relative to shrub microsites at the Woodland Site (33%). The ground surface underneath shrubs at the Sagebrush Site was covered by litter (76% cover) and some moss (10%), woody dead debris (5%), and basal plant (4%) covers. The ground surface under shrubs at the Woodland Site had only 41% litter cover and 34% moss and biocrust, 3% woody dead, and 2% basal plant covers. Litter depth averaged 3-5 mm on shrub plots across both sites. Bare soil on shrub microsites averaged 3% at the Sagebrush Site and 19% at the Woodland Site. Interspaces at the Woodland Site had minimal foliar cover, whereas, interspaces at the Sagebrush Site had 9% total foliar cover. At the Sagebrush Site, interspaces were mostly bare (74% bare soil) at the ground surface but had some litter (11%), mosses and biocrusts (10%), woody dead debris (2%), and plant bases (1%). Interspaces at the Woodland Site were also mostly bare (55% bare soil) but had 36% biocrust cover and 7% litter cover. Litter depths were minimal (1-2 mm) in interspaces at both sites. Tree microsites sampled at the Woodland Site had only 4% total foliar cover but were 100% covered by a nearly 50 mm thick accumulation of litter and woody debris.

Soils were generally similar across the study sites, but bulk density and soil water repellency exhibited microsite-specific patterns at each site. Soils across both sites had a loamy sand texture at the surface (0-5 cm depth). Soil bulk density was 1.69-1.73 g m^{-3} across all shrub plots and woodland interspace plots, lowest for tree plots at the Woodland Site (1.45 g m^{-3}), and highest for interspace plots at the Sagebrush Site (1.99 g m^{-3}). The mineral soil surface was strongly water repellent directly under sagebrush canopies at the Sagebrush Site and under tree canopies at the Woodland Site, but soils were wettable in interspaces at both sites.

Table 1. Mean response variables for rainfall simulations (Wet Run, 0.5 m^2 plots) on wet soil conditions at the Sagebrush (*Artemisia* spp.) and Woodland study sites. Means within a row followed by different lowercase letters are significantly different ($p < 0.05$).

	Sagebrush Site		**Woodland Site**		
	Inter-space	**Shrub**	**Inter-space**	**Shrub**	**Tree**
Wet Run (100 mm h^{-1}, 45 min)					
Antecedent soil moisture (%)	26 a	21 a	26 a	22 a	18 a
Post-simulation soil moisture (%)	33 a	34 a	32 a	34 a	29 a
Mean runoff rate (mm h^{-1})	34 b	5 a	23 b	2 a	19 b
Cumulative runoff (mm)	26 b	4 a	17 b	2 a	15 b
Cumulative sediment (g m^{-2})	104 b	8 a	85 b	10 a	22 ab
Percent of plots with runoff	100%	89%	92%	50%	100%

Few plots generated runoff for the Dry Run overall, therefore rainfall simulation results are restricted to the Wet Run experiments. The Wet Run results showed interspaces as the primary source of runoff and sediment delivery at both sites (Table 1) and that repellency effects persisted even with soil moisture contents approaching 20%. Across the sites, runoff rates and sediment yields were high for interspaces (23-34 mm h^{-1}, 85-104 g m^{-2}), moderate for tree plots (19 mm h^{-1}, 22 g m^{-2}), and low for all shrub plots (2-5 mm h^{-1}, 8-10 g m^{-2}) (Table 1). Runoff rates typically peaked early for water repellent tree and shrub plots and then declined throughout the remainder of rainfall simulation. Litter and moss covers showed variable effectiveness in limiting runoff from water repellent tree and shrub plots.

Discussion and Conclusions

The preponderance of evidence across spatial scales shows pinyon and juniper encroachment into the sagebrush vegetation type in the study area has altered plant community physiognomy and hydrologic function. The Woodland Site intercanopy (68% of area) was mostly devoid of understory vegetation and the ground surface there was mostly bare or covered by biocrusts (Fig. 1b). Shrub and herbaceous covers were well distributed and bare ground was isolated at the Sagebrush Site (Fig. 1a). For the Sagebrush Site, the fine vegetation structure buffered the effects of high runoff rates and sediment discharge from isolated interspaces and the formation of concentrated overland flow, as evident by limited erosion features at that site (Fig. 1a). At the Woodland Site, extensive sparsely vegetated intercanopy areas facilitated connectivity of runoff and sediment sources from contiguous interspaces (Fig. 1b), as evidenced by the presence of numerous water flow and erosion features (Fig. 1b). Consistent with other woody plant transition studies (Pierson et al., 2007, 2010; Williams et al., 2014; Roundy et al., 2017), our experimental results demonstrate how coarsening of the community structure with sagebrush-to-woodland conversions increases hydrologic vulnerability and soil loss through expanded connections of runoff and sediment sources along hillslopes. This study documents the impacts of PJ woodland encroachment into sagebrush steppe on vegetation cover and hydrologic and erosion processes. Studies documenting vegetation, soils, and hydrologic functioning commonly focus on either the sagebrush ecological state or, more often, the PJ woodland state, with encroachment effects inferred. This study is unique in capturing intact sagebrush state attributes and those of the PJ woodland state for the same ecological site. The results contribute to conceptualizing and predicting ecological and hydrological responses for similar ecological state transitions in other ecosystems.

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Interaction of plant functional traits of *Stipa tenacissima* L. in arid montane rangelands and grazing frequency.

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Key words: adaptation; aspects; elevation; leaf moisture.

Abstract

Mediterranean biotic and abiotic conditions, with severe drought, high temperatures, decreasing rainfall and increasing human disturbances are expected to have negative impacts on vegetation. Functional traits can be used to understand the relationship between plants and the environmental conditions, including grazing, under which they grow. Plant traits of *Stipa tenacissima* L., the most abundant and multi-used species in North African montane arid rangeland, are studied under three grazing regimes (full exclusion, seasonal and continuous grazing). Results confirmed that *S. tenacissima* traits are strongly affected by the grazing regimes. Leaf water content, bio-volume (the volume occupied by the above ground biomass) and the specific contribution of *Stipa* (the proportion of the species among the total plants founded) are higher under seasonal grazing. Hence this last management is recommended for the sustainability of both plant and rangelands.

Introduction

The functional traits of species are the resulting evolutionary and adaptive responses to the specific conditions of their environment (Reich et al. 2003). Climate change and human disturbances, particularly grazing, are considered among the most challenges confronting our world (Mikhaylov et al. 2020). They affect key habitat elements critical for the maintenance of species (Krichen et al. 2019). To evaluate vegetation behaviour and highlight adaptation to grazing and climate change, it is important to understand the plant's responses through their functional traits such as those associated with their colonization, survival, growth, and mortality (Reich et al. 2003).

Stipa tenacissima L. is a dominant perennial Poaceae in southern Tunisia, particularly in the montane rangeland chain of Matmata. It is subject to a wide range of climate and soil stresses. *Stipa* helps to prevent soil erosion by its developed root system and its adaptability to environmental shifts (Yang et al. 2024). *Stipa* constitutes an integral part of local economies according to its multiple uses as artefacts (baskets, strings, shoes) and for livestock feeding in summer (Ben Salem 2012).

Methods

Study area

Three sites located in the region of Toujane (south-east Tunisia) in the Matmata Mountain Chain are studied (Fig. 1). The mean annual precipitation is approximately 150 mm. The three sites have similar soil substratum, topography and geology, but differ in altitudinal range and grazing regime. Zmerten (33°26′07.20″ N, 10°07′29.02″ E, 3000 ha)) has been protected from grazing for 44 years. Its natural vegetation is dominated by *Juniperus phoenicea* L., *S. tenacissima* and *Rosmarinus officinalis* L. Brighith (33°29′23.40″ N, 10°12′02.88″ E, 100 ha) is dominated by *S. tenacissima* and is devoted to seasonal grazing. The control (33°29′14.95″ N, 10°11′58.24″ E) is dominated by *S. tenacissima* and continuously open to grazing.

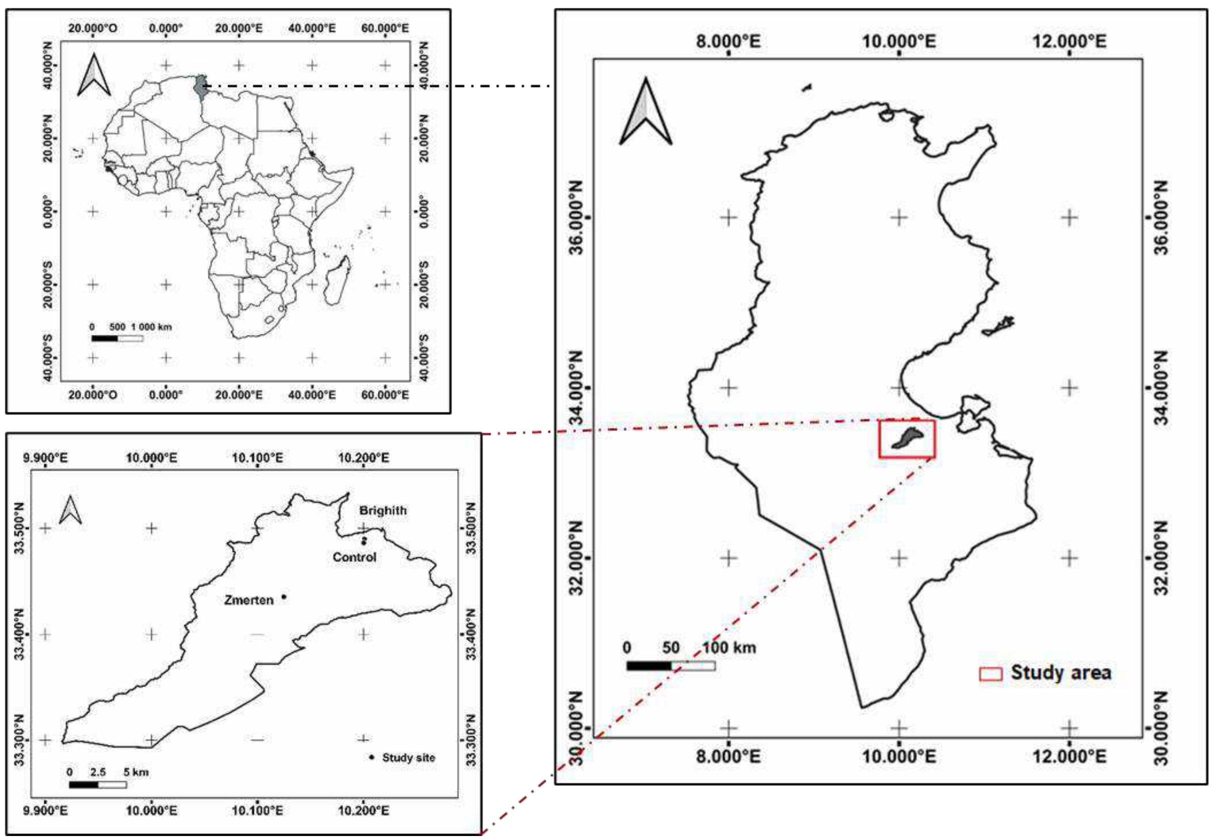

Fig. 1 Geographical location of the three study sites.

Methodology

At each site, nine tufts of different sizes (three big, three medium and three small) are measured in each altitude (low, medium and high) and aspect (south and north expositions to sunlight). The methodological approach is a pseudo replicated-nested design, with the three grazing treatments confounded with site. In total, 54 measurements are made within each site. Five leaves are collected from each tuft to measure the leaf traits. They were placed in moistened paper, and put in a refrigerator to prevent dehydration. In the laboratory, the leaves were weighed (to obtain their fresh matter (FM)), flattened, fixed and photographed. The photos are then analyzed using ‘Image J’ software to calculate the leaf area (LA). The sampled leaves are then oven dried for 48 hours at 60°C to obtain their dry matter content (DM). The leaf water content

(LWC), as a percentage of FM, was then calculated. The leaf dry matter content (LDMC), in mg g^{-1} FM, is DM/FM. Specific leaf area (SLA), in cm^2 g^{-1} DM, is LA/DM. The biovolume (in m^3) is calculated as BV = $((4/3)\,\pi r^3)/2$, where r is the average radius of the tuft and it is obtained as $r = ((D/2) + (d/2) + h)/3$, with: D is the largest diameter, d is the smallest diameter and h is the height of tuft. The canopy cover (CC in m^2) is the area covered by the aerial organs of *S. tenacissima* and it is calculated as CC = πr^2.

To characterize the whole plant community of the sites, three 20 m line-transects, 100 m apart, are installed at each level and aspect (in total, 18 lines per site). Data are collected using the quadrat point method. A metal fine pin is entered vertically into the vegetation every 20 cm along the transect (100 hits per line). The plant species touching pin are recorded. The total vegetation cover (Vc in %) is calculated as: Vc = $(n/N) \times 100$ where n is number of points where the vegetation is present and N is the total number of the measured points along the line.

The specific contribution (Sc in %) reflects the proportion of the species in the vegetation cover and was calculated as $Sc_i = FS_i / \Sigma FS \times 100$, where FS_i is the specific cover of the species and ΣFS the sum of the cover of all species. All these measurements are taken during the springs of 2019, 2020 and 2021.

Results

To summarize and investigate the patterns of the studied functional traits, a principal component analysis (PCA) is used (Fig. 2). PCA showed two principal components explained together 76.27% of the total variance. PC1 explained 53.36% of variation, while PC2 explained 22.91%. PC1 displayed a high positive association with BV, CC, Vc, Sc and LWC while it had high negative association with LDMC, SLA and LA. PC1 indicated a grouping of sites that exhibited high BV, CC, Vc and LWC. PC2 showed a positive loading with LDMC and a negative one with SLA, LA and LWC.

As showed in Figure 2, three site-groups are identified according to the hierarchical clustering. The first group included ZN1, ZS1, ZS2, ZS3, CS1 and CS2. Higher LDMC characterizes this group. The second one contained ZN2, ZN3, CN1, CN2, CN3, CS3. It is distinguished by a high LA and SLA. The last group contained all the seasonally grazed sites (BN1, BN2, BN3, BS1, BS2 and BS3) and it is characterized by a higher BV, CC, Vc, Sc and LWC. This distribution clearly proved the positive correlation of seasonal grazing on both functional traits of *Stipa* (BV, CC, Sc and LWC) and on the whole community (Vc).

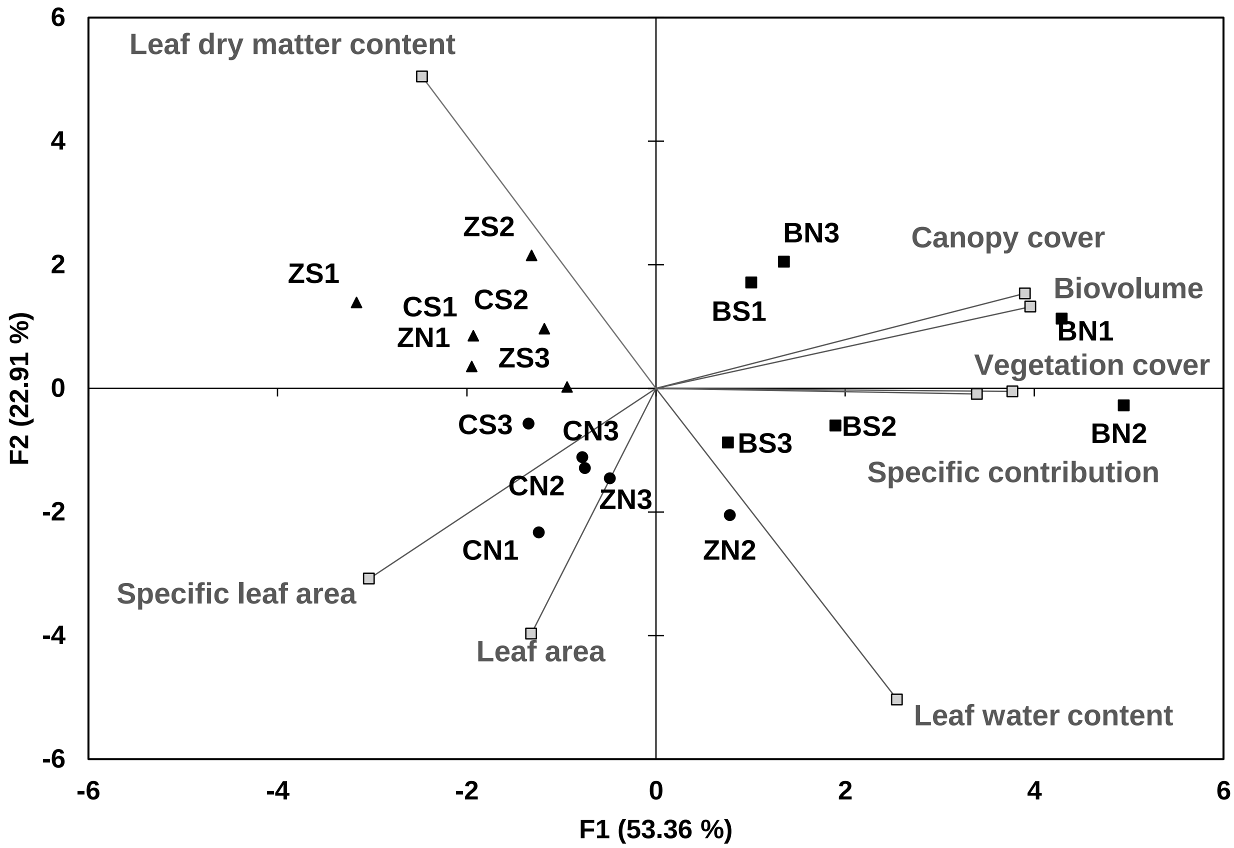

Fig. 2. Principal component analysis applied on the data of eight variables in 18 locations, meaned over the springs of 2019, 2020 and 2021. B: Brighith (seasonally grazed), C: control (continuously grazed) and Z: Zmerten (Livestock exclusion). N: northern aspect, S: southern aspect, 1: low elevation, 2: medium elevation, and 3: high elevation. For example: BN1 is Brighith North, low elevation.

Discussion

The CC, BV and Sc at the site under seasonal grazing are higher than those of the fenced and control sites. These may relate to improvements in soil characteristics. Seasonal grazing with controlled animal numbers has increased soil organic matter content and improved its physical and chemical conditions in Argentina (Vecchio et al. 2018).

Leaves are the most appropriate indicators of plant water status (Hamdani et al. 2019). SLA and LWC are closely linked to the productivity and water status of plant (Chirino et al. 2017). Hence, the low SLA with high LWC in the seasonal grazing site shows the adaptive capacity of *Stipa* to moderate grazing compared with the fenced and continuously grazed plants.

The Vc in the protected site is lower than the one in seasonal grazing. Thus, short grazing periods alternated with fencing during the growing season, seems better than strict protection (Msadek et al. 2021). Some grazing will temporarily decrease the aerial organs and allow the root systems to revitalize the remaining plant materials. Thus, individual plants are reinvigorated and vegetation cover increases (Louhaichi et al. 2012).

In conclusion, these experiments, revealed that seasonal grazing, with a controlled animal charge, is more beneficial for species and plant communities than grazing exclusion and continuous grazing. Seasonal grazing is rehabilitating degraded rangelands using selected local plants adapted to different biotic and abiotic constraints.

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Local flora for ecological restoration: the flore project

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Key words: native seeds; restoring nature; Mediterranean region

Abstract

The territories of south-western Europe are still recognised as a biodiversity hotspot. However, it is very much subject to the dangerous consequences of the intensification of human activities, climate change, wild fires and the abandonment of the agricultural and forestry activities in marginal land areas, with the consequent degradation of the land, vegetation and the ecosystems. There, the Interreg SUDOE FLoRE project, started in January 2024, is being implemented to test, analyse and scale-up the implementation of different ecological restoration solutions based on native and locally sourced herbaceous plant seeds. We develop: a) practical tools adapted to the current needs of the target groups; b) create a network of pilot projects in sites with diverse environments and land degradation (due to wildfires, overgrazing, mining, invasive vegetation); and c) lead a multi-stakeholder participatory process to design and test new models of economic cooperation, aimed at the self-production of seeds by users or the supply of products and services to sector players. The project will engage public authorities, non-profit private organization and private companies with the ambition of introduce this type of species into their restoration processes and organise dissemination days for the general public.

Three working groups (WG) were created: WG1 - Operationalise and disseminate existing knowledge on ecological restoration using local seeds, to facilitate the information and learning process by stakeholders, and encourage their commitment and the implementation of good practices.; WG2-Test, monitor and evaluate different ecological restoration solutions from local seeds; and WG3-Develop a strategy to involve all the stakeholders in large-scale actions to support the sustainability of the ecological restoration solutions tested, and formulate recommendations for professionals and decision-makers on the different means of action available to them.

Introduction

Our lives depend on nature, but we are degrading it, and it is imperative that we reverse this trend. A number of factors are putting pressure on ecosystems and species populations, including: pollution, climate change, habitat loss and invasive species (80% of habitats are in poor condition, 10% of bee and butterfly species are in risk of extinction and 70% of soils are in an unhealthy state) (European Council 2024). Soil degradation represents a major threat to ecosystem services and biodiversity conservation. In addition, degradation processes are continuing and worsening (EC 2023).

The semi-enclosed nature of the Mediterranean Sea and the complex topography result in unique physiographic and ecological features. The latest IPCC results show an increasingly arid future for the Mediterranean, with less rainfall and more frequent and longer heat waves (Ali et al. 2022). Some of the consequences of climate change are: reduction of river low flows and annual runoff by 5-70%; yields of rainfed crops may decrease by 64% in some places; desertification will affect more areas, especially in the south and south-east.

The EU Environmental Council adopted the Nature Restoration Law (NRL). They intend to intervene in at least 20 per cent of the EU's land and sea areas by 2030. Restoration plans are intended to cover the period up to 2050. One of the measures envisaged is to restore of at least 30% of the habitats that are in poor condition.

In this context, the FLoRE project was created as part of the INTERREG-SUDOE programme, which aims to consolidate South-West Europe as an area of territorial cooperation in the of innovation, competitiveness and environmental protection. The major challenge of the FLoRE project is to ensure the preservation of the quality of life and the attractiveness of rural areas by demonstrating the economic and organisational viability of scale-change in the implementation of various ecological restoration techniques aimed at valuing native and local wild herbaceous species.

Project Workplan

The Interreg SUDOE FLoRE project, started in January 2024 and will finish in December 2026. The consortium is made up of eight partners (three in France: Conservatoire d'Espaces Naturels d'Occitanie (project leader), FAB'LIM - Le Labo des Territoires Alimentaires Méditerranéens, Conservatoire d'espaces naturels d'Auvergne; three in Spain: Comunidad Autónoma de la Región de Murcia, Asociación Forestal de Soria, Cámara Oficial de Comercio, Industria y Servicios de Badajoz and two in Portugal: National Institute of Agricultural and Veterinary Research, MORE CoLAB on mountain regions. Three groups of tasks were drawn up into three working groups (WG 1, WG 2 and WG 3); all the beneficiaries will take part in each WG, but one beneficiary is responsible for coordinating each WG.

WG 1 - Operationalisation and dissemination of existing knowledge on ecological restoration

Here, the focus is disseminating and applying existing knowledge on ecological restoration techniques using native and locally sourced wild herbaceous species, to facilitate their use by stakeholders (professionals in the sector, landowners, managers, national bodies), in order to encourage their involvement in changing practices and identify the remaining gaps in technical and socio-economic knowledge. To do this, we will update the current state of knowledge on initiatives, scientific publications and public policies aimed at supporting ecological restoration. Then, to facilitate access to information, the most frequently asked questions by stakeholders will be identified and answered, along with other types of dissemination actions. The deficits and gaps in knowledge identified will be revealed and addressed at a later stage of the project. (INIAV is the responsible beneficiary).

WG 2 - Experimentation and evaluation of different solutions for seed production and ecological restoration

A network of demonstration sites is being set up in different environments to publicise different solutions (including different restoration and seed multiplication techniques). Most of our pilot sites are already in place and are located in:

- Occitanie: representing altered agricultural systems and highly anthropized environments and Auvergne: representative of wetlands, meadows and pastures in Auvergne (France)

- Soria: captures truffle farms, recently cleared environments and forest environments and Murcia: degraded natural spaces and eroded areas (Spain)
- Serra da Estrela: I an example of mountain burnt areas in the centre of Portugal and the left bank of the Guadiana river- south-east Portugal represent grasslands (Portugal). This last pilot site is the responsibility of INIAV.

Based on the mapping of grasslands of ecological interest carried out, different techniques for obtaining and recovering seeds will be developed (brushing, mowing, hay transfer). Transnational co-operation will enable us to provide a range of restoration solutions adapted to the regulatory contexts of each country and the realities of each territory, given the diversity of environments representative of the SUDOE area[5]. The experiments carried out and their monitoring (based on indicators developed by the consortium) will make it possible to consolidate protocols and identify the relevant adaptations to be made depending on the contexts and restoration objectives. We will also measure the real benefit or added value, as well as the possible impacts of the restoration operations carried out. (*Asociación Forestal de Soria* is the responsible beneficiary)

WG 3 - Development of a strategy to involve stakeholders in a large-scale action

A medium/long-term strategy (from three to eight years) will be developed jointly based on the sharing of results from the multi-stakeholder group animation work at a transnational level, i.e., from the workshops involving different types of stakeholders (from scientific researchers and public decision-makers to seed vendors and farmers) from various countries, specifically from the SUDOE European region (southwest of France, Spain, and Portugal). Its main objective will be to guide professionals (landscapers, consultants, public and private buyers, scientists, local development associations, site managers) and decision makers (elected representatives, company managers, etc.) towards the means of action available to them supporting long-term viability of the technical solutions tested during the project (collection, planting and monitoring of native and locally sourced wild herbaceous species, etc.). This strategy will define realistic objectives (taking into account the constraints of these stakeholders) but ambitious enough to support the development of the proposed solutions. This may be broken down into several action plans, tailored to each type of public concerned and their respective areas of competence. We will identify a number of economic and public policy levers that can support this strategy. To facilitate its implementation, the strategy will be accompanied by a number of resources available in open access e.g. training modules for field workers and decision makers, awareness-raising content, a letter of engagement, feedback from multi-stakeholder groups, etc. (*FAB'LIM* is the responsible beneficiary).

Goals to be achieved

By carrying out the different tasks (WG1-3), we aim to achieve the following goals:

-1.Obtain commitment from: (i) the managers of the pilot ecological restoration fields to guarantee the sustainability of the solutions tested, (ii) the professionals to collectively implement the economic and organisational models co-constructed in accordance with the initial ethics, (iii) the beneficiaries of the multiplied seeds for use in projects of collective interest and (iv) the communities and companies to introduce this type of seed in their ecological restoration processes in favour of biodiversity.

[5] Interreg Sudoe is a European Union funding programme to support regional development and cohesion in the regions of south-west Europe.

-2.Training organisations that adopt the tested solutions to manage them independently over time.

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Management for biodiverse rangelands

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XII INTERNATIONAL RANGELAND CONGRESS AUSTRALIA 2025

Restoring biodiversity in a hyper-arid desert ecosystem in Saudi Arabia

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Key words: reintroduction; site fidelity; home range; IUCN Red List

Abstract

The global biodiversity crisis has manifested itself on the Arabian Peninsula with wildlife population declines and extinctions particularly of the large iconic mammals. Protected areas are increasingly being established to provide refuge, enhance wildlife populations, and reintroduce missing keystone species. Since 2018, eight royal reserves have been established in Saudia Arabia, two in the hyper-arid central region. Understanding current species occurrence, richness, abundance, and diversity is crucial to targeting management and reintroduction efforts. Due to the scarcity of data on wildlife presence and spatial abundance in the region, we utilized camera traps placed on trails, at water stations, and at burrows, as non-intrusive tools for baseline biodiversity assessment in these protected areas. These camera traps revealed the presence of 12 species listed as threatened on the IUCN Red List, underscoring the regional and global importance of these areas. Additionally, these findings contribute valuable information on species distributions in hyper-arid areas for global assessments. The data on the spatial abundance of top predators and meso-predators is crucial for designing feasibility studies for reintroduction programs and can guide spatial management strategies that will enhance biodiversity.

Introduction

Biodiversity has shown an alarming downward trend in the last decades (Díaz et al., 2019). Effective ecological structure and functioning of ecosystems requires the full trophic network of wildlife species to be present. Large predators have cascading trophic effects through predator avoidance by herbivores (Suraci et al., 2016), resulting in spatial variation in vegetation communities in areas these grazers avoid (Boyce, 2018). The presence of large herbivores increases plant diversity through selective browsing (Cook-Patton et al., 2014; Olff & Ritchie, 1998) and the improvement of soil fertility through dung and urine deposits (van der Waal et al., 2011). Birds and small mammals facilitate regeneration through seed dispersal (Kellner et al., 2016). And insects are not only food for many animals, but they are also very important for nutrient recycling. Therefore, an ecosystem with a diverse and abundant wildlife population can enhance the natural regeneration and diversity of the vegetation which in turn supports wildlife communities.

Various species of large mammals used to roam the desert ecosystems of Saudi Arabia, having adapted to the harsh climate conditions. However, most have now disappeared from the wild. These include the

Arabian oryx (*Oryx leucoryx*) which is deemed extinct from the wild since the early 1970s (Henderson, 1974), and the sand gazelle (*Gazella marica*), the mountain gazelle (*Gazella arabica*), and the Arabian grey wolf (*Canis lupus arabs*) are currently only present in small remnant populations in Saudi Arabia (Habibi & Grainger, 1990; Ross et al., 2019, 2020). Overhunting and habitat degradation have resulted in their population decline (Alatawi, 2022) and these species are currently listed on the IUCN Red List as vulnerable to extinction (Mallon et al., 2023). Protected areas are a key component in global biodiversity conservation management and have shown to be effective in conserving terrestrial mammals (Chen et al., 2022). To support the Saudi Vision 2030 and in aligned with international treaties, particularly the Convention of Biological Diversity, the Saudi government has pledged to have 30% of its terrestrial and marine areas protected by 2030. Since 2018, eight royal reserves have been established, covering 13.5% of the total terrestrial land. Two reserves are located in the central hyper-arid desert, the King Khalid Royal Reserve (KKRR) and the Imam Abdulaziz bin Mohammed Royal Reserve (IARR). No studies on the presence and abundance of wildlife have been published for these areas. Monitoring wildlife to assess diversity using camera traps, especially for elusive and nocturnal animals, is now a standard method (Palencia et al., 2021). We used camera traps as point-based sampling units to increase our understanding of wildlife species' occurrence, richness, and relative abundance at two study sites in the recently protected areas.

Methods

The study areas are within KKRR and IARR, approximately 100 km northeast of Riyadh. KKRR is 1,162 km^2 and has four main habitats, the pediplain, plateau, wadi (valley) and catchment. The pediplain is about 250 km^2 and contains numerous catchment areas. It is bordered by the escarpment of the Urumah Mountain plateau to the east and at all other sides by roads and has been fenced for over 40 years allowing the vegetation to regenerate (Al-Harigi et al., 2023). Between 2021 and 2024, 45 Arabian oryx (*Oryx leucoryx*), 120 sand gazelles (*Gazella marica*), 11 Arabian gazelle (*Gazella arabica*), and 15 Asian houbara (*Chlamydotis macqueenii*) have been reintroduced in this pediplain. IARR is 11,300 km^2 and has six main habitats, the pediplain, plateau, wadi, catchment, sand plain, and sand dune. This reserve harbours 13 catchment areas with Rawdhat Khuraym being the largest, with eight main wadis draining into it and a popular destination for people in the winter; Kasr Almuzayri is the second largest catchment. Ten Asian houbara were reintroduced in Rawdhat Khuraym in 2023.

In KKRR, camera traps were positioned at 53 locations, predominantly in the fenced pediplain. In IARR, 11 cameras were placed in Rawdhat Khuraym and 2 in Kasr Almuzayri. To increase the observations of diverse animal assemblages we placed cameras next to water sources (50-60 cm height), burrows (10-15 cm height), and on wildlife trails (50-60 cm height). Photos that were taken two minutes or less apart were combined into a single continuous sequence and reported as a single observation. Species richness was based on the incidence of rare species (Chao et al., 2014; Hsieh et al., 2016). We used Hill numbers to quantify community diversity with q representing species richness (q = 0), Shannon diversity (q = 1), and (1-) Simpson diversity (q = 2). The widely used Relative Abundance Index (RAI), calculated as the ratio of photographic captures to camera trapping effort, provides a baseline species abundance for unmarked populations at each feature type (Rovero and Marshall, 2009; Tanwar et al., 2021).

Results

Species Richness

In total, 59 vertebrate species were observed, 35 birds, 17 mammals (of which 3 were domestic) and 7 reptiles. Of these species, 12 are listed on the IUCN Red List: 2 as Endangered (steppe eagle, Egyptian vulture); 8 as Vulnerable (Eastern imperial eagle, Arabian wolf, sand cat, Egyptian spiny-tailed lizard, and the reintroduced Asian houbara, Arabian gazelle, sand gazelle, and Arabian oryx); and 2 as Near-threatened

(Arabian wildcat, honey badger). Placing cameras at different features resulted in slightly different species assemblages (Fig.1 left panel) with, as can be expected, burrowing animals (*Meriones libycus, Jaculus jaculus, Uromastyx aegyptiae*) being pervasive at burrows; pigeons, domestic cats (*Felix catus*), and raptors (e.g. the steppe eagle, *Aquila nipalensis*, Egyptian vulture, *Neophron percnopterus*) at water sources; and on trails the wolf (*Canis lupus arabs*), Arabian gazelle and oryx were frequently captured. However, overlap in species assemblages was quite large.

Species diversity indices showed similar values for richness among feature types (Fig. 1 right panel), suggesting a similar number of species in each habitat. However, the Shannon and Simpson diversity indices, which account for both species richness and evenness, are lower at wildlife trails. This is likely driven by the occurrence of rare species, such as the rarely observed honey badger, Indian crested porcupine, false cobra, sand skink, and the Arabian babbler. The slightly higher Shannon and Simpson diversity indices at burrows, despite overlapping standard errors with water sources, suggest a more even distribution of species resulting from the frequent observations of burrowing animals.

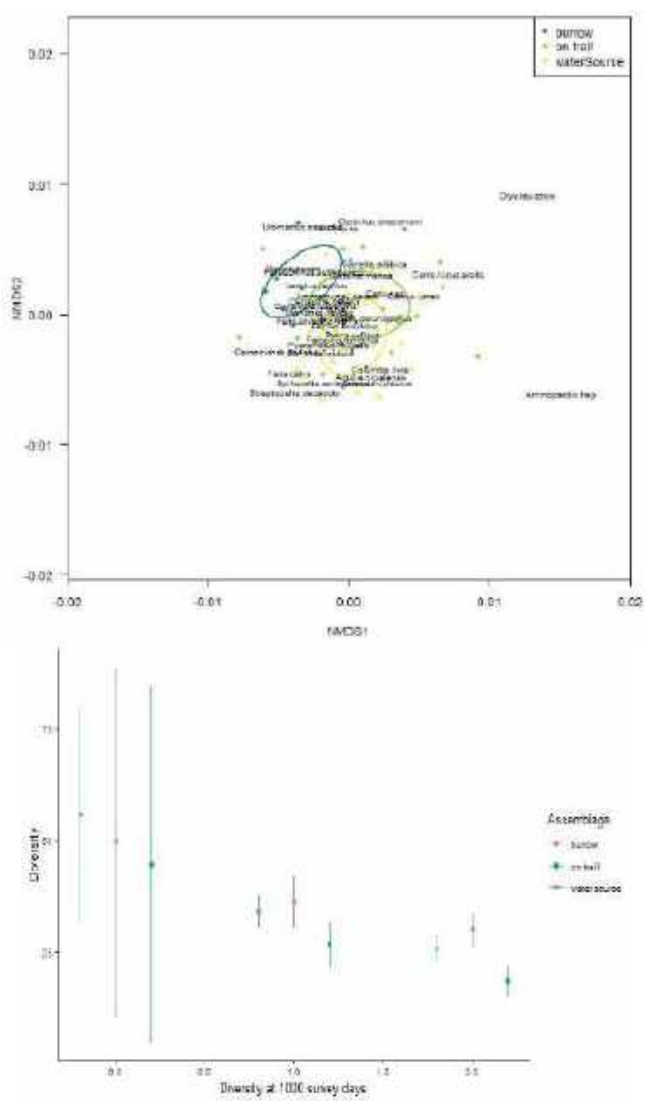

Figure 1. *Left panel*: Non-Metric Multi-Dimensional Scaling (NMDS) plot of species encountered at burrows, water sources or along wildlife trails. *Right panel*: Predicted diversity indices with 0 = species richness, 1 = Shannon diversity, and 2 1-Simpson diversity

Relative Abundance Index (RAI)

Most species had a higher RAI at water sources compared to the other features with only the burrowing species being restricted to observations at burrows (Fig. 2). In KKRR, the reintroduced sand gazelle was the most prominent species at water sources, followed by foxes (*Vulpes*), pigeons, ravens (*Corvus*), and stray dogs (*Canis lupus familiaris*). In IARR, no large herbivores have been reintroduced, and the most abundant species were pigeons, white-eared bulbuls (*Pycnonotus leucotis*), house sparrows (*Passer domesticus*), and feral cats (*Felis catus*) that were all attracted to water sources.

Discussion

Our study demonstrated that the recently established protected areas hold both regional and global significance, as 20% of the observed species are listed as threatened on the IUCN Red List. Providing a refuge for these animals will enhance their survival chances. Water provision also proved crucial for these threatened species, including migrating raptors and native gazelles and oryx. These observations are valuable for biodiversity restoration efforts through reintroduction and wildlife species enhancement programs.

Interestingly, the diversity at water sources, which attracted a high abundance of animals, showed similar species richness with considerable overlap in species assemblages compared to trails and burrows. Only burrowing animals were almost exclusively seen at their burrows, while species mostly associated with urbanized areas (pigeons, sparrows, stray cats, and stray dogs) were predominantly observed at water sources. This was especially notable in Rawdhat Khuraym, which experiences high levels of disturbance in the winter due to thousands of visitors from surrounding areas. Restoring wildlife biodiversity in this area will depend on the restoration of the currently degraded habitat. As a first step the native vegetation, including palatable species for native ungulates and reptiles, will need to be restored and natural regeneration needs to be stimulated. After the successful establishment of these plants for food and shelter, it is expected that wildlife will reoccupy the area from its surrounding and missing keystone species can be reintroduced, increasing the biodiversity.

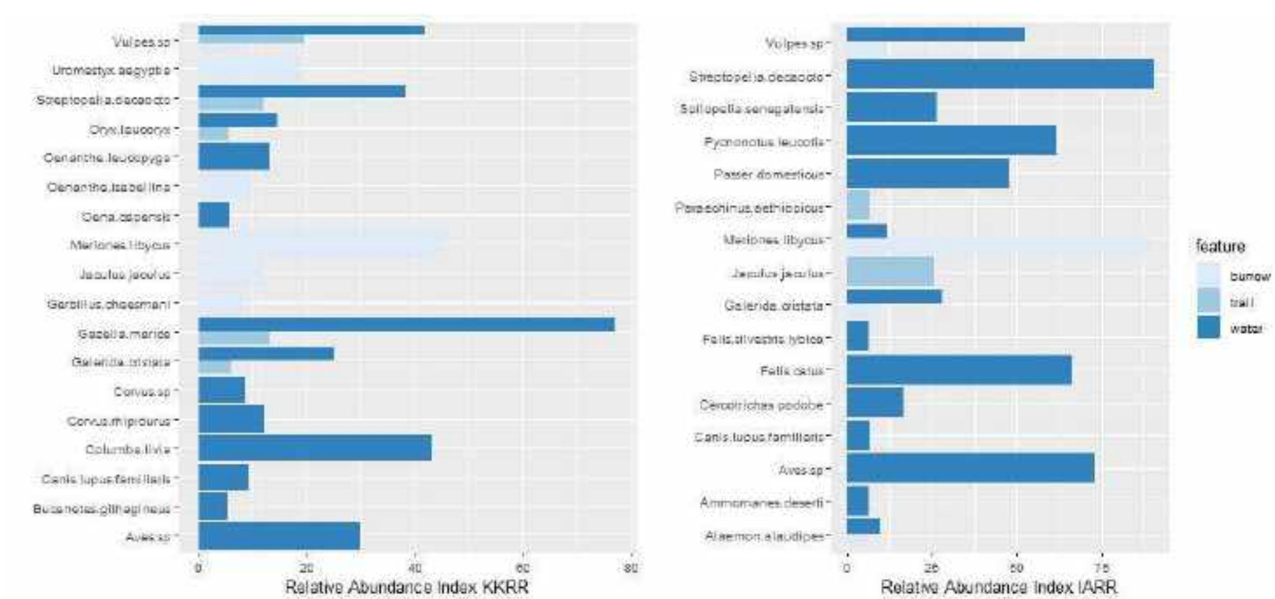

Figure 2. Relative Abundance Index of species frequently encountered (i.e., RAI >5)

For the success of reintroduction programs, it is important to understand the spatial abundance of potential predators near release sites. For example, releasing Asian houbara in areas with low predator abundance (foxes, wild cats, honey badgers) will increase their survival rate, especially after a hard release when they still need to find suitable habitat for shelter. Equally important for species conservation is identifying the locations of stray cats and dogs, as they not only compete for resources with wild cats and wolves but also pose a risk of interbreeding, which can lower genetic integrity. Additionally, dogs can prey on small gazelles or even attack oryx when in packs, and could outcompete the remnant wolves.

Results from our study provide insights into the spatial occupancy of predator and prey animals and highlighted areas of high abundance. Furthermore, they offer crucial information on the spatial abundance of threatened species, which can inform spatial management strategies to effectively protect and conserve these animals.

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Grazing management and low-stress herding to prevent livestock predation by grizzly/brown bears: a case study in the Rocky Mountains, USA

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Key words: depredation; livestock-carnivore coexistence; low-stress livestock handling; range riding; stockmanship

Abstract

Low-stress herding is a method to apply strategic grazing management, and possibly to reduce vulnerability to predation by rekindling herd instinct and increasing effective stocking density, facilitating collective anti-predator behaviour—similar to the group-size effect in wild prey species (Barnes 2015a,b).

We collaborated with ranchers and agency partners on a grazing allotment in the Wind River Range of northwestern Wyoming, USA, where permittees were having difficulty implementing a grazing rotation without cross-fences, and cattle had been lost to grizzly bears (North American brown bears; *Ursus arctos*) and other predators including gray wolves (*Canis lupus*). For 3 years, we hosted workshops on low-stress livestock handling, including hands-on practice in the field, and we attempted a grazing rotation through 7-9 mostly unfenced units, with at least one rider on the allotment most days.

In the 3 years prior to the project (minimal grazing management), cattle tended to scatter, and the ranchers lost 0.8-19.1% of calves per year, as well as a few yearlings and adult cattle, to all causes during the summer grazing season. In the year of highest losses, one rancher lost 19.1% of calves, and bear predation accounted for 6.7% of calves (about 1 of every 3 deaths). During the 3 years of the project (rotation by low-stress herding) the cattle self-organized into larger groups, although never a single large group: a modest improvement over previous years (but not all that is possible with low-stress herding). Losses to all causes were 2.8-7.7% of calves per herd per year, as well as a few yearlings and adult cattle, with 0 confirmed predation losses. This reduction in both total and predation losses followed a modest improvement in handling skill, herd instinct, and effective stock density. While we cannot conclusively attribute causality, this result continued for the 3 years of the project.

Introduction

Livestock producers may be able to reduce vulnerability to predation by managing herds in ways similar to the group size effect (prey aggregation), a well-known anti-predator behaviour in wild prey, through strategic grazing management that involves increased stock density and movement around the landscape (Barnes 2015a,b). Low-stress livestock handling (LSLH) techniques have many benefits including rekindling the herd instinct (Cote 2004; Hibbard and Barnes 2016), which when applied to herding (low-stress herding; LSH) can facilitate strategic grazing management (Barnes 2015b; Barnes and Hibbard 2016) and possibly reduce predation, as theorized by Barnes (2015a). Other LSH practitioners have noted that their methods appear to reduce predation losses through associated behavioural changes (Zaranek 2016) and are transferrable (Louchouarn and Treves 2023), and thus are important practices for range riders where potential predators, especially species of conservation concern such as grizzly bears and wolves, are present.

Methods

We collaborated with ranchers and agency partners on a summer grazing allotment on the Shoshone National Forest in the Wind River Range of northwestern Wyoming, USA, where before the project, the two ranches (permittees) who shared the allotment were having difficulty implementing a grazing rotation without cross-fences, and cattle had been lost to grizzly bears and likely other predators including gray wolves. During the project, for 3 years (2014-2016), we hosted workshops on LSLH, including hands-on practice in the field, and we attempted a grazing rotation through 7-9 subunits (with only one cross-fence separating two of the subunits), with at least one rider on the allotment most days.

Ranches differed in initial livestock handling and adoption of the methods. Ranch A believed they were already practicing LSLH, though their methods were more accurately described as relatively skilled conventional handling; one of several individuals from the ranch attended the workshops, and may have made modest improvements in handling, but overall ranch A did not make major changes. Ranch B had practiced conventional handling; both of two individuals attended the workshops and did their best to adopt LSLH. Thus this case study has a design similar to before-after-control-impact (BACI), but more accurately a non-equivalent groups design where ranches A and B are not replicates, and ranch A is not strictly a control treatment, but rather ranch A had a lower level of treatment or impact than ranch B. Before the project, grazing management was relatively extensive and handling was conventional; during the three-year project, grazing management intensified somewhat, and became more low-stress, albeit less so for ranch A than ranch B.

At least one individual from one or both ranches functioned as a range rider on most but not all days, and attempted to combine smaller groups of cattle into larger groups—ideally (but rarely) a single large group—and attempted to follow the grazing rotation to the best of their ability.

To assess the effect of these management changes, we compared livestock loss data from the three years before the project (2011-2013) to the three years during the project (2014-2016), for the herds from ranches A and B (herds A and B). Losses were obtained from U.S. Forest Service (USFS) 'Actual Use' forms submitted by each permittee each year, and were categorized as: confirmed grizzly; suspected predator (possibly grizzly, wolf, black bear, or mountain lion, but not confirmed); sickness or other (including poisonous plants); and unknown (including missing). Confirmation was determined by the Wyoming Game and Fish Department. In one year, missing cattle were recorded by the permittee as suspected predation, but because there was no evidence these were recategorized as unknown.

The project was considered to end after 2016 because of personnel turnover at the conservation organization, one of the ranches, and the USFS.

Results

Grazing management

We were modestly successful at improving grazing management. Before the project, herd A had been more cohesive than herd B. During the project, overall, the cattle tended to be in fewer, larger groups, and there was more mixing of the cattle from the two herds, but they did not form a single socially-cohesive herd. More but not all of the cattle were in the appropriate subunit as intended in the planned rotation. Overall utilization was light and rangeland health was good, with two small areas used slightly more than desired, one by each base herd (M. Buzalsky, USFS, pers. comment). Herd A behaved mostly similarly to before the project. Commensurate with the greater degree of adoption of LSLH on ranch B, herd B made more improvement, in terms of cattle being in larger groups and more often with cattle from herd A.

Livestock losses

Most livestock losses were to sickness or unknown causes, rather than confirmed or suspected predation, both before and during the project. Losses to confirmed grizzly bear predation and suspected predation were substantial before the project, but stopped completely during the project, while losses to sickness and unknown causes continued. (Fig.1)

Before the project, all confirmed predation was in herd B; suspected predation was more prevalent in herd A. herd A had suspected predation of mean 2.1% (range 0-5.0%). Herd B had confirmed predation of mean 2.6% (range 0-6.7%), and confirmed plus suspected predation of mean 2.8% (range 0.6-6.7%).

Total losses were initially lower in herd A than herd B; they increased slightly in herd A, while they decreased substantially in herd B. Before the project, across both herds, total losses were from 0.8-19.1% of calves per herd per year; and lower in herd A (mean 3.2%, range 0.8-5.0%) than herd B (mean 10.6%, range 5.8-19.1%). During the project, total losses were 2.8-7.7% per herd per year; similar in herd A (mean 4.8%, range 2.8-7.7%) and herd B (mean 4.3%, range 3.2-6.0%).

Discussion

We provided training in LSLH, so that two ranches could practice LSH to implement a rotation and possibly reduce vulnerability to predation. One of two ranches (A) made slight improvements, while the other (B) embraced LSLH. Even with imperfect implementation, the two ranches eliminated confirmed (herd B) and suspected (herd A) predation by grizzly bears and other potential predators. It is possible that some of the unknown losses before and during the project were to predation. The herd (B) that had all of the confirmed predation before the project, and whose operators made greater management changes, also experienced reduced total losses to about the level of the other herd (A), while the herd (A) whose operators mostly continued previous practices had a slight increase in total (likely non-predation) losses.

These results are consistent with the hypothesis that LSLH, particularly when used in the form of LSH to increase stock density or group size and facilitate strategic grazing management (Cote 2004; Barnes 2015b; Hibbard and Barnes 2016), can reduce vulnerability to predation, and should be considered an important aspect of range riding in predator habitat (Barnes 2015a; Zaranek 2016; Louchouarn and Treves 2023). In this case study, we cannot conclusively attribute causality, but the results are compelling. Future studies should employ rigorous experimental or quasi-experimental design (e.g., BACI), if feasible given the challenges of field conditions.

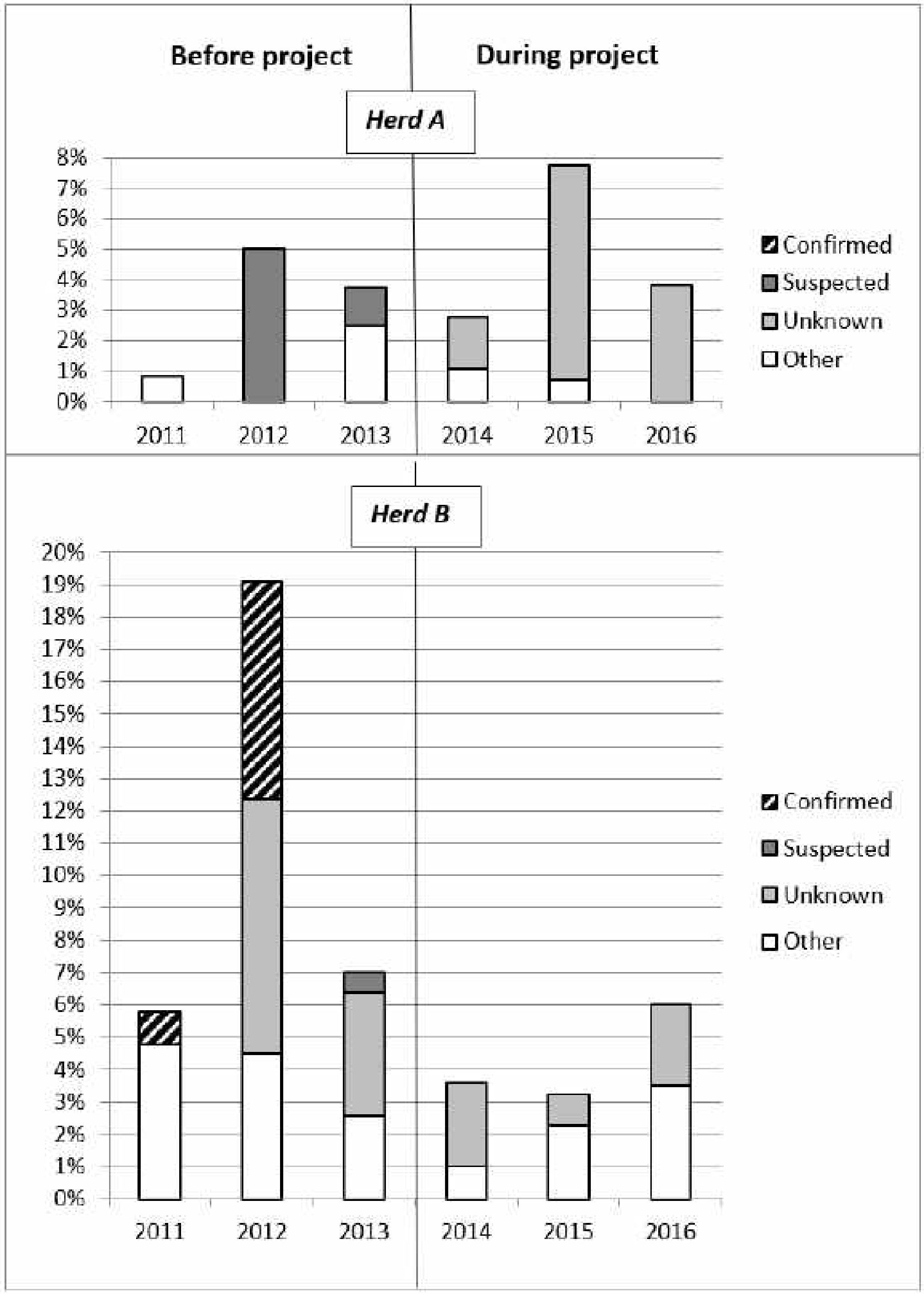

Fig.1. Cattle loss to confirmed (grizzly bear) and probable (bear, wolf, or cougar) predation, unknown causes, and other known losses (sickness), before and during a herding project, in two herds (A, B) that shared an allotment. Operators of both herds received training in low-stress livestock handling, but the methods were more fully adopted by the operators of herd B.

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Fencing the future: enhancing livestock management and wildlife conservation with virtual fencing

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Key words: fencing; technology; ecosystem health; human-wildlife conflict

Abstract
Virtual fencing technology presents a potentially transformative approach to livestock management across extensive rangeland systems with significant implications for wildlife conservation. Virtual fencing enables remote and dynamic management of livestock movement, offering solutions to mitigate the adverse impacts of traditional physical fencing on landscape connectivity, reduce wildlife-livestock conflicts, and exclude grazing in sensitive habitat areas. In this paper, we present a framework outlining the diverse applications of virtual fencing to conservation efforts and present insights from several pilot case studies from the North American Great Plains and Greater Yellowstone Ecosystem, USA. We examine the operational approaches, and adaptive strategies employed to integrate virtual fencing into existing rangeland management practices, and their potential impact in achieving wildlife conservation goals as part of a working livestock operation. Despite the promising potential of virtual fencing, pilot applications have encountered a range of technological, social, and policy barriers. The findings from the case studies underscore the necessity for continued innovation, stakeholder engagement, and policy reform to harness the full potential of virtual fencing. We argue that, by addressing these considerations, virtual fencing technology can substantially contribute to the co-objectives of livestock production and wildlife conservation. By enhancing landscape connectivity, reducing human-wildlife conflicts, and minimizing habitat impacts, virtual fencing represents a pivotal step towards more sustainable rangeland management.

Introduction

Livestock grazing is the most extensive land use globally, occupying approximately 25% of the Earth's terrestrial surface (Asner et al., 2004). Physical fencing is a key grazing management tool to control the spatiotemporal distribution of livestock (Bailey, 2004) and plays a large role in human socio-ecological interactions worldwide (Xu and Huntsinger 2022). While nearly universally associated with grazing, traditional fencing has only recently received widespread conservation attention (McInturff et al., 2020), including the recognition that fencing can have considerable ecological and economic drawbacks.

Traditional fencing can create social conflicts by reducing human mobility and weakening social relationships, fragment landscapes that reduce wildlife mobility, cause direct mortality due to collision and entanglement, facilitate the spread of invasive species, and reduce native plant diversity, leading to potential widespread ecological consequences (Harrington and Conover, 2006, Jakes et al., 2018, McInturff et al., 2020, Xu et al., 2021, Xu and Huntsinger 2022). From an economic perspective, fencing is a major input and expense for livestock producers. For instance, new fencing in the western USA can be upwards of $25,000/mile and requires significant physical and financial maintenance once erected. Given these challenges, there is a need and demand for new ways to contain livestock while offsetting some of the potential negative effects of traditional fence.

There is a growing interest in technological solutions that can meet the needs of livestock management while minimizing negative ecological impacts and reducing costs for producers. Virtual fencing provides a potential win-win solution that can enhance livestock operations while providing significant conservation benefits that extend beyond simply reducing physical fencing. Below, we provide an overview of emerging virtual fencing technology, detail the specific functions virtual fencing can provide to realize conservation benefits, and provide insights from initial pilot applications.

Methods

We employed two complementary approaches to identify conservation opportunities and implementation challenges associated with virtual fencing technology: an expert stakeholder workshop and semi-structured interviews with key stakeholders involved in pilot projects. In June 2024, we convened a three-day workshop in Bozeman, Montana, that brought together over 40 experts from across technology, agriculture, government, and conservation sectors. Expert workshops have been shown to be effective for synthesizing diverse knowledge and identifying priorities in conservation planning (Sutherland et al., 2011). The workshop, co-hosted by the Property and Environment Research Center and the Beyond Yellowstone Program, with support from multiple conservation organizations, focused on understanding the current state of virtual fencing technology, evaluating its conservation potential, and identifying barriers to adoption. Participants included virtual fencing technology developers, ranchers with direct experience implementing the technology, conservation professionals, researchers, and government agency representatives. Through facilitated discussions and working sessions, participants identified key functions of virtual fencing that enable conservation benefits and developed strategies for scaling adoption.

To complement the workshop findings, we conducted 15 semi-structured interviews with key stakeholders involved in four pilot projects implementing virtual fencing technology for conservation benefits (Young et al., 2018). Interview subjects included ranchers operating the technology and conservation professionals involved in project implementation. Semi-structured interviews are particularly valuable for understanding complex social-ecological systems and documenting stakeholder experiences with new conservation technologies. These interviews explored practical challenges encountered during implementation, documented early conservation outcomes, and identified opportunities for improving virtual fencing applications. The interviews provided detailed insights into the real-world application of virtual fencing technology and helped validate the functions and challenges identified during the expert workshop. Together, these methods provided a comprehensive understanding of both the theoretical potential and practical realities of using virtual fencing to achieve conservation outcomes.

Results

Key Functions and Potential Conservation Benefits

Based on the expert workshop, we identified five key functions of virtual fencing that provide significant conservation benefits. First, virtual fencing can reduce the need for physical infrastructure, helping restore landscape connectivity by removing barriers that fragment habitats, impede wildlife movement, and cause wildlife mortalities through entanglement and collisions (Jakes et al., 2018; Harrington and Conover, 2006). Second, virtual fencing enables precise livestock exclusion from sensitive areas through dynamic, remotely adjustable boundaries. This capability allows managers to protect critical habitats such as riparian zones (Belsky et al., 1999), breeding areas, and post-fire restoration sites (Boyd et al., 2022), with the flexibility to modify exclusion zones based on seasonal needs or changing environmental conditions.

The third function involves the strategic concentration of livestock, which can serve multiple conservation purposes. Operators can focus grazing pressure to control invasive species, create fuel breaks for wildfire management (Boyd et al., 2022), and reduce predation risk by grouping cattle away from areas that provide cover for predators (Kluever et al., 2009). The fourth function utilizes the technology's precise livestock tracking capabilities to aid in predator conflict mitigation. Real-time monitoring can detect abnormal herd movements indicating predator presence and enable rapid carcass removal to reduce predator attractants (Morehouse and Boyce, 2011).

Finally, virtual fencing provides unprecedented flexibility in timing grazing rotations, enabling sophisticated management strategies such as high-density, short-duration grazing. This approach can create habitat heterogeneity that benefits various wildlife species (Fuhlendorf et al., 2010; Krausman et al., 2009) while allowing for more strategic rest periods that promote ecosystem recovery (Briske et al., 2008). The technology's adaptability is particularly valuable in the context of climate change, as managers can rapidly adjust grazing patterns in response to changing environmental conditions, contributing to the overall resilience of grazed landscapes.

Challenges and Promise in Pilot Efforts

Based on the interviews with stakeholders involved in pilot virtual fencing projects, we identified several implementation challenges during early adoption phases. Initial efforts were often more ambitious than what could be realistically achieved in the first few years of deployment, with participants encountering technical obstacles such as collar retention issues and limited battery life. The learning curve for adopting the technology proved steeper than anticipated, requiring significant time investment from operators to become proficient with the system. Additionally, effective communication between conservation organizations and ranchers emerged as a critical factor for success. In one pilot project, misaligned expectations regarding timelines, funding arrangements, and technology deployment created challenges that could have been avoided through more structured communication protocols.

Despite these initial obstacles, stakeholders universally expressed optimism about the technology's potential and demonstrated strong commitment to continuing their virtual fencing programs. While documented conservation benefits have been limited thus far, largely due to implementation challenges that shifted focus away from specific conservation objectives, participants identified numerous promising applications for future deployment. Stakeholders emphasized that achieving conservation outcomes would require patience as operators progress through the learning curve and technical improvements enhance system reliability. The need for more durable collar designs was consistently highlighted as a priority for advancing the technology's effectiveness. As these pilot projects mature, participants plan to expand their focus on specific conservation applications, building on the operational experience gained during initial implementation phases.

Discussion and Conclusions

Virtual fencing represents a transformative technology for both livestock management and conservation, but realizing its full potential requires addressing several key challenges. While innovative producers are successfully implementing virtual fencing systems across large operations, widespread adoption faces three primary barriers. First, ongoing technological improvements are needed, particularly in areas of battery life, collar retention, and system reliability across diverse landscapes. Second, the significant learning curve for both operators and livestock requires substantial time investment and may initially disrupt established routines. Third, cost remains a critical factor, especially where existing physical infrastructure is functional. Although virtual fencing can be cost-competitive when compared to new fence installation or intensive range riding operations, the initial investment and ongoing maintenance costs can be prohibitive for many operators without external support or clear evidence of return on investment (Umstatter, 2011).

Conservation organizations can play a crucial role in accelerating adoption of virtual fencing technology through strategic partnerships and targeted support. Cost-share programs focused on critical conservation areas, such as migration corridors or sensitive habitats, could help overcome financial barriers while ensuring implementation achieves meaningful conservation outcomes. The success of such programs is evident in existing conservation initiatives, such as the USDA's investment of over $290 million in wildlife-friendly fence modifications since 2014 (USDA-NRCS, 2021). Similar programs could be adapted or developed specifically for virtual fencing adoption. However, these initiatives must be coupled with research to demonstrate conservation effectiveness and identify best practices for implementation.

Looking forward, the implications of successful virtual fencing adoption extend beyond individual ranch operations to landscape-scale conservation outcomes. The technology's ability to create dynamic, adaptable boundaries while reducing physical barriers could fundamentally reshape how we approach grazing management and wildlife conservation in working landscapes. However, realizing these benefits requires proactive engagement with the agricultural community and careful attention to both technical and social aspects of adoption. Strategic partnerships between conservation organizations and livestock operators, supported by targeted research and policy initiatives, will be essential for capitalizing on virtual fencing's potential to advance both agricultural productivity and biodiversity conservation goals.

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Frequency distribution, species richness and egg per gram of gastrointestinal parasites in free-ranging Papio Ursinus species in a semi-arid savanna ecosystem of Zimbabwe

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Keywords: baboons, wildlife-livestock interface, zoonosis

Abstract:
A cross-sectional study of the free-ranging baboon (*Papio ursinus*) troops was undertaken at the Epoch Mine campus, Insiza district, Zimbabwe with the objective of investigating the frequency distribution, species richness and eggs per gram (EPG) of gastrointestinal parasites among three baboon troops. Baboons are general feeders and have been observed to interact with both livestock and humans at Epochmine campus this can lead to cross exchange of parasites among these organisms. One hundred and twenty (120) fresh faecal samples were collected from February 2023 to September 2023. Floatation technique was utilised to process the faecal samples, thereafter samples were placed in Mcmaster slides and viewed under a microscope. Parasite ova were identified based on morphological features like size and shape. There was significant difference in the parasite frequencies among the troops (P=0.041). No significant difference (P = 0.311) was observed in parasite species richness. There was significant differences in egg per gram among the three troops (P=0.00193). The high frequency and EPG of gastrointestinal parasites among the three troops can be attributed to eating less of fortified food among peoples' resident bins and limited use of natural herbs. The high species richness among the baboons can be attributed to larger baboon home range thereby resulting in acquisition of many different gastrointestinal parasites along the way. The observed research outputs calls for active surveillance of gastrointestinal disease outbreaks among humans and livestock since the baboons carry potential zoonotic parasites.

Introduction
Parasites are a common threat in natural animal populations impacting the health of wild animals. The most prevalent of these parasites are the gastrointestinal (GIT) (Obanda *et al*. 2019). Parasites weaken the physical health of the host thereby affecting its ability to forage and consequently being fatal in some instances (Mason *et al*. 2022). Baboons are known to host parasites including those of zoonotic importance (Banda *et al*. 2024). Papio species easily adapt to different environments and interact often with humans

and livestock in the human-wildlife-livestock interfaces making baboons, humans and livestock prone to cross-species disease transmission (Ebbert *et al*. 2013). About 68-70% of the known primate parasites have been reported as multi-host species (Pedersen *et al*. 2005). Close interactions in wildlife-livestock interfaces due to sharing resources like grazing land and water sources can facilitate parasite spill over, spillback and species hybridization (Khanyari *et al*. 2022).

Zoonotic diseases of parasitic origins affect the health and behaviour of baboons and livestock which in turn impacts foraging patterns, vegetation patterns, range land biodiversity and poses a risk to livestock productivity and wildlife conservation (Talukdar *et al*. 2020). Understanding baboon-parasite dynamics and parasite epidemiology across multi-use rangelands is imperative to conservation strategies and mitigation of emerging parasitic diseases (VanderWaal *et al*. 2014). Parasite species richness is another metric often used in primate studies to understand parasite-host dynamics (Deere *et al*. 2021). In light of the foregoing, the study aimed to test the null hypothesis that frequency distribution and parasite species richness would be similar among the three troops present at the Gwanda State University, Epoch Mine campus where wild animals interact with livestock and humans. Especially more often the baboons interact with livestock, eating the animal feed, goat kids if unattended and drinking from livestock water points. This association will likely lead to cross exchange of parasites between baboons and livestock.

Materials and methods

Study site

The study was done at Gwanda State University, Epoch Mine campus, Filabusi, Insiza district. Insiza district is situated in Zimbabwe's natural agro-ecological region 4, which receives mean annual rainfall of 350mm and has mean temperature ranges from 9.93°C to 33.8°C (Chisadza *et al*. 2023). Other primates present in the study area were Vervet monkeys (*Chlorocebus pygerythrus*) (Banda *et al*. 2024).

Sample collection and analysis

Using a descriptive and analytical cross-section design (Larbi *et al*. 2020), the study was undertaken to investigate the frequency distribution, species richness and egg per gram (EPG) of gastrointestinal parasites among three free-ranging baboon troops. One hundred and twenty (120) fresh faecal samples were collected from February 2023 to September 2023. The troops were trailed and fresh faecal samples were randomly collected immediately after defecation or when the baboons had left the immediate vicinity (Banda *et al.* 2024). Collected faecal samples were immediately preserved in 10% formalin. Analysis of samples was done at the Bulawayo Provincial Veterinary Laboratory using the centrifugal floatation technique to process the faecal samples (Hansen and Perry 1990). Thereafter the McMaster technique was used to quantify the observed parasite ova using a compound light microscope (Optika brand, Italy) at x100 magnification (Zajac *et al*. 2021). Parasite ova were identified based on morphological features like size and shape (Taylor *et al*. 2015). Identification was done to suborder and genus level.

Data analysis

Frequency distribution was analysed graphically and a Chi-square test was used to determine if there was significant difference among the troops (Fowler et al. 2013). Margalef index (D_Mg) was used to measure parasite species richness (Aslam 2009). A Kruskall-Wallis test was conducted to test for significant differences among troops. Egg per gram was counted using the McMaster egg counting technique. A Kruskall-Wallis test was conducted to test for significant differences among troops. Analysis was done using the R Studio package version 4.3.2 (R Core Team, 2022).

Results

Six parasite taxa were observed (Figure 1). Troop 1 had the highest number of samples infected with one or more parasite taxa. *Strongylid* nematodes had the highest frequency across the three troops followed by *Schistosoma* spp.

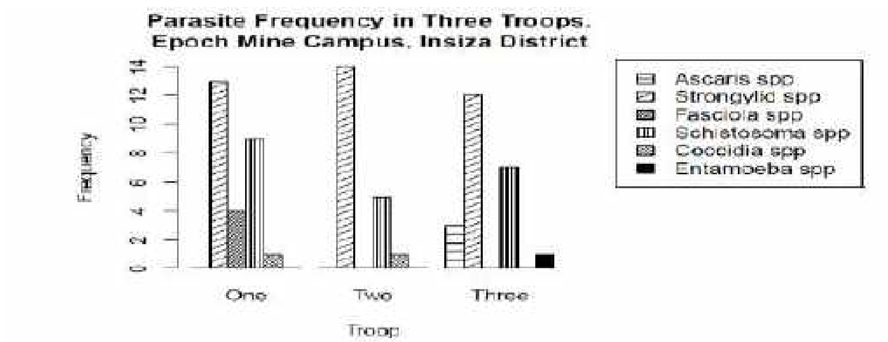

Figure 1 Frequency of parasites in three *Papio ursinus* troops at the Epoch Mine campus, Zimbabwe

A Kruskall-Wallis test indicated significant differences among the troops frequencies (*P*= 0.041). Furthermore, pairwise comparison using Dunn's test (post-hoc analysis) showed no significant differences (*P*= 0.541) between Troop 2 and Troop 3 troops frequencies. However, Troop 1 significantly differed from Troop 2 troops (*P*= 0.026) and Troop 3 (*P*= 0.012) frequencies.

Parasite Species Richness

The Margalef Index (D_Mg) indicated that Troop 3 had the highest parasite species richness (D_Mg =1.361) followed by Troop 1 (D_Mg =1.315), whilst troop 2 had the lowest (D_Mg =1.038) However, there was no significant difference in parasite species richness among the three troops (*P* = 0.311).

Egg per gram

Schistosoma spp. in troop 2 had the highest average EPG among all three troops across all species. The average EPG for Strongylid was the highest in troop 2 (303.85 EPG), while lowest in troop 3 (195.83 EPG). *Coccidia* spp and *Entamoeba* spp had the same and the least average epg. There was a significant difference in average epg among the three troops (Kruskal-Wallis, *P*= 0.00193). A pairwise comparison indicated that troop 1 significantly differed from both troop 2 and 3 (Dunn's test, *P*=0.037; *P*=0.002, respectively), however troop 2 and 3 are not significantly different (Dunn's test, *P*= 0.145).

Discussion

The study observed four helminths and two protozoa taxa. There was a significant difference among the troop frequencies. Strongylid nematodes are common parasites of baboons and they co-occurred in all troops with high frequency (Obanda 2015). Strongylid nematodes have been observed to cause severe diarrhoea; weight loss leading to death if left untreated; affect the respiratory and the gut system in livestock (Income *et al*. 2021). Schistosomiasis caused by *Schistosoma spp* is a neglected tropical disease infecting primates, livestock and humans (Jones *et al*. 2011). Schistosoma species have been found to hybridise, this suggests the probability of exponential growth in emerging zoonotic parasites which might be of public health and veterinary importance (Tober *et al*. 2021). Despite *Coccidia spp* and *Entamoeba spp* being asymptomatic and recording low frequencies in the study, there is a need for further research on the pathogenicity of such species (N'da *et al*. 2022).

The parasite species richness in this study included six species, which is comparable within the range of most parasite species richness observed in most baboon populations of five to eight species (Obanda 2015). No significant differences were noted in parasite species richness among the troops which may be attributed to similar intermediate host ecology in the study area and parasite migration which may occur due to a new individual joining another troop after being chased away from their own troop (Ebbert *et al*. 2013). Five of the taxa have been well-documented in primate studies except for *Fasciola* spp. which was observed in troop 1 only (Banda *et al*. 2024). Further research on spill over and transmission of parasites from baboons to domestic, wildlife species and humans in the study area is imperative. Parasites of zoonotic potential observed in this study highlight the necessity for caution regarding monitoring emerging, re-emerging infections and conservation efforts (Hahn *et al*. 2003). The significant differences in average EPG among different troops may be due to variations in the troops foraging areas. Some troops may be eating more of fortified food from human dustbins, while others forage where livestock graze, thus exposing them to high risk of parasites from livestock (Ryan *et al*. 2012).

Conclusion

The presence of gastrointestinal parasites in baboons suggests future health and livestock productivity implications due to disease emergence and re-emergence. The study highlights the need for active surveillance system to be put in place so as to curb public health and veterinary diseases. Further on, a wider scope/area coverage study is needed as this is a study in a University campus which may differ from the real situation in the country. Strongylid nematodes were not identified to species level hence it is difficult to conclude whether the high frequency observed was a result of a single species or mixed infection of Strongylid nematodes (Ryan *et al*. 2012). This underscores the need for molecular analysis of parasites to the species level to ascertain the potential health implications.

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Soils and rare plant habitat in the Colorado Plateau

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Key words: endemic plant, soil depth, species conservation, rangeland planning

Abstract

It is common for botanists and plant ecologists to study the soil of rare plants by sampling the soil surface horizon and analyzing pH and a few other chemical properties, often looking for a "silver bullet" to explain rare plant distribution. It is rare in these studies to investigate the whole soil in a landscape context. However, multiple pedological studies of rare plants in the arid and semiarid climate of western North America's Colorado Plateau reveal a unique soil physical habitat where few other plants exist. These rare, endemic plants adapted and survived in soil environments and edaphic conditions that most plants are unable to survive in, effectively creating a competition-free zone. Shrubby reed-mustard (*Schoenocrambe suffrutescens*), Jones' waxy dogbane (*Cycladenia humilis* var. *jonesii*), Parachute beardtongue (*Penstemon debilis*), and Debeque phacelia (*Phacelia submutica*) all occur in shallow soils in distinct sedimentary rock strata. In the case of *Schoenocrambe suffrutescens*, the habitat was successfully modelled using remotely sensed and topographic data in order to locate new occurrences, and we believe there is potential for modelling potential habitat for the other species. In some cases, the harsh soil physical environment was also associated with one or more chemical properties that are challenging for most common plants. Understanding where these rare endemic plants occur and how they persist facilitates rangeland planning decisions.

Introduction

It is common for botanists and plant ecologists to study the soil of rare plants by sampling the soil surface horizon and analyzing pH and a few other chemical properties, often looking for a "silver bullet" to explain rare plant distribution. It is rare in these studies to investigate the whole soil in a landscape context. There is a relatively high concentration of rare endemic plants in the Colorado Plateau known only to occur in small, specific geographic areas, generally fragmented into smaller subpopulations.

The Colorado Plateau was a basin subject to more than 300 million years of sediment deposition. About 20 million years before present, the region began uplifting and continues to uplift today, reaching elevations of more than 3000 m. The region of 390,000 km^2, centered at the four corners where the states of Utah Arizona, New Mexico and Colorado meet, was dissected by the Colorado River and its tributaries, resulting in tablelands, plateaus, mesas. The elevation ranges from 750 to 3840, the mean elevation is 1936 m, and the climate is mainly arid to semiarid.

We hypothesize that the uplift and dissection of the Colorado Plateau over 20 million years has led to genetic isolation and speciation of plants. The objective of this study was to determine the soil and landscape habitat of four rare endemic plant species in the Colorado Plateau to develop concepts that can help guide rangeland planning that is compatible with conservation efforts.

Methods

Three of the plant species, *Penstemon debilis*, *Cycladenia humilis* var. *jonesii*, and *Phacelia submutica* are listed by the US Fish and Wildlife Service (USFWS) as "Threatened" and one, *Schoenocrambe suffrutescens*, is listed as "Endangered" (USFWS, 2024). *Penstemon debilis*, commonly known as Parachute beardtongue and thought to tolerate toxic trace elements, is a mat-forming perennial that was reported to occur only in the Parachute Creek member of the Green River Formation in western Colorado (McMullen, 1998). *Cycladenia humilis* var. *jonesii*, commonly known as Jones' waxy dogbane and reported to be a gypsophile (Welsh et al., 2015), sometimes thought to be an indicator of selenium (Se) and/or uranium (U), is a perennial that occurs in several Jurassic and Triassic sedimentary rock formations of southern Utah and northern Arizona. *Phacelia submutica* commonly known as Debeque phacelia and thought to tolerate high shrink-swell capacity in soil, is a tiny, low-growing spring annual that occurs only in western Colorado in the "clay barrens" of the Atwell Gulch and Shire members of the Tertiary Wasatch Formation (Langton, 2015). *Schoenocrambe suffrutescens*, commonly known as shrubby reed-mustard and also classified in the literature as *Hesperidanthus suffrutescens* and *Glaucocarpum suffrutescens* (Lewis and Schupp, 2014), is a perennial that occurs only in northeastern Utah in the Green River Formation.

We investigated the soil and landscape characteristics at five populations for *Penstemon debilis*, four populations for *Cycladenia humilis* var. *jonesii* in southern Utah, five populations of *Phacelia submutica*, and three populations of *Schoenocrambe suffrutescens*. We manually excavated soil pits to 1m depth or to a hard rock contact, whichever was shallower. We described soil morphology and sampled soils following standard methods (Schoeneberger et al., 2012). We sampled soil at least 50 cm away from the rare plant in its habitat. In the case of *Schoenocrambe suffrutescens* we also sampled at least 50 cm away from a similar plant in a similar habitat. We determined selected soil physical and chemical properties in the laboratory, including particle-size distribution, pH, calcium carbonate equivalent, gypsum content (if present), and total elemental composition (Soil Survey Staff, 2014). In the case of *Schoenocrambe suffrutescens* we also modeled topographic and remotely sensed spectral characteristics (Baker et al. 2016).

Results

Penstemon debilis occurs in soils formed in shale of the Parachute Creek member of the Tertiary Green River Formation. Plants occurred at elevations ranging from 2425 to 2740 m on steep slopes of 45 to 67% gradient. The soils surface was bare, with very high rock fragment content between very few plants. Soils were shallow, ranging from 17 to 55 cm in depth, and roots were observed in between rock fragments in the fractured shale. In contrast to these similar physical properties, different populations had dissimilar soil chemical properties, with pH ranging from 6.8 to 8.3 and the total elemental content of Se, As, and Hg highly variable. Plants were observed to survive on steep, unstable, shale slopes, with stems appearing to elongate as leaves were buried by shifting talus (McMullen, 1998).

Cycladenia humilis var. *jonesii* soils all had similar site and soil physical properties (Boettinger and Sipes, 1997). The plants occurred on stable slopes of 5 to 50% gradient. Soils were mostly bare, with few plants. Soil parent materials ranged from mudstone to shale to siltstone, all fractured in situ. Soil depth to bedrock ranged from 25 to 50 cm in depth with extremely high rock fragment content in subsoil (90 to nearly 100%

by volume) in the lower part. Roots were observed in between rock fragments in the fractured rock. We were unable to sample sufficient fine-earth fraction material (<2 mm) to characterize texture in the laboratory for most horizons. As with *P. debilis*, the soils at each population had dissimilar soil chemical properties. The soil pH ranged from 6.8 to 8.3. Trace element content of the whole soil (<2-mm and rock fragments) was highly variable. Gypsum was present in soils of only half of the populations – soils in the Castle Valley and Onion Creek populations in southeastern Utah contained gypsum, whereas soils in the San Rafael Swell and Deer Creek populations in southcentral Utah lacked gypsum, which is evidence that *Cycladenia humilis* var. *jonesii* is not an obligate gypsophile.

Phacelia submutica soils all had similar site and soil physical properties (Langton, 2015). Plants occurred on stable slopes of 5 to 85% gradient. Elevation ranged from 1,532 to 1,958 m. Soil were bare with very few plants, and all were less than 30 cm depth to hard bedrock. Soil textures were clay with high clay content ranging from 40 to 85% with a mean of 70%. Soils all had strongly alkaline pH, ranging from 7.7 to 9.7 with a mean of 9.0. The electrical conductivity of some soils was relatively high (3 to 5 dS m^{-1}) in the horizon directly overlying bedrock. The roots of these short-lived annuals did not extend to the bedrock.

Schoenocrambe suffrutescens soils were generally bare with very few plants. The depth to hard bedrock in all soils was less than 59 cm, with most ranging from 9 to 39 cm, and all had high rock fragments (greater than 50% by volume). Soil textures were silt loam to loam. All soils were strongly alkaline, with pH ranging from 8.0 to 9.0, with a mean pH of 8.7. Calcium carbonate equivalent was greater than 50% by mass in the fine earth fraction. Available phosphorus (P) was low (less than <2 mg kg^{-1} soil). The edaphic habitat for *Schoenocrambe suffrutescens* was topographically and spectrally distinct, which facilitated modelling of potential habitat and subsequent identification of new occurrences (Baker et al., 2016).

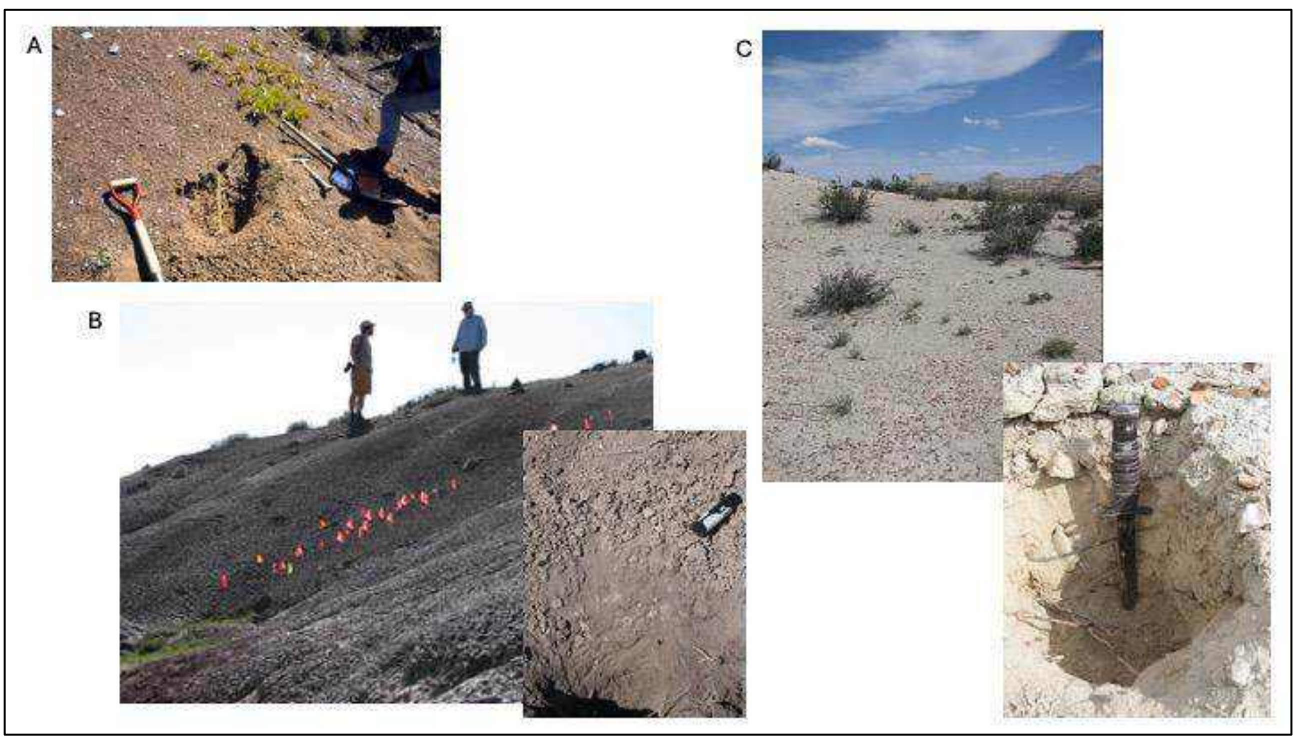

Fig. 1. Typical landscapes and soils of rare endemic plants of the Colorado Plateau. A) *Cycladenia humilis* var. *jonesii* plants (top) and high rock fragment soil on a steep slope in southeastern Utah; depth of soil is 35 cm. B) Red flags mark locations of *Phacelia submutica* on a steep slope in western Colorado; depth of

soil is 30 cm (inset photo). C) *Schoenocrambe suffrutescens* landscape on slope in northeastern Utah; depth of soil is 29 cm (inset photo). All photos by senior author.

Discussion

The key commonality is that all four endemic plant species of the Colorado Plateau can clearly tolerate harsh physical soil conditions. All soils were shallow and the rock fragment content for three of the four species (*Phacelia debilis*, *Cycladenia humilis* var. *jonesii*, *Schoenocrambe suffrutescens*) was very high (50 to 100% by volume). All species were able to tolerate steep slopes and *Phacelia debilis* appeared to have adapted to survive by stem elongation as rock fragments creep downslope due to gravity. The high clay and low rock fragment contents of the *P. submutica* soils were unusual, but still physically challenging for perennials. However, this very shallow-rooted annual is not adversely affected by shallow soils and completes its life cycle in spring when soils are moist, thus avoiding the damaging effects of shrink-swell.

Some endemic plant species of the Colorado Plateau can tolerate gypsum, high concentrations of calcium carbonate, and relatively high concentrations of potentially toxic trace elements such as Se, As, and Hg. However there appears to be no “silver bullet” in terms of a soil chemical property or set of properties that “restricts” these plants to a particular habitat; these species appear to tolerate these chemical conditions rather than require them. In addition, strongly alkaline soils with high pH and/or high concentrations of calcium carbonate have low nutrient availability (e.g., P), adding stress to the harsh soil and landscape physical environment.

These rare, endemic plant species are clearly stress tolerators able to survive in soil and landscape conditions where competitively dominant plant species cannot. We suggest that conservation of rare plant species that occur on otherwise bare areas, on steep slopes, and in shallow soils depends on habitat conservation of these small geographic areas. The occurrence of these plants on bare soil surfaces on distinct geologic formations and often steep slopes can facilitate spectral and topographic modeling of potential plant habitat, which can help locate additional plants and delineate specific geographic areas for conservation.

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Management impacts on rangeland soil carbon and nitrogen

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Conventional grazing decreases soil organic carbon by destroying physical and mineral protections

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Key words: Grazing; Soil organic carbon; Physical protection; Mineral protection

Abstract

Conventional grazing, with high grazing pressure imposed during the plant growing season, destroys soil structure and carbon (C) protection mechanisms. Soil C is protected from decomposition by encapsulation in soil aggregates or adsorption with metal oxide mineral fractions. However, the processes by which conventional grazing affects soil C protection and the level of soil organic carbon (SOC) remain unclear. We sampled 15 pairs of sites (180 plots) contrasting grazing exclusion inside the fence and conventional grazing outside the fence, in the temperate steppe of Inner Mongolia, China, to elucidate processes affecting soil C protection and to assess the relative contribution of physical versus mineral protection to SOC. We characterized the physical and mineral protection of C by soil aggregate stability (mean weight diameter, MWD) and soil Fe/Al associated organic C, respectively. Our results showed that conventional grazing decreased SOC content (-14.83%) and weakened SOC physical (-4.88%) and mineral (-10.88%) protection, mainly due to increased soil bulk density and pH, and decreased microbial biomass C, compared with grazing exclusion. In addition, conventional grazing-induced reductions in plant inputs (root biomass) could indirectly weaken the physical and mineral protection of C. Declined root-derived C inputs will limit microbial biomass C, thus hindering microbial contribution to soil aggregation and the formation of mineral C fractions. More importantly, we found that destroying physical (57.90%) and mineral (36.76%) protection combined governed the loss of SOC in conventionally grazed grassland. These results imply a need to manage rangelands in a way that retains more litter or root-rich plant species to ensure more plant inputs, promoting physical and mineral protection of soil C.

Introduction

Grassland ecosystems, account for 20% of the world's land area (Yang et al. 2021) and store 10-30% of the global soil organic carbon (SOC) (Ward et al. 2016). As the most widespread land use, livestock grazing profoundly affects SOC by altering plant inputs and soil environment, resulting in a solid potential to regulate SOC dynamics (Lai & Kumar 2020). Conventional grazing is a high-intensity grazing pattern at the peak of the plant growing season. However, previous research has not clarified the mechanism of conventional grazing affecting soil carbon (C) sequestration.

Physical and mineral protection are two fundamental mechanisms for stabilizing SOC (Bai et al. 2020; Chen et al. 2021). Soil aggregates, as the physical protection, are formed by aggregating mineral particles and organic matter (Blanco-Canqui & Lal 2004). While soil metal mineral ions and their oxides (mainly iron, aluminum, and calcium) can interact with organic material through covalent bonds and chelation, limiting SOC mobilization and degradation to act as mineral protection (Ye et al. 2018). Little attention is paid to their relative contribution to SOC in previous research.

Biotic factors ("litter effect" and "root effect") and soil abiotic factors may alter SOC protection in grazing grassland ecosystems (Witzgall et al. 2021; Ye et al. 2018). Increasing litter mass enhanced the input of litter-derived C to soil organic matter by promoting microbial metabolism (Wang et al. 2021), facilitating the bonding and formation of soil aggregation and mineral-associated C. Researchers have generally considered that plant roots might play a dominant role in the protection compared to aboveground plants (or litter) (Sokol & Bradford 2018). Importantly, as a potential soil C pool to maintain SOC stability, root biomass seems to suffer less under grazing disturbance than the changes in litter mass (Yang et al. 2021). Soil abiotic factors could also directly or indirectly influence SOC protection. Grazing might induce extreme trampling to increase soil compaction, directly destroying soil aggregates (Wiesmeier et al. 2012); simultaneously, soil compaction may inhibit root growth and soil microbial activity, especially mycelial extension, thus restricting polymerization of soil aggregates and organo-mineral complexes (Poirier et al. 2018). However, few studies have elucidated the relative contribution of biotic and abiotic factors to the physical and mineral protection in grazed grasslands.

Here, we investigated SOC under conventional grazing and grazing exclusion at 15 sites in a semiarid grassland of northeast China. We tried to elucidate the drivers of physical and mineral protection and the relative contributions of physical and mineral protection to SOC in conventional grazing systems.

Methods

The study site is located in the Hulunbuir Grassland, Inner Mongolia (48.38-50.17°N, 116.73-120.19°E, and 524-780 m altitude). The dominant plant species were *Leymus chinensis* Tzvel. and *Stipa capillata* L. A regional (including 15 sites) field survey was conducted in August 2021. The grassland was fenced into two natural treatments: inside the fence for grazing exclusion and outside the fence for conventional grazing. Grazing was excluded for 2 ~ 35 years in theses 15 sampling grassland.The conventional grazing sites in our study were judged to be heavy grazing based on grazing intensities response ratios for the different intensities of aboveground biomass, SOC content, and soil bulk density in a Chinese grassland meta-analysis (Jiang et al. 2020). Each site was sampled in pairs inside and outside the fence (six pairs of 1m × 1m plots), with a distance of 30m between each pair of sample plots (Song et al. 2018). The soil types were consistent between each pair of sampling plots.

Plant litter was collected in each sample plot and then dried at 65 °C for 48 h. Root biomass was obtained by taking three cores mixed with a root drill in each sample plot, removing stones and soil to retain roots, washing plant roots and then drying them at 65°C for 48h and weighing them. Soil bulk density (BD) was determined using the cutting ring method. After three soil cores were taken by soil drill within each sample plot, they were mixed and passed through a 2 mm sieve to remove stones and roots, and the resulting soil samples were divided into two parts (air-dried and frozen). Frozen soil was used for the determination of soil microbial biomass carbon (MBC), which was fumigated with chloroform and extracted with 0.25 M K_2SO_4 and determined on a TOC analyzer (Multi N/C 3100) (Ding et al. 2016). Air-dried soil was used to determine other soil properties. Soil pH (soil: water of 1: 2.5) was determined using a pH meter. Soil total nitrogen (TN) content was determined using an elemental analyzer (Vario Macro, Germany), and SOC content was determined using an elemental analyzer for soil samples after hydrochloric acid fumigation. The physical protection of soil C was represented by the soil aggregates stability (mean weight diameter, MWD), which was determined by the wet sieving method using a soil aggregates wet apparatus (081301, Eijkekamp, Netherlands) to sieve the soil into macroaggregates (0.25 mm), microaggregates (0.053-0.25 mm), and silt and clay (<0.053 mm) (Kemper & Rosenau 1986). MWD is the sum of the product of the particle size of each aggregate and the weight percent of each fraction (Xu et al. 2021). Mineral protection of soil C was represented as soil Fe/Al associated organic C (Fe/Al-OC), which was extracted from the soil using the CBD method and determined by a TOC analyzer (Fang et al. 2019).

The grazing response ratio of each index was $Ln\ (Index_{conventional\ grazing} / Index_{grazing\ exclusion})$. A mixed linear model was used to test the effect of grazing on each variable, with the site as a random factor. Structural equation modeling (SEM) was used to analyze the pathways by which conventional grazing reduces physical and mineral protection of soil C, and multiple regression analysis was used to analyze the relative contribution of physical and mineral protection to SOC.

Results

SOC content in conventional grazing grassland was 14.84% lower than in grazing exclusion ($p < 0.01$, Fig 1a). For physical protection, the MWD was significantly lower in grazed than grazing exclusion grassland ($p < 0.01$, -4.88%, Fig 1a), resulting from the decrease in weight percentage of macroaggregates and increase in microaggregates ($p < 0.05$, Fig 1a). For mineral protection, soil Fe/Al-OC content was significantly lower in the grazed area than in the grazing exclusion area, reduced by 10.88% ($p < 0.05$, Fig 1a). In addition, Grazing reduced litter mass, root biomass, and MBC ($p <0.01$, Fig 1b). Regarding soil abiotic factors, grazed grasslands had lower soil BD and pH than the grazing exclusion grasslands ($p <0.05$, Fig 1b).

Concerning physical protection, grazing affected soil properties by decreasing root biomass (Fig 1c). Grazing-induced changes in MBC were determined by soil properties (Fig 1c). The changes in MWD were indirectly affected by grazing and jointly determined by MBC, root biomass, and soil properties (Fig 1c). For mineral protection, grazing-induced change in litter mass reduced soil Fe/Al-OC (Fig 1c). Additionally, changes in soil Fe/Al-OC resulted from reduced MBC and increased soil BD and pH by grazing (Fig 1c). Multiple regression analysis indicated that soil physical protection and mineral protection governed SOC content ($p< 0.001$, Fig 1d).

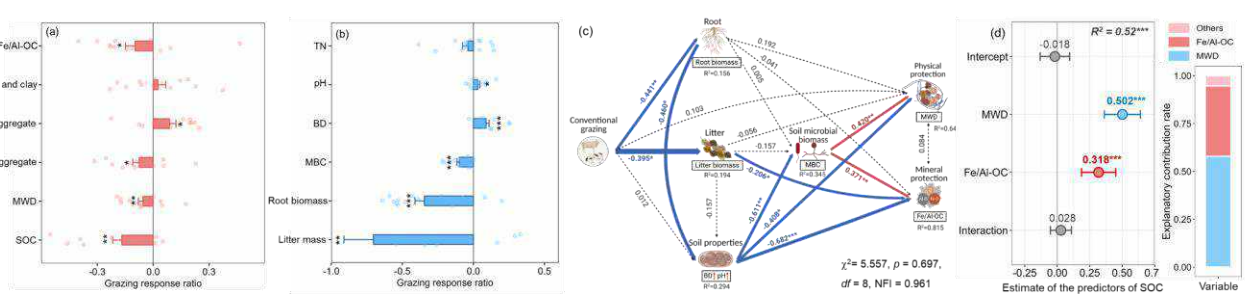

Figure 1 Grazing response ratios for each variable (a, b) with mechanisms by which grazing reduces soil organic carbon and its physical and mineral protection (c, d). The thickness of the arrows in the structural equation model represents the magnitude of the path coefficients, with red arrows representing positive relationships and blue arrows representing negative relationships. “*”, “**”, and “***” indicate that the result was significant at p <0.1, <0.05, <0.01, and <0.001, respectively. SOC: soil organic carbon; MWD:

mean weight diameter of soil aggregate; Fe/Al-OC: Fe/Al associated organic carbon; MBC: microbial biomass carbon; BD: soil bulk density; TN: soil total nitrogen.

Discussion

Plant roots and soil conditions are the main factors influencing SOC physical protection in grazing grasslands. In our study, grazing-induced decreases in root biomass may affect the formation of soil aggregates and alter root-derived C, driving SOC destabilization (Dijkstra et al. 2021). Previous studies found that continuous livestock grazing might inhibit root growth, and lower the input amount of root-derived C into the soil. That might aggravate the negative effects of physical entanglement in the aggregate and root exudates production (Poirier et al. 2018). We found that soil abiotic factors can mediate microbial pathways under grazing, indirectly affecting SOC physical protection. Soil microbial activity and biomass could be inhibited by soil abiotic factors such as soil pH and BD by filtering out some acidophilic microorganisms and reducing oxygen in grazed grasslands. Meanwhile, soil microorganisms decomposed the small molecular organic matter, mycelium, and other binding substances released as a result of the crushing soil aggregates (Fig 1a), thus destroying the physical protection of the SOC (See et al. 2022; Witzgall et al. 2021). All these processes may contribute to SOC destabilization, and the role of soil microorganisms should be considered more in the future.

In particular, grazing-induced reduction in litter mass and root biomass might decrease the potential input amount of plant-derived C, resulting in less production of soil mineral-associated organic C (Yang et al. 2021). Nevertheless, some organic acids (e.g., oxalic acid) in root deposits disrupt covalent metal bonds and mineral adsorption with mineral-associated organic C and increase soil hydrogen ions (Keiluweit et al. 2015). Previous research illustrated that soil microbial biomass and activity were significantly affected by below-ground input (Sokol & Bradford 2018). Then, the lack of microbial-derived C was associated with the decline in vivo turnover of soil microorganisms and the ability of microbial residues to interact with minerals (Lavallee et al. 2020). Our results also suggested that MBC was essential in regulating SOC chemical protection in grazing grasslands.

The multiple regression analysis suggested that SOC physical and chemical protection interact with each other and jointly benefit the retention of SOC. The involvement of soil metallic minerals in forming soil aggregation was like forming stable metal bonds and metal bridges (Bronick & Lal 2005). The adsorption of metal oxides to small molecules of organic matter enhanced the stability of the physical aggregation structure, especially iron and aluminum oxides (Regelink et al. 2015). Grazing negatively affects SOC physicochemical protection and thus promotes SOC loss.

Conventional grazing decreased physical and mineral protection of soil C and SOC compared with grazing exclusion in semiarid temperate grasslands. We highlighted that plant roots were key to maintaining SOC protection and SOC. However, litter mass and soil abiotic factors had a crucial effect on mineral protection. Targeting to improve the physicochemical protection of SOC in grasslands is essential to mitigate the decline in soil C sequestration induced by livestock grazing.

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Moderate grazing helps reduce greenhouse gas emissions from typical steppe

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Key words: Ecosystem respiration; Methane; Nitrous oxide; Grazing; Mowing

Abstract
Grasslands represent a significant ecosystem that exerts a profound influence on atmospheric greenhouse gas levels in the context of global change. Appropriate grassland management represents an effective means of reducing greenhouse gas (GHG) emissions from grasslands. However, the information on the management effects on GHG emissions from natural grasslands is still insufficient for developing the best practice in grasslands for both production and carbon. The effects of three major management measures, fencing, grazing, and mowing, on ecosystem respiration (CO_2), methane (CH_4) uptake, and nitrous oxide (N_2O) emissions were investigated in a typical grassland area of Xilingol, Inner Mongolia. The results demonstrated that moderate grazing reduced aboveground biomass, decreased CO_2 emissions, promoted belowground nutrient cycling, and increased CH_4 uptake. While mowing increased pasture production and soil carbon and nitrogen content, it was accompanied by higher CO_2 emissions. Reducing grazing frequency slowed biomass loss to some extent, while reducing N_2O emissions. Climatic conditions largely control grassland GHG emissions or uptake, and different management practices control GHGs mainly by affecting the soil micro-environment and soil nutrient content. The results of the study provide data support for carbon sequestration and emission reduction in grasslands. It can be concluded that moderate grazing intensity and frequency are the optimal management practices to mitigate GHG emissions from grasslands. Furthermore, the advantages and disadvantages of increased pasture production and increased GHG emissions from mowing should be weighed to further optimize grassland management.

Introduction
Grassland degradation can induce biodiversity loss and productivity decline, reduce carbon (C) and nitrogen (N) cycling and other ecosystem services, and increases greenhouse gases (GHGs) emissions contributing to global warming (Bai *et al.* 2018). It is imperative to implement sustainable management measures to enhance grassland production while concomitantly minimizing the adverse environmental impact (Taube *et al.* 2014). The main management methods for the Inner Mongolian steppe grasslands are grazing, mowing for hay, and enclosure (Dong *et al.* 2020). Grazing regulates grassland GHG emissions by altering of vegetation and soil physicochemical properties through livestock foraging, trampling and excreta deposition (Tang *et al.* 2019). Mowing or hay harvesting removes a large part of plant aboveground biomass and nutrients, thus alters C and N cycling processes that occur within the ecosystem and thereby altering

greenhouse gases flux (Niu *et al.* 2013). However, the effects of these management measures on grassland GHG emissions are unclear. The function of grassland ecosystems in C sequestration and emission reductions under various grassland management remains a matter of contention, largely due to the high spatial heterogeneity and discrepancies in research methodologies (Piao *et al.* 2022). Further investigation is required to ascertain the implications of differing management practices on GHG emissions in grassland ecosystems.

Here, at a typical steppe located in central of Inner Mongolia, China, we determined the GHGs fluxes in grasslands subjected to experimental mowing, grazing and enclosing (no grazing nor mowing), and analyzed the mechanisms underlying the GHGs variation across management practices. We hypothesized that: (i) grazing at moderate intensity increases ecosystem respiration rate (ER, i.e., CO_2 emission) and N_2O emission, but decreases CH_4 uptake; (ii) In contrast to grazing, mowing decreases ER and N_2O emission, but increases CH_4 uptake; (iii) Management regulates GHG fluxes mainly by altering plant production and soil moisture.

Methods

GHG fluxes measurement in this research was carried out at the designated experimental grassland located at the Observation and Research Station for the Typical Steppe Ecosystem of the Ministry of Education of China (44°10' N, 116°28' E, 1101 m a.s.) with a mean annual temperature of -0.5 °C and a mean annual precipitation of 315 mm. The natural vegetation is typical steppe in this region with *Leymus chinensis* (Trin.) Tzvel., *Stipa krylovii* Roshev and *Cleistogenes squarrosa* (Trin.) Keng. as the dominant species.

A randomized block design was used to arrange four treatments of management practices, with three replications in 12 grassland plots, and the plot size is 33 m × 33 m. The four management practices were (i) whole plant growing season grazing (WG): from May to September; (ii) Spring and summer grazing (SG): only in May and July; (iii) Autumn mowing (AM): mowing around August 20th, leaving a stubble at 6 cm and removing the hay; and (iv) enclosed grassland (EN): no grazing nor mowing. Six sheep were introduced to the grassland for grazing on the 20th day and removed when the stubble height of the dominant grassland species reached approximately 6 cm.

GHG fluxes assessment were conducted via the static chamber technique coupled with gas chromatography test, from June to September. Three gas chamber bottom frames with grooves were set up in each plot for natural sampling. The surface air temperature (AT), soil temperature (ST) and soil volumetric moisture content (SM) was recorded during the collection of gas samples. Gas collection was made once a week during the growing season. At the same time, we monitored plant species richness (SR), aboveground biomass (AGB) and belowground biomass (BGB) and measured soil ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), soil inorganic nitrogen (SIN), pH, soil total organic carbon (TOC), total carbon (TC), total nitrogen (TN) and bulk density (BD),

2.4. Statistical analyses

One-way analysis of variance (ANOVA) was used in IBM SPSS Statistics.27.0 to assess changes in GHG fluxes, and the environmental factors, including climatic (precipitation, temperature), soil physical (AT, ST, SM, pH, BD, texture) and chemical (TOC, TC, TN, NH_4^+-N, NO_3^--N, C/N, SIN), as well as plant (AGB, BGB, SR) factors, across management practices. An analysis using boosted regression trees model (BRTs) was performed to explore the relative importance of various environmental variables on GHG emissions and uptake by *gbm* package in R v.4.2.1.

Results

Management implications on vegetation and soil

Grassland vegetation and soil were significantly affected by management practices. Compared to EN, grazing (both WG and SG) reduced AGB by 44.03%. Mowing (AM) increased plant AGB by 17.39%, while it did not affect BGB. Compared to EN, WG and AM significantly increased AT and ST, while SG had no such an overall significant effect. Compared to EN, both WG and SG increased soil BD but decreased soil inorganic nitrogen; WG, SG and AM significantly increased TC, SG significantly increased TN, WG significantly increased the C/N ratio, and AM significantly enhanced TOC (Table 1).

Table1. Plant and soil properties of the grassland under different managements

	Managements			
	EN	WG	SG	AM
AT	26.53±0.45**bc**	27.78±0.59**ab**	26.12±0.48**c**	28.27±0.58**a**
ST	22.29±0.33**c**	24.21±0.53**ab**	22.68±0.76**bc**	24.48±0.57**a**
SM	7.90±0.17	8.01±0.24	7.73±0.26	7.93±0.29
AGB	86.18±3.43**b**	47.77±2.73**c**	57.21±2.27**c**	99.06±4.49**a**
BGB	357.97±69.82	362.08±48.01	418.24±22.23	382.48±76.23
SR	5.63±0.30**b**	6.61±0.36**ab**	6.10±0.38**b**	7.21±0.31**a**
PH	8.45±0.16	8.41±0.17	8.42±0.15	8.44±0.18
Sand (%)	74.48±1.37	71.81±1.43	71.23±1.01	74.11±0.48
Silt (%)	22.86±1.22	25.23±1.26	25.66±0.87	23.06±0.38
Clay (%)	2.66±0.27	2.96±0.18	3.11±0.12	2.83±0.13
BD ($g·m^{-3}$)	1.23±0.02 **b**	1.29±0.01 **a**	1.33±0.01 **a**	1.25±0.01 **b**
TOC ($g·kg^{-1}$)	11.5±0.31 **b**	12.09±0.31 **ab**	12.11±0.28 **ab**	12.41±0.25 **a**
TC ($g·kg^{-1}$)	16.51±0.4 **b**	18.65±0.48 **a**	18.31±0.41 **a**	18.36±0.38 **a**
TN ($g·kg^{-1}$)	1.44±0.04 **b**	1.53±0.04 **ab**	1.57±0.04 **a**	1.53±0.04 **ab**
NH_4^+-N ($mg·kg^{-1}$)	3.07±0.35	2.86±0.29	2.92±0.31	3.00±.29
NO_3^--N ($mg·kg^{-1}$)	6.53±0.89	5.32±0.31	5.03±0.53	6.54±0.59
SIN ($mg·kg^{-1}$)	9.6±0.71 **a**	8.18±0.22 **b**	7.95±0.26 **b**	9.55±0.41 **a**
C/N	11.55±0.18 **b**	12.24±0.23 **a**	11.74±0.23 **ab**	12.04±0.16 **ab**

Values are mean ± S.E. (standard error). Different letters indicate significant differences among management practices within the rows ($P < 0.05$).

Management implications on GHG emissions

Grassland ecosystem respiration (CO_2 release) showed a nearly unimodal curve throughout the plant growing period with peaks observed in late July. CO_2 release was significantly lower under the two grazing management and EN than under AM and EN. The studied steppe functioned as a CH_4 sink throughout the plant growing period with peak uptake occurring in Jun. The soil CH_4 absorption under WG was significantly higher than that under EN and AM. The N_2O emissions during the growing season were more volatile and variable and showed two peaks. The average N_2O emission rates were the lowest under SG, which was significantly lower than the highest rate under AM, EN and WG. (Fig. 1)

Factors driving the emission of the three GHGs under different managements

BRTs model demonstrated the relative contribution of all factors to GHGs fluxes, which explained 86.69 %, 59.28 %, and 59.92 % of the variation in CO_2, CH_4, and N_2O fluxes, respectively. Climatic, soil physical and chemical factors were the major explanatory factors for GHG emissions in grasslands, but their contribution differed to each of the three GHGs. Climatic factors (46 %) had the biggest contribution to CO_2 release followed by soil physical factors (25 %); climate (35 %) and soil chemical (32 %) and physical factors (26 %) are major factors affecting for N_2O emission; while CH_4 uptake was more regulated by soil physical (40 %) and chemical factors (25 %) than by climate factors (21 %). In addition, plant factors also had a certain contribution to variation in GHGs emissions. (Fig. 2)

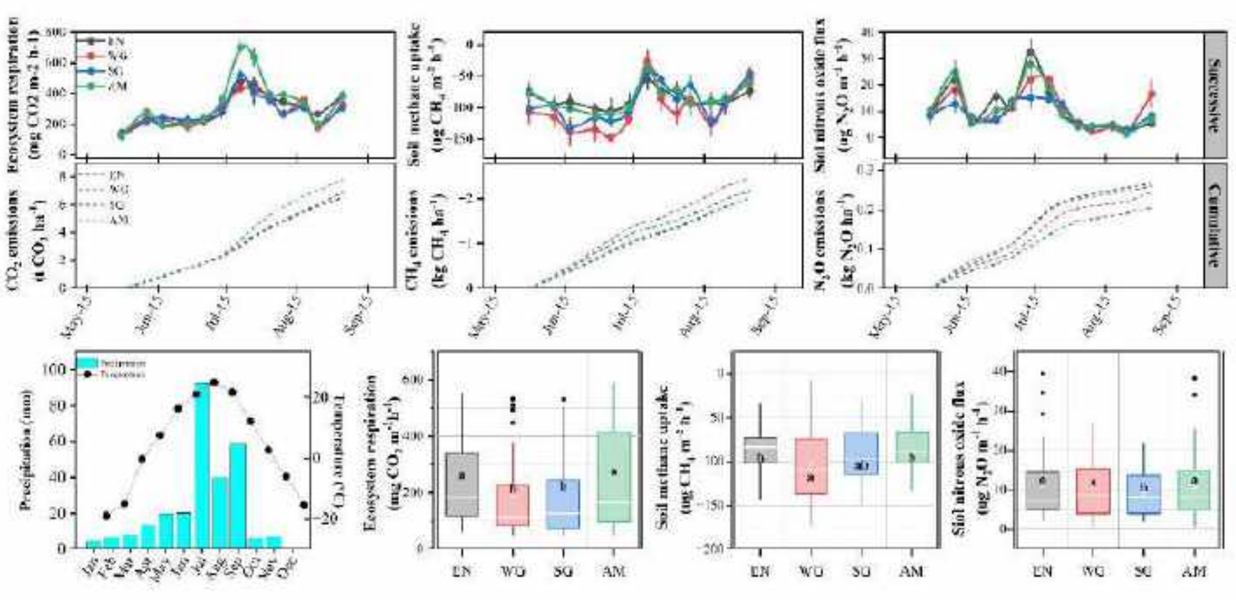

Fig. 1 GHG flux to different managements in growing period and monthly mean temperature and precipitation in the experimental period

Discussion [Conclusions/Implications]

The emission of GHGs from grassland ecosystems is a complex biological and ecological process, and is affected by numerous factors (Dangal *et al.* 2020). Light grazing may induce plant over-compensatory growth thus increase ER (Zhou *et al.* 2017), while mowing has no effect or reduces ER (Jia *et al.* 2012). Grazing reduces plant AGB and plant respiration thus decreases ER, while mowing increases ST that stimulates soil microbial activity and respiration thus enhances ER (Benot *et al.* 2014). Grazing reduces AGB and increases ST, which, in turn, stimulates methanotrophic activities and thus CH_4 uptake (Zhou *et al.* 2007). The increased ST was accompanied by decreased SM and increased soil aeration, which enhances the CH_4 diffusion from atmospheric to the soil (Liu *et al.* 2007). CH_4 uptake is typically inversely correlated with SIN content because NH_4^+-N can be oxidized by methanotrophic instead of CH_4, whereas NO_3^--N enhances soil oxidation potential, influences the activity of methanotrophic, and might reduce the CH_4 uptake (Zheng *et al.* 2024). N_2O is mainly generated through the processes of nitrification and denitrification, which can easily be altered by the variations in soil temperature, moisture, and nutrients induced by grazing and mowing (Xia *et al.* 2022). Soil inorganic nitrogen content may be the reason for a reduction in N_2O emissions under SG, as studies have shown that SIN is a substrate for nitrification and denitrification, and has a significant controlling effect on soil N_2O emissions (Müller *et al.* 2002).

Our BRTs mode indicates that temperature or precipitation are the major controlling factor for GHG emission and uptake in typical steppes, followed by soil physical and chemical properties. The effects of climate and grassland management on grasslands are inextricably linked (Reichstein *et al.* 2013). Some studies have indicated that climate (precipitation) exerts a more pronounced influence on CO_2 release than grassland management (grazing and mowing) (Zhang et al., 2023). However, global-scale studies have demonstrated that grassland management (grazing) exerts a more pronounced effect on grassland carbon stocks than climate change (Zhou *et al.* 2019).

While the climatic factors are dominant in controlling GHGs emissions form ecosystems, different management practices equally affect the GHGs fluxes by altering plant standing biomass and thereby influences soil physical and chemical properties and soil microbial activities. Further investigation into the mechanisms underlying these interactions is essential, especially under the implication from both natural and anthropogenic factors. The implementation of effective emission reduction strategies demands a comprehensive understanding of these complex interactions.

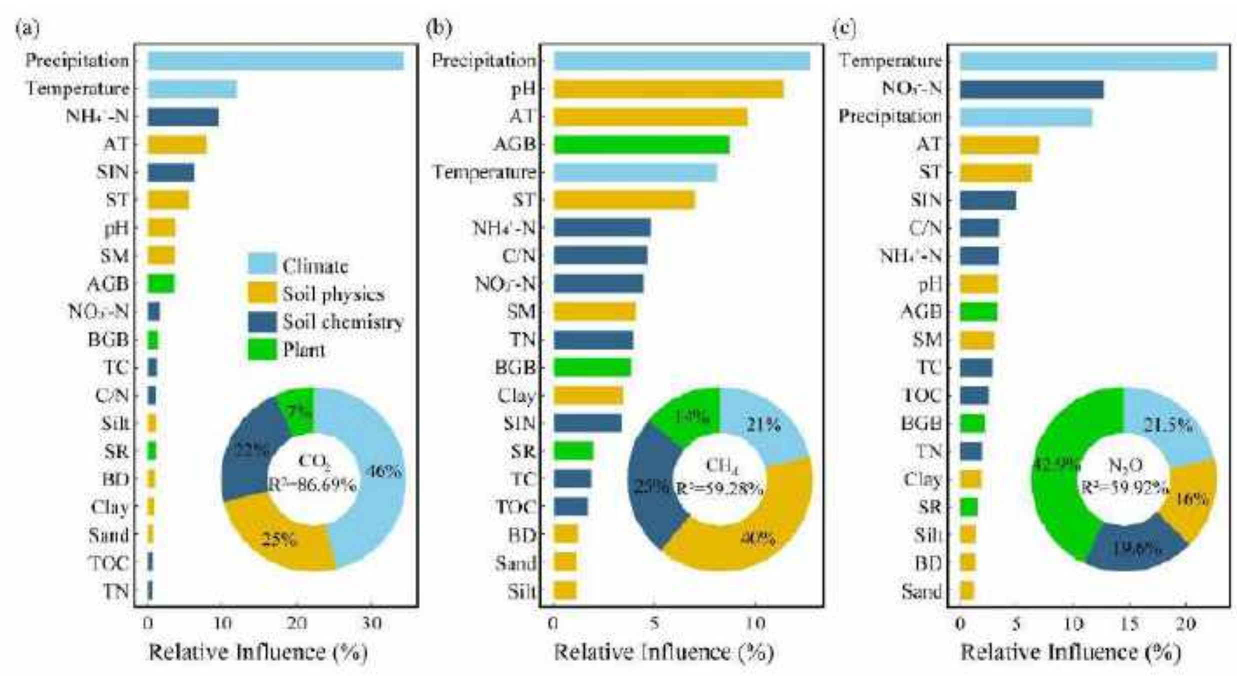

Fig. 2 Relative contribution of environmental factors to the ecosystem respiration (a), soil methane uptake (b), and soil nitrous oxide emission (c) under grazing, mowing, or enclosure based on the boosted regression trees (BRTs) model.

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Defoliation effects on carbon allocation in grasslands

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Key words: Grazing; dissolved organic carbon; microbial biomass carbon; soil organic carbon; ^{13}C

Abstract

Grazing represents a multifaceted interaction between livestock and grasslands, encompassing three main mechanisms: defoliation, dung and urine return, and trampling, each of which profoundly affects soil carbon (C) storage processes. To better understand the impact of grazing on soil C dynamics, we conducted an in-situ ^{13}C pulse labeling experiment on a field-simulated grazing platform, incorporating separate or combined treatments of defoliation, excreta return, and trampling. We tracked ^{13}C allocation in dissolved organic carbon (DOC), microbial biomass carbon (MBC) and soil organic carbon (SOC). We found that mowing significantly promoted the accumulation of root-derived DOC and MBC. Trampling also increased root-derived DOC. A positive correlation was observed between root-derived DOC and MBC, whereas no significant correlation was found between root-derived SOC and either root-derived DOC or MBC. Overall, we disentangled the complex grazing behaviors, quantified and tracked the pathways of C among different C pools under different grazing disturbance. Our study also highlights the distinct impact of mowing, trampling, and dung and urine return by ungulates on SOC, and future research should thoroughly consider these mechanisms to improve grassland management practices.

Introduction

Grasslands occupy approximately one-fifth of the Earth's land surface and store an estimated 200–300 Pg of carbon. As a result, carbon allocation dynamics within grasslands play a critical role in shaping the global carbon balance (Bai & Cotrufo, 2022). In these ecosystems, minor shifts in plant and soil carbon pools can affect atmospheric CO_2 concentrations. Investigating the turnover and sequestration of grassland carbon is therefore essential for understanding its impact on global climate change. As active components of the soil carbon pool, dissolved organic carbon (DOC) and microbial biomass carbon (MBC) are critical indicators for predicting soil carbon release and stability.

Grazing represents a complex interaction between livestock and grasslands, encompassing three key mechanisms: mowing, dung and urine return, and trampling. Each of these mechanisms can significantly impact soil carbon storage processes. Although DOC accounts for only a small fraction of soil organic carbon (SOC) (approximately 0.25%), it represents the most dynamic and mobile component of SOC (Angst et al., 2023). DOC plays a pivotal role in SOC formation and the processes of soil carbon transport and transformation. Labile compounds within DOC contribute directly to SOC through the *in vivo* turnover process of the soil microbial carbon pump, while some recalcitrant components can also form SOC directly through mineral adsorption (Liang et al., 2017). Grazing by livestock can significantly alter the composition and diversity of plant communities, which may, in turn, affect the quantity and composition of root exudates DOC and the leached DOC from surface litter, ultimately influencing the formation of SOC (Wei et al., 2023). Plant-derived DOC plays a crucial role in the process of being converted into stable SOC, with the involvement of soil microorganisms. MBC is an important driving force for the decomposition and transformation of SOC. Microorganisms fix or release carbon into the soil or atmosphere through the decomposition of organic matter. Dung and urine return can increase available nutrients, which is more conducive to the formation of MBC. Overall, grazing promotes SOC formation through living root inputs. However, further evidence is still needed to determine whether the changes in DOC or MBC under grazing conditions will ultimately affect SOC.

Methods

Study site and experimental design

The study was conducted in a semiarid steppe at the Duolun Restoration Ecology Station of the Institute of Botany, Chinese Academy of Sciences (42° 02′ N, 116° 17′ E), located in Inner Mongolia, China. The site experiences a mean annual temperature of 2.1°C and an average annual precipitation of 378 mm.

In May 2015, a simulated grazing experiment was initiated using a randomized block design with factorial treatments. The treatments included mowing to simulate defoliation by livestock (with and without mowing), the addition of a liquid mixture of dung and urine (with and without addition), and simulated trampling (with and without trampling). Trampling was performed by a man who wore hoof-shaped shoes and carried a counterweight walking in the plots. These factors were combined to create eight distinct treatment combinations (Liu et al., 2015). The experiment was replicated across eight blocks, resulting in a total of 64 plots. Detailed information on the experimental design is available in Wei et al. (2023) and Liu et al. (2015).

$^{13}CO_2$ pulse labeling

The labeling experiment began on July 29, 2022, during the 8th year of the ongoing experimental treatments. In each of the eight treatments, five replicate subplots were selected for labelling (40 total). Labeling was conducted on consecutive sunny days, with one plot labeled per day, requiring a total of 5 days to label all 5 replicate plots. We constructed a labeling chamber using steel pipe supports and transparent polyethylene film (with a light transmittance of over 92%), measuring 0.5 m × 0.5 m × 0.6 m. The bottom of the chamber was inserted into the soil to a depth of 5 cm.

The $^{13}CO_2$ pulse was generated by slowly injecting a sodium bicarbonate solution, made by dissolving 1.0 g of sodium bicarbonate ($NaH^{13}CO_3$, 99 atom% ^{13}C) in 40 mL of water, and then adding 100 mL of 1.0 M H_2SO_4. To prevent excessive $^{13}CO_2$ concentrations, the sodium bicarbonate solution was added to the sulfuric acid solution in two stages. Twenty-four hours after labeling, we collected soil samples and measured for DOC, MBC and SOC.

MBC and DOC were measured using the chloroform fumigation-extraction method. Two soil subsamples, each equivalent to 7.5 g dry weight and stored at −20°C, were prepared for analysis. One subsample underwent chloroform fumigation in the dark for 24 hours, while the other remained unfumigated as a control. Following treatment, both subsamples were extracted by shaking them with 30 mL of 0.25 M K_2SO_4 for 1 hour, and the resulting solutions were filtered. Total organic carbon in the extracts was quantified using a TOC/TN analyzer (Multi N/C 3100, Analytik Jena, Jena, Germany). DOC was determined from the unfumigated samples, while MBC was calculated as the difference in organic carbon content between the fumigated and unfumigated samples.

Data analysis was conducted using R version 4.3.0. Initially, we employed linear mixed models (LMMs) with 'treatments' as a fixed effect and 'block' as a random effect to examine the impacts of mowing, trampling, and dung and urine return on ^{13}C-DOC and ^{13}C-MBC. These models were implemented using the lmer function from the lme4 package. Linear regression analysis was performed using R software to explore the relationships between ^{13}C-SOC and ^{13}C-DOC or ^{13}C-MBC.

Results

Defoliation significantly increased root-derived DOC (+33.03%) and MBC (+33.85%) ($p < 0.05$, Fig. 1 a, b). Trampling also increased DOC (+34.43%, $p < 0.05$, Fig. a). MBC was positively correlated with root-derived DOC (p < 0.05, Fig. c). While SOC showed no correlation with MBC or DOC (Fig. d, e).

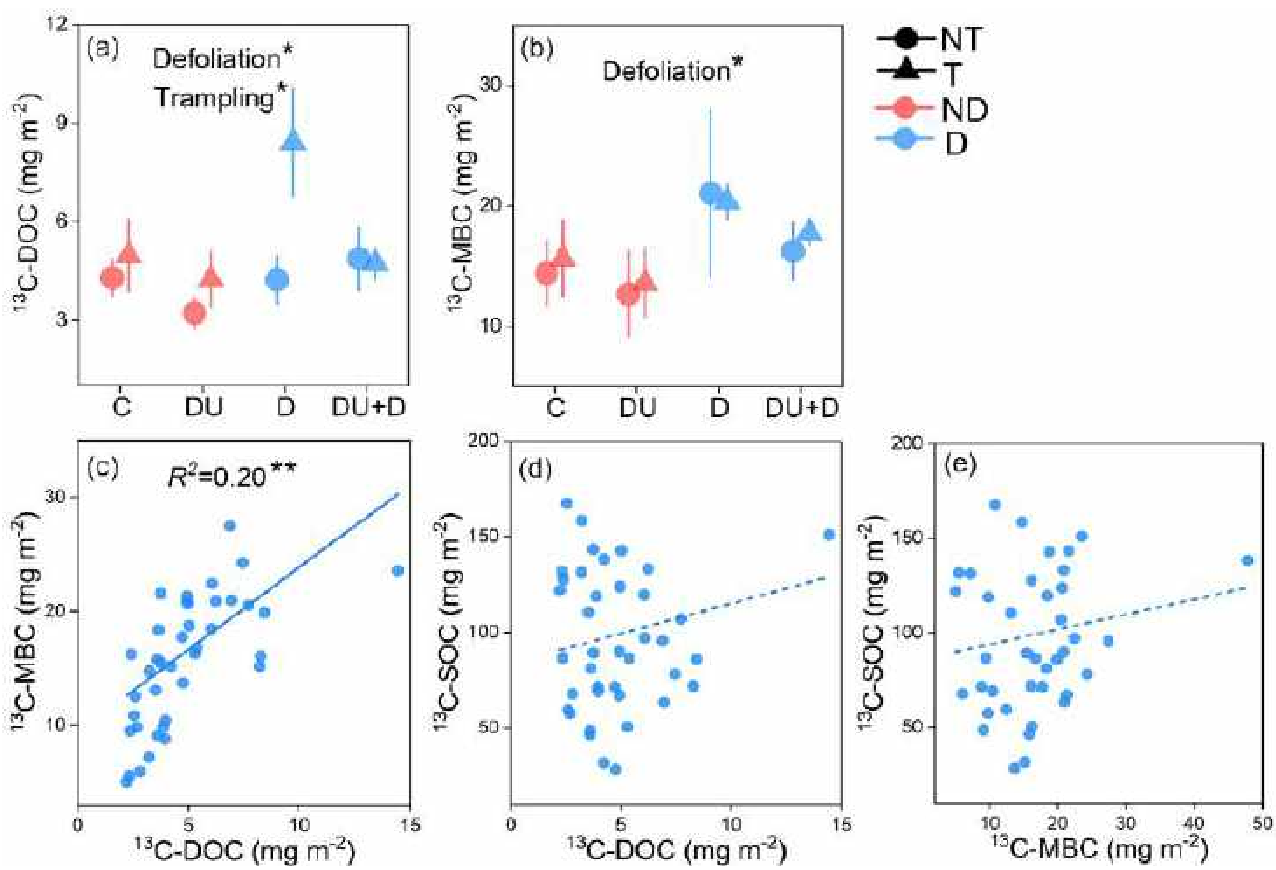

Fig. 1 The effects of grazing treatments on root-derived DOC (a), MBC (b). The relationship between ^{13}C-MBC and ^{13}C-DOC (b), ^{13}C-SOC and ^{13}C-DOC (d), ^{13}C-MBC (e). Note: C: control, D: defoliation, DU: Dung and urine addition, T: trampling.

Discussion

This study employed a ^{13}C isotope pulse labeling to quantitatively analyze the impact of living root-derived carbon inputs under grazing conditions on DOC and MBC. It also explored the relationship between root-derived DOC, MBC, and root-derived SOC under grazing.

Defoliation leads to increased root biomass (or specific root area). The positive correlation between root exudation and SRL suggests that changes in root functional traits enhance plant tolerance to defoliation, promoting the formation of root-derived DOC (Huang et al., 2021). DOC, as an unstable carbon source, is more readily utilized by microorganisms, serving as a carbon source for microbial activity. The positive correlation we found between ^{13}C-DOC and ^{13}C-MBC supports this hypothesis. However, the lack of a relationship between ^{13}C-SOC and either DOC or MBC indicate that other pathways may be ultimately dominating SOC formation under grazing, such as soil microbial necromass carbon. Liang et al. (2019) reported that microbial necromass carbon contributes more than 50% to SOC in grasslands. Therefore, future research could focus more on the changes in soil microbial necromass carbon to better understand SOC formation.

Livestock trampling compacts soil and promotes the contact between soil and roots, which may destroy soil aggregates to a certain extent, promote root growth and produce more root-derived DOC (Wei et al., 2021). Trampling has been shown to break plant material into fragments, facilitating the incorporation of litter into the soil (Mancilla-Leyton et al., 2013). This process, in turn, may enhance litter decomposition by stimulating microbial activity.

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Large ungulate grazing effects on soil carbon sequestration: evidence from a field-simulated grazing experiment

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Key words: Grazing; soil organic carbon; particulate organic carbon; mineral-associated soil organic carbon; ^{13}C

Abstract

Grasslands store 10–30% of the world's soil organic carbon (SOC) and have the potential to partially mitigate rising atmospheric CO_2 concentrations. Large ungulate grazing plays a crucial role in regulating SOC storage in grassland ecosystems. However, a more detailed mechanistic understanding of how grazing influences SOC dynamics is still needed. We investigated soil C formation among different C pools, including particulate organic carbon (POC) and mineral-associated soil organic carbon (MAOC)in a multiyear field experiment by quantifying litter-derived C inputs, in response to mowing, trampling, and dung and urine return (and combinations), treatments. We found that mowing significantly enhanced litter-derived SOC and POC formation. Trampling increased SOC, POC and MAOC pool, possibly by enhancing mixing of litter and soil, and increasing C accessibility for soil microorganisms. Our results elucidated the specific mechanisms of large ungulate grazing by quantifying the C inputs and formation processes. Accurately quantifying the contribution of plant C input to SOC pool under various management practices in grasslands is the next critical step toward improving predictions of SOC dynamics.

Introduction

Ninety percent of the terrestrial carbon stocks are stored underground in the form of root biomass and soil organic carbon (SOC) (Bai & Cotrufo, 2022), is highly sensitive to small fluctuations. The C balance of grassland soils is affected by carbon inputs that affect long-term carbon sequestration, especially litter C inputs. For analysis, soil carbon was divided into two distinct carbon pools: mineral-associated soil organic carbon (MAOC, <53 μm) and particulate organic carbon (POC, >53 μm). The MAOC pool is stable over long timescales and is considered to cycle more slowly than the POC pool. Because of the large extent of grasslands globally, it is important to have a quantitative understanding of the dynamics of soil C to make a credible estimate of the possible impacts of grazing management on the global C cycle.

Grazing is a complex interaction of livestock and grasslands, involving three potentially important mechanisms: defoliation, dung and urine deposition, and trampling, each of which may strongly influence processes of soil C storage. Defoliation reduces plant biomass, height, and coverage (Zhu et al., 2012), which in turn increases UV exposure and affects soil parameters such as moisture (Li et al., 2022). Soil moisture is crucial for litter decomposition in semi-arid grasslands, and grazing limits litter decomposition by reducing soil moisture (Wang et al., 2020). Besides, trampling alters soil physical properties. For instance, it increases bulk density (Liu et al., 2015) but decreases aeration and moisture (Wang et al., 2018), thus limiting microbial activity and litter decomposition. Trampling also breaks up litter and incorporates it into the soil, making it more accessible to microbes, which promotes the formation of SOC or POC (Wei et al., 2021). Furthermore, dung and urine return increasing nitrogen availability (Liu et al., 2015), which accelerates litter decomposition by enhancing soil microbial biomass, and increasing MAOC formation. Overall, grazing can promotechang soil organic carbon formation through litter decomposition. However, evidence for this mechanism remains limited. This study investigated the effects of grazing on organic carbon formation from litter carbon, ^{13}C-labeled litter was used to trace the fate of carbon in the different C pools.

Methods

Study site and experimental design

We conducted the study in a semiarid steppe at the Duolun Restoration Ecology Station of the Institute of Botany, the Chinese Academy of Sciences (42° 02′ N,116° 17′ E, mean annual temperature is 2.1 ◦C, mean annual precipitation is 378 mm), Inner Mongolia, China.

In May 2015, we applied a factorial combination of mowing (M+ or M-, adding a liquid mixture of dung and urine (D+ or D-), and trampling (T+ or T-), which resulted in eight different treatment combinations (Liu et al., 2015). Eight replicant blocks were established, resulting in 64 plots total. Please refer to Wei et al. (2023) for specific experimental design.

In early June 2018, decomposition collars were placed in each plot (Wei et al., 2023). Soil samples from the 0-5 cm depth were extracted using a homemade auger (diameter = 11 cm, height = 5 cm), sieved (5 mm), and roots and residual plant material were removed. PVC collars (diameter = 10 cm, height = 6 cm) were inserted into the core holes, and the sieved root-free soil was refilled. PVC rings (diameter = 10 cm, height = 1 cm) with a 1 mm mesh were placed over the collars to prevent fresh litter from entering. The 1 mm nylon mesh provided limited protection against solar radiation. Two decomposition PVC collars were set up in each subplot, with the PVC collars matching the treatment of the subplot. At the end of September, one PVC collar received marked litter (2.5 g per collar, spread on the soil surface), while the other collar served as a control (bare soil). The litter was collected from 3-month-old *Stipa kilovii* plants, labeled with ^{13}C-CO_2, with a carbon content of 461.5 g kg^{-1}, nitrogen content of 16.2 g kg^{-1}, and a C:N ratio of 28.5. Prior to application, the litter was cut into 1-2 cm pieces and applied evenly. Each year (i.e., 2019 and 2020), soil and remaining litter samples were collected from the four collars in each plot. Soil samples from the corresponding bare soil controls were also taken.

Soil carbon was fractionated into POC and MAOC pools. A physical fractionation method was used to separate organic carbon into these two pools. Soil samples (10 g air-dried soil) were shaken with 30 mL of a chemical dispersant (sodium hexametaphosphate: NaHMP, 50 g L^{-1}) at 200 rpm for 18 hours. After shaking, the sample was passed through a 53 µm sieve under water using a vibrating sieve (AS 200 Control, Retsch, Germany) to ensure that all MAOC was thoroughly washed. The two fractions were dried at 65°C and weighed.

All analyses were performed using R 4.1.2. We firstly performed linear mixed models (LMMs) that included 'treatments' as a fixed effect and 'block' as a random effect to test the effects of mowing, trampling, and dung and urine on litter-derived SOC, POC and MAOC using the lmer function in the package lme4.

Results

Mowing significantly enhanced litter-derived SOC formation after two years of decomposition ($p < 0.05$), with increases of 15% and 34% in newly formed SOC, respectively (Fig. 1 a, d). Both mowing and trampling promoted POC formation after two years of decomposition, but only trampling enhanced MAOC formation (Fig. e, f). However, no effect of grazing treatments on litter-derived POC was observed during the first year of decomposition (Fig. 1b). The return of dung and urine had a limited impact on SOC formation in both years, but promoted the formation of MAOC after one year decomposition (Fig. 1c).

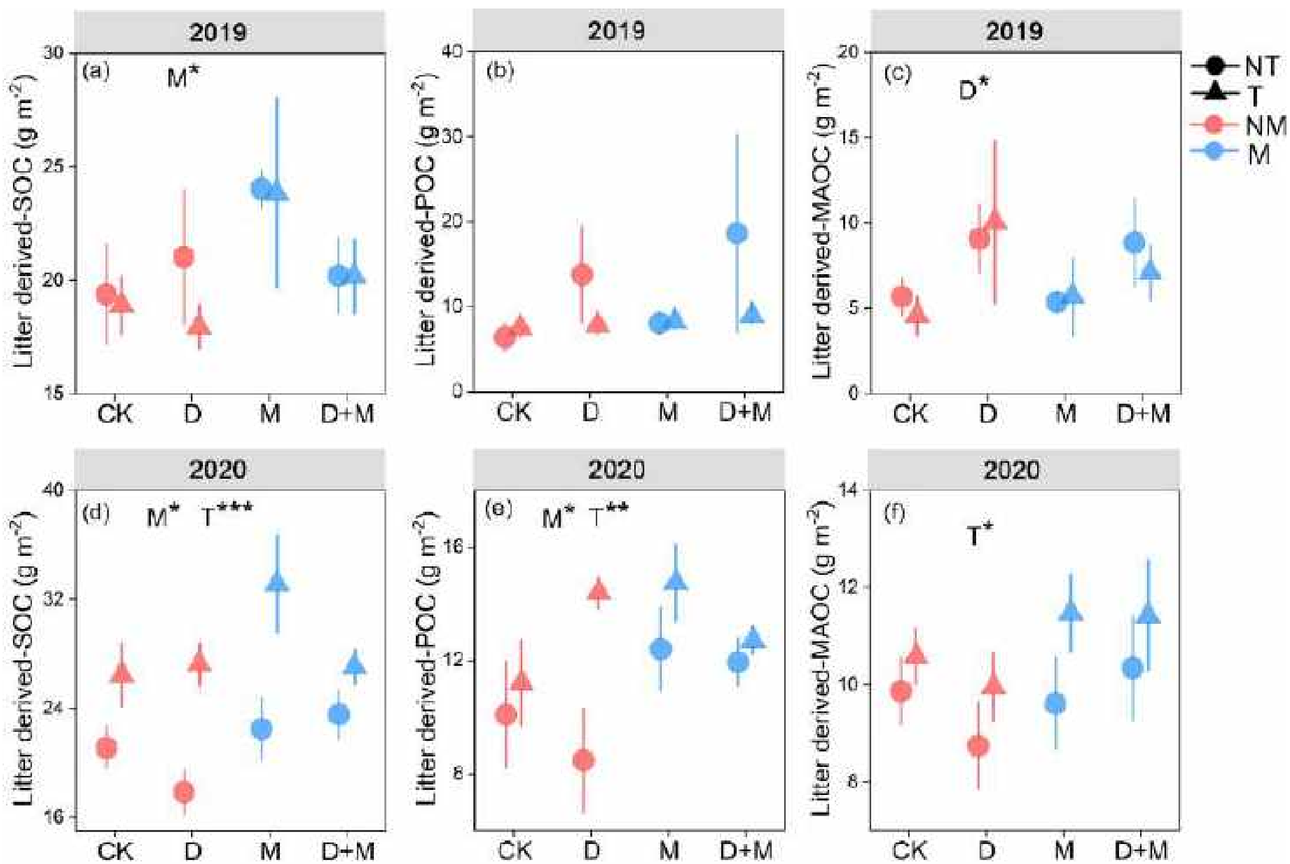

Fig. 1 The effects of simulated livestock grazing treatments on litter-derived SOC, POC, MAOC in 2019 (a, b, c) and 2020 (d, e, f). Note: CK: control, M: mowing, D: dung and urine return, T: trampling.

Discussion

Previous studies have demonstrated the impact of livestock grazing on changes in plant carbon inputs to the soil and the decomposition of litter inputs (Zhou et al., 2017). In this study, we used a ^{13}C isotope tracing method to quantify the effects of plant carbon inputs on SOC and the contribution of decomposed litter carbon to the SOC pool under grazing.

Mowing reduced aboveground biomass, plant height, and plant coverage, thereby increasing canopy light transmittance and UV exposure at the soil surface. In arid and semi-arid ecosystems, UV-induced litter decomposition plays a critical role in the decomposition of aboveground litter (Wang et al., 2017). Studies have shown that UV-induced increases in litter biodegradation, such as the decomposition of complex compounds, are more important than direct UV-driven abiotic degradation (Jiang et al., 2022). Changes in the physicochemical properties of litter compounds can accelerate subsequent microbial decomposition, a process known as the photodegradation effect (Wang et al., 2017). Therefore, the increased UV intensity in mowed areas promotes microbial involvement in organic carbon formation. However, it is undeniable that the increase in UV radiation, which leads to reduced soil moisture, may also somewhat limit the transfer of litter decomposition to the soil carbon pool.

Trampling causes soil compaction, increasing the proximity of soil microbes to litter, making it easier for microbes to decompose the litter and promoting the formation of POC (Helgason et al., 2014). Furthermore, trampling mixes litter with soil, increasing the proximity of litter to microbial communities and enhancing litter decomposition (Liu et al., 2018). Previous laboratory incubation experiments have found that trampling facilitates the incorporation of litter into the soil, promoting microbial utilization of litter carbon and the physicochemical stabilization of decomposed litter carbon (Wei et al., 2021).

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Impacts of fire on rangeland vegetation and diversity

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Effectiveness and durability of common fuel treatments in sagebrush-dominated rangelands

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Key words: fire modelling; juniper woodland; sagebrush steppe treatment evaluation project; treatment durability

Abstract

Increased wildfire size and frequency pose major challenges to rangeland conservation. A common strategy for mitigating fire risk in sagebrush-dominated rangelands is to use fuel treatments that alter the amount and structure of burnable material, resulting in lower fire intensity, and creating access points for fire suppression resources. For fuel treatments to be practical in management, durability (lasting effectiveness) is critical. We present 15 years of data on fuel accumulation and resultant modeled fire behavior through time in prescribed fire, mechanical, herbicide, and control plots using data from the Sagebrush Steppe Treatment Evaluation Project (SageSTEP). In shrub-dominated plots ('shrubland network'), fire and mechanical treatments reduced fuel beds by up to 49%, resulting in modeled flame lengths that were significantly lower than untreated control plots. In sagebrush systems experiencing conifer expansion ('woodland network'), however, treatments increased surface fire spread rate by 15-21 times that of untreated areas due to increased herbaceous fuels. However, treatments also completely removed the risk of canopy fire spread. By 15 years post-treatment, durability was limited in shrubland systems, though prescribed fire and mechanical treatments continued to perform better than herbicide or untreated control treatments through year 10. In woodland plots, the infilling and growth of trees began to limit durability by post-treatment year 15. An improved understanding of fuel treatment effectiveness and durability will allow natural resource managers to evaluate tradeoffs and synergies in conserving rangeland ecosystems and reducing the potential for fast spreading and high intensity wildfire.

Introduction

Fire regimes in sagebrush-dominated ecosystems historically were typified by long periods without fire, facilitating a patchwork of late successional sagebrush canopy with intermittent native bunchgrass prairies in recently burned areas. In the last century, much of the sagebrush steppe has become degraded by invasive annual grasses, conifer encroachment, human land use and ignitions, climate change, and altered fire regimes (Balch et al., 2013). Cheatgrass (*Bromus tectorum*) is an invasive annual that is particularly problematic, as it recruits well after disturbance (Peterson, 2005; West and Hassan, 1985) and creates continuous, highly flammable fuels that aid fire spread (Brooks and Pyke, 2000), which further promotes invasive recruitment and increases fire risk (Bradley et al., 2018; Link et al., 2006). Similarly, higher elevation sagebrush ecosystems are at risk from increases in pinyon and juniper trees, which outcompete the shrub and grass understory, often reducing surface fuels but increasing the risk of high severity crown fires. Land managers implement fuel treatments to reduce or redistribute burnable material in hopes of decreasing fire intensity and burn severity (Reinhardt et al., 2008). In annual grass-invaded sagebrush, herbicide, mowing, and prescribed fire treatments can reduce fuel loads and reduce subsequent wildfire risk (Ellsworth et al., 2022). For areas with increased shrub and tree fuel, treatments such as prescribed fire (Davies and Dean, 2019) and conifer reduction (Dittel et al., 2018) may break up continuous woody cover, decreasing the spread of invasive species, reducing flammable fuel loads, and providing access points for fire suppression (Davies and Dean, 2019; McIver et al., 2010).

Long-term experimental data provide information on the effects of fuel treatments on vegetation change and fuel accumulation; however, modelling allows us to leverage that data to estimate potential fire behaviour. Here we used the long-term treatment plots in the SageSTEP network (McIver et al., 2010) to 1) understand how fuel treatment type affects fuel accumulation in shrublands and woodlands 2) understand the durability of treatments over long time periods; and 3) develop management recommendations for retreatment intervals that maximize restoration and conservation of sagebrush ecosystems while mitigating fire risk.

Methods

The SageSTEP network spans an elevation range of 262-2500 m and a precipitation range of 164-458 mm providing an opportunity to examine responses to fuel treatments across climatic and productivity gradients (McIver and Brunson, 2014). At each of 19 sites, woody fuel treatments were applied across the entire area of each treatment plot (prescribed fire, mechanical, herbicide, or untreated control). Prescribed fires were intended to remove all woody vegetation. Mechanical treatments in shrubland network plots consisted of mowing shrubs to remove approximately half of the canopy. Mechanical treatments in woodland network plots consisted of cutting and dropping all trees. Herbicide treatments were done in the shrubland network plots only; Tebuthiuron, an herbicide that targets broadleaf plants, was applied to remove approximately half of the shrub canopy. Pre-treatment data were collected, and treatments were applied in year 0 and post-treatment data were collected in years 1, 2, 3, 6, 10, and 15 following treatments. Tree height and woody and herbaceous plant biomass and cover data were collected by species at each sampling event and were used to create custom fuel models for each site at each sample year.

To estimate the impact that fuel treatments had on fire behaviour over the 15 year study period, we parameterized the fire behaviour modelling system Fuel Characteristic Classification System (FCCS) in the Fuel and Fire Tool (FFT) (Prichard et al., 2013) with these custom fuel models. Slope assumptions for each model run were based on the average % slope (range 0-10%) (McIver and Brunson, 2014) and wind speed assumptions were based on the 80th percentile wind speed over the summer (June-September) from the nearest remote automated weather station for the study years.

Environmental scenarios were chosen to represent the range of fuel moisture expected as vegetation phenology progresses from the active growing season (fully green scenario; D2L4 scenario in FFT), through partially curing stages (1/3 cured and 2/3 cured scenarios; D2L3 and D2L2, respectively), to late in the summer, when fuels are completely dry and risk of high intensity fire is greatest (fully-cured scenario;

D2L1). Model outputs chosen to characterize fire behavior included rate of spread (ROS; m min^{-1}), flame length (FL; m), and reaction intensity (RI; the rate of heat release per unit area of the flaming front; kW m^{-2} min^{-1}) (Byram, 1959). Linear mixed models were also used to test for differences in the rate of spread, flame length, and reaction intensity (response variables) as a function of environmental scenario (*i.e.* fuel moisture conditions), treatment, and time since treatment.

Results

In the shrubland network, reduction of woody fuels and subsequent release of the herbaceous understory from shrub competition resulted in changes in modelled fire behaviour metrics (rate of spread, flame length, reaction intensity) that differed by shrub fuel treatment. Prescribed fire plots had the greatest reductions (49%) in modelled fire behaviour metrics, as this treatment was the only one to remove a large portion of the total fuel load from the sites. Shrub and downed woody fuel remained present but was sparse throughout the fifteen years after prescribed fire, while herbaceous fuel increased. The increases in herbaceous fuel in this study were primarily driven by perennial deep-rooted grasses through year six. In years 10- 15, perennial cover returned to levels seen in the control and there was a concomitant increase in annual grasses. The increase in herbaceous fuel likely increased fuel continuity assuring rapid fire spread, while the reduction of woody and shrub fuels decreased flame length. The reduction in reaction intensity with prescribed fire was short-lived. We anticipated a reduction in modelled flame length due to the mow treatment, but we found that mowing was nearly as effective as prescribed fire at reducing reaction intensity and fire rate of spread. However, the reduction in modelled fire spread and reaction intensity lessened in year 3 onward, whereas reduced modelled flame lengths were maintained for at least 10 years, with variability in sites. Herbicide treatments did not alter fuel loads or modelled fire behaviour.

In the woodland network, prescribed fire reduced shrub fuel but substantially increased herbaceous fuel, while mechanical tree reduction resulted in both increased live shrub fuel and downed wood. These changes in vegetation structure and fuel loads modified predicted fire behaviour such that fuel treatments increased surface fire behaviour for the first fifteen years post-treatment. By year fifteen, however, all treatments prevented crown fire spread, which was possible in control plots in later years of the study due to increased density of small pinyon and juniper trees. These findings demonstrate a significant management trade-off between short-term increases in surface fire behaviour for restoration of shrubland plant communities and long-term reductions in the potential for crown fire spread.

Discussion and Conclusion

Fuel treatments are commonly applied in sagebrush ecosystems to reduce fire risk associated with annual grass invasion and conifer encroachment. These fuel treatments can have significant effects on vegetation communities and fuel loads, thus affecting future fire behaviour. While these treatments may provide useful tools for managers, we need to better understand the durability and long-term effects of fuel treatments on vegetation and fuels, particularly along productivity and climatic gradients. As there are proposed fuel breaks for 11,000 miles in the Intermountain West, USA, it is imperative we understand the short- and long-term implications of these fuel treatments in current and future climate conditions. While there are important site-specific results to consider, we commonly saw woody fuel treatments in the shrubland network that remained durable through years 10 to 15 post-treatment. In the woodland network, in contrast, regeneration of young trees limits the efficacy of treatments in the long term. We recommend that site-specific regeneration dynamics be closely monitored, and manual removal of small trees be done at 5 year intervals to preserve treatment integrity.

The efficacy and spatial arrangement of fuel treatments, as well as initial site conditions are highly influential on potential for access and fire suppression, as well as for protecting valuable natural resources. Treatment effectiveness may depend on weather conditions for prescribed burning, appropriate use of machinery, and adequate herbicide application. Additionally, practitioners should consider the broader landscape to strategically place treatments where they are readily accessible by fire personnel and take advantage of existing roads, prevailing wind direction, and local topography to best protect valued resources. Repeated treatments will need to be considered when initial treatment begins to lose effectiveness, as we begin to see in the later years of this study. Finally, understanding pretreatment condition and inherent site characteristics, such as resilience to disturbance and ability to resist invasion, can help guide placement of treatments and estimate the likelihood that the fuel treatments will be ultimately beneficial rather than contribute to further degradation (Chambers et al., 2019, 2014; Shinneman et al., 2019).

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Effect of prescribed fire on plant α- and β-diversity and their spatial patterns in mesquite-oak savanna

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Keywords: prescribed fires; beta diversity; alpha diversity; spatial pattern

Abstract

Fire is a fundamental process in the rangelands of the Great Plains, and dynamic mosaics of areas burned at different times are essential for maintaining and supporting biodiversity, livestock production, and wildlife habitats, among other ecosystem services. The semi-arid rangelands of the Southern Great Plains typically have strong spatial heterogeneity in vegetation structure, which can affect the pattern of fire and its impact on plant diversity and spatial pattern but have received little attention in research. In this study, we investigated the effect of prescribed fires on plant α- and β-diversity and their spatial pattern in a mesquite-oak savanna landscape in the Edwards Plateau. In an 182.2 ha (450-acre) burn unit in a research ranch managed with a pyric herbivory regime, we sampled 288 randomly located 1-m^2 plots in both the pre-fire and post-fire seasons and collected data on plant species composition and abundance. We also mapped the areas burned within the burn unit using high-resolution (21 cm) multispectral data and machine-learning classification. Plant α-diversity was measured using species richness, evenness, and Shannon's H index, and β-diversity using the Sørensen index of dissimilarity and its turnover and nestedness components. Our results show that the prescribed fire appeared to promote α-diversity in soils with sufficient moisture but weakened the overall spatial structure of α-diversity. The prescribed fire negatively affected β-diversity, likely through both direct effects of fire on plants and indirect effects of intensified selective grazing after fire. Differential changes in species composition of forbs and grasses had an important influence on β-diversity. Burn pattern significantly influenced spatial patterns of post-fire β-diversity. These complex effects of prescribed fire on plant α- and β-diversities and their spatial pattern likely have implications for these heterogeneous savanna landscapes' ecosystem functions and services.

Introduction

Previous research on the interaction of fire and grazing (Fuhlendorf et al. 2006, 2009, 2017) has primarily focused on areas burned uniformly in the Southern Great Plains. However, processes in patchy burns across heterogeneous wooded savanna rangelands with variable herbaceous fuel continuity and seasonal precipitation remain underexplored, particularly regarding their influence on α- and β-diversity, including turnover and nestedness components (Anderson et al. 2011; Baselga 2012; Heydari et al. 2017). Plant diversity, often measured through α-diversity (e.g., species richness within a specific area) and β-diversity (variation in species composition between areas), plays a crucial role in ecosystem dynamics. Fire is a key ecological driver that shapes species composition, ecosystem stability, and resilience, yet its spatial effects on plant diversity across different soil types (Winter et al. 2011) remain unclear. Studies have shown that fire influences ecosystem stability and species composition spatial variability (McGranahan et al. 2018), affecting turnover and nestedness components of β-diversity (Anderson et al. 2011; Baselga 2012; Heydari et al. 2017). By analyzing pre- and post-fire spatial patterns, we can better understand fire's role in diversity changes and its broader implications for ecosystem, function, structure, and services, particularly in maintaining habitat heterogeneity and species diversity in fire-adapted semi-arid rangelands. This study addresses these gaps by examining patchy prescribed fires in mesquite-oak savannas. Specifically, it aims to 1) quantify burn patterns and changes in diversity, 2) assess the magnitude and spatial variability of these changes, and 3) determine how burn status spatially influences diversity. These findings will advance the understanding of fire's role in shaping plant diversity and ecosystem dynamics in semi-arid rangelands.

Methods

This study was conducted on a Texas A&M AgriLife Research ranch (Fig. 1a) in the eastern Edwards Plateau of Texas (30.809670 N; -99.865701 W). The study area includes two nearby pastures, where prescribed burns were conducted in February 2019 (Fig. 1b). The monthly rainfall pattern around the study period (2018-2019) is shown in Figure 1c.

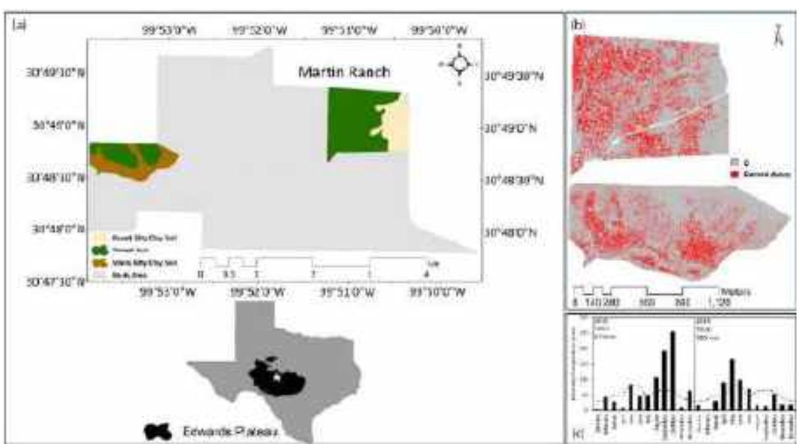

Figure 1. The (a) study area in the ranch with the map of soil types in the study area (TA = Tarrant, VaB = Valera, KaB = Kavett), (b) the maps of burn patterns from the burn units, and (c) the monthly precipitation (bars) from 2018 to 2019 compared to PRISM 30-yr standard (dash line) at the study site in the eastern Edwards Plateau of Texas.

Field data was collected in September-December 2018 (prefire) and September-December 2019 (postfire). Quadrat placement was randomly stratified by soil type, with 120 quadrats in each dominant (TA and VaB) and 48 in the secondary (KaB) soil series, consistently for both periods. Maps of burn status (burned, unburned) were developed by classifying high-resolution (21-cm) aerial imagery using the random forests

(RF) classification method. The α-diversity at each sampling point was calculated based on the percent cover data of plant species for prefire and postfire seasons. The incidence-based β-diversity (β.SOR, β.SIM, and β.SNE) was calculated for all pairs of sampling points (Baselga 2012; Baselga & Orme 2012). The prefire to postfire change in each diversity measure ($x\Delta$ = post - pre) was the dependent variable, and soil type and burned status were the fixed factors of the two-way ANOVA models with Bonferroni corrections on the adjusted p-value. To test normality and homogeneity of variance before ANOVA, Shapiro-Wilk and Levene's tests were run on the data without transformations. For both α-diversity and β-diversity, simple Mantel (xD), cross-Mantel tests (xB, $X_{pre}X_{post}$), and partial Mantel tests (X_{post}D.B) were performed to assess the spatial structure and cross-correlation in terms of spatial continuity; where D is a spatial distance matrix (Euclidean distance between sampling points and B is a variable distance matrix (absolute value of the difference in burn status between sampling points).

Results and Discussion

Prefire and postfire measures of α-diversity and their spatial patterns

Fire likely promoted α-diversity in soils with sufficient moisture as changes were 3 times more negative in unburned areas, especially in KaB soil with higher water-holding capacity (Fig. 2ab). There were significant differences in prefire to postfire changes α-diversity (Shannon index, p = 0.014) of all species between burned and unburned areas in the KaB soils alone or the study area (Fig. 2a). As shown in Figure 2b, the changes in α-diversity were primarily driven by annual and perennial forbs. The most notable differences between the burned and unburned areas were in the cool and warm season annuals and the warm season perennial forbs (Fig. 2c).

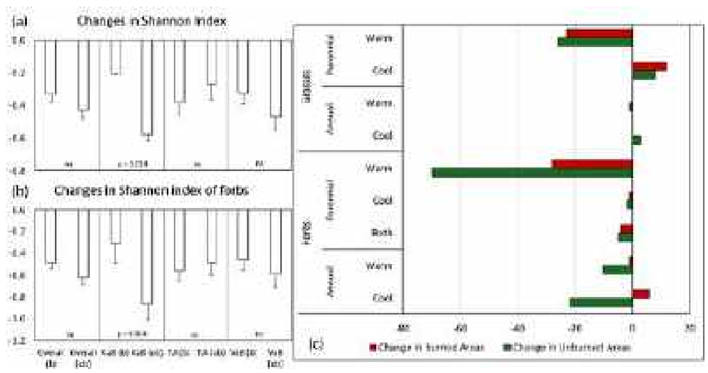

Figure 2. Prefire to postfire change in α-diversity in burned [B] and unburned [UB] areas overall and within each of the soils for (a) all species and (b) forbs. (c) Average changes in species frequency by functional groups in burned and unburned areas in KaB soil.

The spatial pattern of the changes in α-diversity from α_{pre} to α_{post} season in the study area is complex. Moreover, the spatial continuity of α-diversity weakened after the fire (Mantel's r = -0.028, p = 0.038). Still, the spatial pattern remained consistent as both $\alpha_{pre}\alpha_{post}$ spatially correlated (Mantel's r = 0.117, p = 0.017) and α_{post} correlated with burn pattern (Mantel's r = 0.038, p = 0.002). The spatial pattern of the burned areas within the study area was complex, influenced by the strong spatial heterogeneity of the vegetation and fuel characteristics of these semi-arid savannah landscapes (Bradstock, 2010; Singh et al., 2018). As these burned patches were interspersed with unburned areas, the varying changes in α-diversity between burned and unburned areas logically weaken the spatial structure in terms of spatial continuity (the correlation between the differences in variable values and the distance separation between sampling points). These results suggest that prescribed fires likely diminish the spatial structure of α-diversity, at least in the short term, given the typically heterogeneous burn patterns in these diverse savannah landscapes. The spatial pattern of α-diversity can likely be sustained in areas with low soil moisture, where the effects of fire and the changing weather patterns on α-diversity align similarly.

Prefire and postfire measures of β-diversity

Overall, fire negatively impacted β-diversity as the average values of β-diversity (β.SOR and β.SIM) decreased significantly ($p < 0.001$), while that of species nestedness (β.SNE) increased significantly (Fig. 3a). β-diversity measures between sampling points within the burned areas decreased more than those between points within the unburned areas (Fig. 3b). We observed a decline in overall differences in species composition within burned areas. Meanwhile, unburned areas exhibited slightly higher β-diversity, primarily affected by dry-down conditions (Fig. 3b).

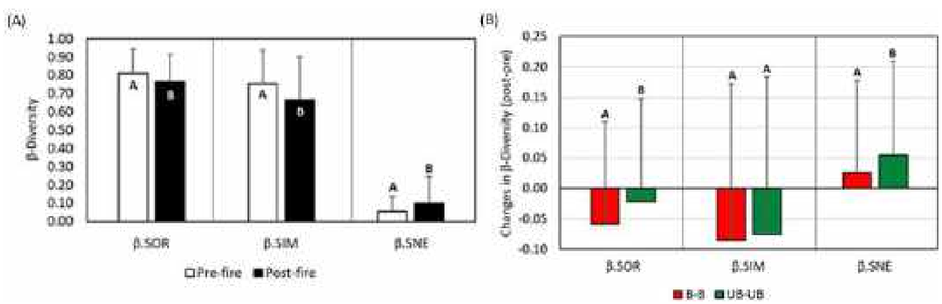

Figure 3. (A) The prefire and postfire β-diversity measures (mean±std), and (B) the change (mean±std) for pairs of sampling points within burned (B-B) and unburned (UB-UB) areas.

Beta diversity decreases after a fire, likely due to reduced herbaceous species frequency, increasing common perennial bunchgrass species (e.g., *Nassella leucotricha*), and stimulating post-fire grazing, which altered its spatial structure. Mantel test showed significant alterations in the spatial structure from β_{pre} (Mantel's $r = 0.019$, $p = 0.05$) to β_{post} (Mantel's $r = -0.021$, $p = 0.03$) β.SOR, but not in either of its components (β.SIM and β.SNE). There was no spatial correspondence between $\beta_{pre}\beta_{post}$ spatial patterns, but β_{post} (Mantel's $r = 0.038$, $p = 0.002$) and its components had a significant spatial correlation with the burn pattern. In terms of β_{post}D.B, spatial structure in β-diversity (β.SOR) remains. These results suggest that the combined effect of burn pattern and dry-down conditions from lack of precipitation influenced the spatial structure of β-diversity.

Conclusions and Implications

Our study highlights the important dynamics of patchy fires on plant diversity during dry-down periods in Mesquite-Oak savanna landscapes. Fire modifies plant diversity within burned areas by influencing α-diversity through soil moisture availability, reshaping species composition based on burn pattern, and altering spatial patterns in response to weather conditions and grazing intensity. Postfire, α-diversity increased based on soil moisture characteristics, while β-diversity declined, disrupting the prefire spatial structure. These findings underscore the ecological ramifications of postfire conditions on plant community dynamics, indicating that heterogeneous fires promote species replacements. These shifts, influenced by interactions among fire, soil, grazing, and weather, reveal the dynamic role of patchy fire in reshaping herbaceous biodiversity. This study provides a foundation for refining prescribed fire practices that promote biodiversity and ecosystem resilience. Also, it provides insights for adaptive fire management strategies considering soil and vegetation dynamics and conservation of fire-dependent semi-arid rangelands.

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Historic fuel treatment effects on plant community dynamics following wildfire

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Key words: fuel treatment, wildfire, sagebrush, invasive species

Abstract

Wildfire has substantially increased in sagebrush ecosystems resulting in degraded wildlife habitat, reduced forage, and altered fire regimes. Mechanical mowing, prescribed burning, and herbicide are fuel treatments aimed to reduce woody or herbaceous fuels; however, their long-term effect on plant community composition, as well as the response after wildfire, is unknown. We utilized data from three SageSTEP sites (https://www.sagestep.org) to examine plant community composition before and after fuel treatments, as well as after three sites had burned in a wildfire. After fuel treatments, reductions in sagebrush coincided with increased native perennial bunchgrass cover but also annual, invasive grass cover. Perennial forb increases were ephemeral after treatments. Immediately prior to wildfire, sites differed in species composition with control plots having the most shrubs and the prescribed fire plots having the most perennial grasses. After wildfire, shrubs were substantially reduced. Perennial grass cover generally increased, particularly in prescribed fire plots, although perennial grass responses were site dependent. Annual grass invasion varied by site and treatment after wildfire, and invasive forbs were dynamic post-wildfire. These results illustrate the need for long-term data to understand plant community dynamics after both fuel treatments and subsequent wildfire. Long-term monitoring of post-wildfire community trajectories will help deduce how strongly historical fuel treatments affect pre-wildfire composition and consequent post-wildfire recovery.

Introduction

Fuel reduction treatments are intended to reduce fuel loading of herbaceous and/or woody fuels. In sagebrush ecosystems in the western United States, woody fuels have increased due to increasing shrub density; herbaceous fuels have increased due to invasive annual grasses, primarily *Bromus tectorum* (cheatgrass). Cheatgrass recruits well after disturbance (West and Hasan 1985, Peterson 2005) and creates continuous, highly flammable fuels that aid fire spread (Brooks et al. 2004), which promotes further recruitment and increases fire risk (Link et al. 2006, Bradley et al. 2018). As a result, annual grass invasion has increased the size, frequency, and duration of wildfires in sagebrush ecosystems (Balch et al. 2013).

In addition to increasing fuel loads, annual grass invasion displaces native plants, which can in turn reduce biodiversity, forage quality, and wildlife habitat (DiTomaso 2000). Fuel treatments are intended to reduce fuel loads and fire risk in efforts to restore native plant communities. However, some fuel treatments may increase invasive species from physical disturbance and the reduction in native species (Potts and Stevens 2009, Freund et al. 2021, Pyke et al. 2022), which may inadvertently increase non-native dominance and further degrade an area. Additionally, fuel treatments may provide open niches for invasive species initially that are exacerbated when a wildfire occurs. We have little information about how fuel reduction treatments and subsequent wildfire interact to alter the post-fire trajectory of ecosystem succession. Considering that fire return intervals have decreased substantially in sagebrush ecosystems (Baker 2006), it is imperative we understand how prior fuel treatments affect post-wildfire plant community responses. While we assume that fuel treatments reduce risk to ecosystems that burn in wildfire, it is possible that the dual disturbances of fuel treatments and subsequent wildfire have negative impacts.

Using data from long-term fuel treatment experiments that burned in wildfires, we examined plant successional trajectories following fuel treatments and wildfire. Three sagebrush shrubland sites in the Sagebrush Steppe Treatment Evaluation Project (SageSTEP) burned in wildfires approximately ten years after fuel treatments were implemented. We present ten years of post-fuel treatment data along with 3-4 years of post-wildfire data on plant functional group responses in control, tebuthiuron, prescribed fire, and mowing plots.

Methods

Experimental Design

The Sagebrush Steppe Treatment Evaluation Project (SageSTEP) is a long-term plot network with 19 sites across six states and a range of environmental conditions in the Intermountain West, USA. Fuel treatments in shrublands were implemented from 2006-2009. Prescribed fire treatments were applied in late summer and early fall with the intention of consuming most woody vegetation. Herbicide treatments included tebuthiuron (Spike 20P; 1.68 kg/ha) and imazapic (Plateau; 22.2% acid equivalent), which were applied to reduce woody and herbaceous fuels, respectively. Mowing treatments were applied to reduce shrub cover by 50%. Annual vegetation, fuels, soil, and climate data have been collected for all treatments at all SageSTEP sites (McIver and Brunson 2014, Pyke et al. 2014, Freund et al. 2020). Three of the original shrubland sites, characterized by Wyoming big sagebrush and invasive annual grasses have burned in recent wildfires: Owyhee, Nevada (2018); Moses Coulee, Washington (2019); and Rock Creek, Oregon (2020).

Field data were collected from April to June each year during the peak growing season in the year prior to treatment, annually post-treatment, and for 3-4 years post-wildfire. Treatment plots contained between 12 and 22 sampling subplots; all subplots were 30 x 33 m in size. Plant cover was measured on five-30 meter transects using the line-point intercept method with 300 points per subplot. We looked at foliar cover across four functional groups (perennial grass, annual grass, annual forb, and shrub) to assess the effect of fuel treatments on the post-wildfire plant community. Full field sampling protocols are available in Stebleton and Bunting 2009, Bourne and Bunting 2011, and Wozniak and Strand 2019.

Statistics

All statistical analysis was performed using R (R Core Team 2024). Total foliar cover data was used across all sites for all functional groups to assess temporal and treatment effects before and after wildfire. Using the glmmTMB (Mollie et al. 2017) package in R, Beta Generalized Linear Mixed Models (Beta GLMMs) were used to model plant community resilience. To meet the distribution requirements of Beta GLMMs, total foliar cover values were scaled for each functional group at each site to range between 0 and 1 by normalizing each functional group's cover value relative to the total cover within each plot. To ensure reliable model performance, the data was filtered to include only those plots where the scaled foliar cover values were greater than 0 and less than 1. In the model, total foliar cover was considered the response variable; treatment, year, and their interaction were considered fixed factors; and plot number was used to account for variability and manage repeated measures within the same plot. A beta distribution with a 'logit' link function was used to appropriately model the proportional response variable. To ensure model fit and reliability, the DHARMa (Hartig 2024) package in R was used to visually inspect residual versus predictor plots and quantile (Q-Q plot) residuals. The model was run for each functional group for each site using the same predictors and response variable. Percent changes were calculated by comparing estimated marginal means of treatments relative to control values, and statistical significance (p-values) was determined through pairwise contrasts (using emmeans), with significance at $\alpha = 0.05$.

Results

At Owyhee post-wildfire (2019-2023), perennial grass cover was not significantly affected by any fuel treatment compared to control (all $p > 0.05$). Annual grass often substantially increased, such as by 260% in tebuthiuron (2019), but these increases lacked statistical significance. In prescribed fire, annual forb cover decreased by 46% in 2022 (p=0.021) and increased by 24% in 2023 (p=0.035) relative to control; annual forb responses were otherwise varied with no significant trends. Shrub cover in mowing and prescribed fire was generally lower than in control, but not significant, except in 2021 when shrub cover in mowing plots was 80% lower than in control (p=0.014).

At Moses Coulee post-wildfire, perennial grass consistently exhibited large and statistically significant increases in all three treatments relative to control. In 2021, perennial grass cover increased by 124–455% ($p \leq 0.001$) depending on the treatment, remained elevated in 2022 (90–209%, $p \leq 0.001$), and continued to be high in 2023 (85–303%, $p \leq 0.002$). Annual grass notably increased in the first-year post-wildfire (2021) in tebuthiuron (93%, p=0.016) and prescribed fire (97%, p=0.011) plots, though subsequent years yielded smaller or non-significant changes. Annual forb responses were not significant aside from a large decrease in prescribed fire plots in 2022 (73%, p=0.001). Shrub cover effects were more limited, with significant reductions observed in 2023 under tebuthiuron (79%, p=0.004) and prescribed fire (69%, p=0.049).

At Rock Creek post-wildfire, perennial grass cover rose by 91–95% across treatments relative to control ($p \leq 0.004$) in 2020, with similar increases (75–113%, $p \leq 0.018$) in 2021. In 2022, prescribed fire produced a significant increase in perennial grass cover (47%, p=0.026). However, by 2023, all treatments again yielded significant perennial grass increases relative to control (60–68%, $p \leq 0.004$). In 2022, annual grass cover in prescribed fire plots was 413% greater than in control (p=0.012). However, in 2023, annual grass cover did not significantly differ between treatments and control. Annual forb changes were variable, highlighted by a notable 170% increase in prescribed fire relative to control in 2022 (p=0.001), with few differences between treatments and control in 2023. Changes in shrub cover relative to control were minimal and lacked statistical significance across all treatments and years.

Discussion

The variability in plant functional group responses to different fuel treatments across the three sites underscores the importance of tailoring post-wildfire management strategies to specific ecological contexts. While previous studies (Chambers et al. 2021, Ellsworth et al. 2022) found that prescribed fire can facilitate herbaceous recovery in sagebrush ecosystems, our findings further demonstrate increases in perennial grasses under prescribed fire. This consistency, especially compared to more variable outcomes under mowing and tebuthiuron, suggests that prescribed fire's broad-spectrum effectiveness is robust across environmental settings and temporal scales. In contrast, the modest or non-significant changes in perennial grass at Owyhee and the inconsistent responses of annual grasses and forbs to mowing and tebuthiuron highlight that these other treatments may only be beneficial under certain pre-fire conditions or site-specific biotic and abiotic factors.

This work enhances our understanding of how fuel treatments interact with local conditions to shape vegetation trajectories. Although shrubs are predictably reduced post-fire due to their fire intolerance, our results indicate that whether gaps left by shrubs are filled by perennial grasses, annual forbs, or annual grasses depends heavily on the chosen treatment and the site's inherent resiliencies or vulnerabilities. This aligns with ecological principles suggesting that community recovery is contingent on environmental gradients, seed sources, and disturbance histories. While managers may find prescribed fire a consistently reliable tool to promote perennial grasses, the more context-dependent results from mowing and tebuthiuron caution against a one-size-fits-all approach. Thus, it is important to integrate local site assessments—soils, climate, seedbank composition, and pre-fire vegetation—before deploying fuel treatments.

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Frequent prescribed fire contributes to soil organic carbon sequestration and pyrogenic carbon stability in South African mesic grasslands

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Key words: Prescribed burning; Soil organic carbon (SOC); Mesic grasslands; Carbon sequestration; Fire management

Abstract

Grasslands serve as crucial terrestrial carbon sinks, storing substantial amounts of organic carbon (OC) in aboveground vegetation, roots, and soils. However, effective carbon sequestration in grasslands depends on management practices. South African subtropical mesic grasslands are fire-adapted ecosystems, dependent on fire as a key ecological force shaping and sustaining them. Fire influences carbon sequestration by removing above-ground biomass, redistributing nutrients, and contributing inputs through thermal mineralisation.

This study assessed the impact of varying fire frequencies and season of prescribed burns on soil organic carbon (SOC) stocks, total nitrogen (TotN), and carbon-to-nitrogen (C:N) ratios, as well as the stability of refractory organic matter (refractory OM) and black carbon (BC) fractions across soil depths up to 30 cm. Results showed that fire frequency and season of prescribed burns significantly influence SOC and TotN stocks, with annual winter and spring burns resulting in the highest SOC stocks and wider C:N ratios in the top 5 cm of soil. Conversely, biennial and triennial burns showed reduced SOC stocks, with triennial burns displaying the lowest levels and even SOC loss below 5 cm. Over 20 years, SOC stocks increased under all fire regimes except for triennial burns, where stabilization or reduction was noted.

Additionally, our findings indicate that increased fire frequency leads to the maintenance of BC within the soil, though BC remains stable across soil horizons. Refractory OM and BC levels were greater in areas that were unburnt or experienced longer burn intervals, likely driven by a decline in soil pH and increased acid saturation associated with less frequent fires. These patterns suggest that while regular fires can contribute to surface SOC stocks, the management of fire intervals is crucial for maintaining deeper, more recalcitrant carbon fractions. This emphasizes the beneficial role of regular grassland fires in carbon sequestration and suggests practical management strategies for fire-adapted mesic grasslands.

Introduction

Grasslands serve as crucial terrestrial carbon sinks, storing significant amounts of carbon in aboveground vegetation, roots, and soils (Bikila et al., 2016; Ward et al., 2016). The management practices applied to these ecosystems play a central role in determining their carbon storage potential (Ward et al., 2016). Prescribed fire management is a common practice in South African grasslands, but its long-term sustainability remains a concern due to carbon and nitrogen losses from biomass during burns (Materechera et al., 1998; Snyman, 2002). Understanding the timing and frequency of prescribed fires is essential for ensuring the long-term sustainability of grasslands and maximising their carbon sequestration potential.

While grasslands managed with prescribed fire have demonstrated substantial carbon sequestration (Teixeira et al., 2022), the specific impact of fire frequency and season of prescribed burns on soil organic carbon (SOC) stocks, total nitrogen (TotN), and carbon stability remain poorly understood. In this context, carbon stability refers to the presence of stable, recalcitrant carbon (RC), a fraction of soil organic matter (SOM) that is resistant to decomposition and is a key to long-term carbon storage. This study examines the maintenance of stable carbon fractions as concentrations through soil depth and evaluates total carbon sequestration over time by comparing current SOC stocks to those measured in 2001 by Fynn et al. (2003), allowing for an assessment of carbon accumulation over a 20-year period. The Ukulinga Grassland Fire Experiment (UGFE), established in 1950 in the subtropics where rainfall is summer-dominant, provides a unique opportunity to examine carbon stocks and turnover following prescribed fire treatments (Fynn et al., 2003). Studies from the UGFE suggest that seasonal burns, particularly in spring, mitigate carbon losses by facilitating rapid litter decomposition and incorporation into soils before burning, while autumn and winter burns reduce surface carbon pools through wind erosion and leaf litter removal (Fynn et al., 2003).

Fire has been noted to influence the turnover of stable carbon fractions such as black carbon (BC) and refractory organic matter (refractory OM), critical for long-term carbon storage (Gao et al., 2017; Glaser & Amelung, 2003). These RC forms resist decomposition, yet their distribution and stability across soil depths may be shaped by fire frequency and soil acidification (Findlay et al., 2022; Masiello, 2020). Suppressed fire regimes can maintain soil acidity in already acidic soils, limiting microbial activity and SOC turnover or availability. In contrast, low-intensity fires, through the deposition of alkaline mineral ash containing inorganic carbonates (e.g., calcium, magnesium, sodium, potassium, silicon, and phosphorus), may contribute towards increasing soil pH and aiding nutrient availability (Agbeshie et al., 2022; Bodí et al., 2014). This study investigates the effects of prescribed fire on SOC stocks and sequestration (20 years), TotN, and stable carbon fractions (refractory OM & BC) in South African mesic grasslands. We hypothesise that fire frequency drives shifts in soil carbon sequestration, stability and pH, with increased fire frequency enhancing surface SOC retention but reducing refractory OM and BC stabilisation in deeper soil layers.

Methods

The Ukulinga Grassland Fire Experiment (UGFE), at the University of KwaZulu-Natal Research Farm in Pietermaritzburg South Africa (-29.667° S, 30.399° E; altitude 843 m), examines the effects of prescribed burning on subtropical mesic grasslands under summer-dominant rainfall. Soils at the site are sandy clay loam, with an orthic A over a soft plinthic B horizon (Soil Classification Working group, 1991), and the mean annual rainfall is 790 mm, ~95% occurring in summer (November to February). Mean temperatures range from 26.4°C in February to 8.8°C in July (Fynn et al., 2003). Vegetation is classified as KwaZulu-Natal Hinterland Thornveld, dominated by native C4 grasses (Mucina & Rutherford, 2006).

The UGFE, initiated by J.D. Scott in 1950 to study historically prescribed burning regimes, was established with a randomized split-plot design, incorporating three replications for each treatment on plots measuring

18.3 × 13.7 m. The UGFE has been entirely excluded from domestic livestock and large wild ungulate grazing regimes. For this study, 9 burn treatments within this experiment, namely annual, biennial, and triennial burning in winter, spring, or autumn, as well as fire exclusion, were utilised. Burns were conducted according to seasonal protocols: spring burns followed the first 12.5 mm of rainfall (usually within September), while winter burns were conducted in early August. The experimental plots in this study were consistently burned in accordance with the established UGFE protocol throughout the duration of the experiment, with no deviations in application and no impact from wildfires. Soil organic carbon (SOC) stocks were assessed at a second time point (2021) and compared to those measured 20 years earlier in a study by Fynn et al. (2003). The rate of carbon sequestration over this 20-year period was then estimated.

To assess prescribed fire history on grassland SOC accumulation, soils were collected in May 2021 using a 2.8 cm soil corer. Four random cores per plot were sampled to a depth of 30 cm, segmented into 5 cm increments and composited. Samples were dried (65°C, 48 hours), homogenised, sieved to 0.5 mm, and analysed for total SOC and nitrogen using a Leco TruMac CNS analyser. Organic carbon and nitrogen concentrations were calculated and converted to SOC and TotN stocks (Mg ha^{-1}) per treatment (FAO, 2020). Recalcitrant carbon fractions (ROC and BC) were quantified using a thermogravimetric analyser (TGA) under a nitrogen atmosphere, with ROC recorded between 475–550°C and BC between 550–650°C.

Hierarchical linear mixed models assessed the effects of fire frequency, season of prescribed burns, and soil depth on SOC stocks (2021), SOC sequestration (20yrs), TotN, C:N ratios, and carbon fractions. Plots were treated as random effects to account for variability between them, and fixed effects included nested interactions between fire treatments and soil depth. Diagnostic checks confirmed model assumptions (normality, equal variance, linearity, independence, & overall fit of the model) were met, and post hoc Tukey HSD tests evaluated significant differences between treatments. Pearson's correlation assessed the relationship between soil pH and BC levels, while one-way ANOVAs examined acid saturation and fire treatment effects. Statistical analyses were conducted in R (R Core Team, 2023), using standard packages for data processing and visualisation.

Results

Total Carbon, Nitrogen, and Refractory Organic Carbon Status

Soil organic carbon (SOC) and total nitrogen (TotN) stocks declined significantly with increasing soil depth (SOC: $\beta = -0.396$, $p = 0.02$; TotN: $\beta = -0.046$, $p < 0.001$, Figure 1). SOC stocks were highest in annual winter burns ($\beta = 0.995$, $p < 0.001$) and fire exclusion treatments relative to SOC stocks in the biennial and triennial burn treatments in autumn and winter ($p < 0.01$). Depth had a marginally positive effect on C:N ratios ($\beta = 0.003$, $p = 0.05$), with fire exclusion significantly reducing C:N ratios ($\beta = -4.310$, $p < 0.001$).

Refractory organic carbon (ROC) concentrations were highest in the top 5 cm of soil (19.62 ± 0.929 g/kg) and declined significantly with depth ($p < 0.001$). Burning treatments did not affect ROC levels, while black carbon (BC) remained stable across soil depths (1.87 ± 0.180 g/kg). Grasslands excluded from fire exhibited the greatest BC concentration (10.27 ± 2.141 g/kg), relative to annual and biennial burns BC quantities. A significant negative correlation between BC and soil pH ($r = -0.384$, $p < 0.001$) revealed that acidified soils retained more BC.

Carbon Sequestration and Fire Frequency

SOC sequestration over 20 years varied by fire treatment and depth, with triennial burns showing negative sequestration in the 5–10 cm soil layer (winter: -0.16 ± 2.0 Mg C/ha; spring: -0.46 ± 3.42 Mg C/ha; autumn: -1.03 ± 2.23 Mg C/ha). In contrast, annual winter burns exhibited the highest SOC sequestration (1.1 ± 1.0

Mg C/ha) in the top 5 cm. Depth was the strongest predictor of changes in SOC sequestration with SOC decreasing with increasing depth ($p = 0.001$).

Soil Acidification and Fire Exclusion

Plots with fire exclusion and triennial treatments had significantly lower pH than more regularly burned plots ($p < 0.001$, $F_{9,80} = 4.67$). Soils excluded from burning had the lowest pH, with a mean of 4.2 ± 0.3, while annual winter burns had near-neutral pH levels (pH 6.1 ± 0.4). Acid saturation was notably greater in unburnt soils and those with extended burn intervals, indicating maintained acidification with reduced fire frequency.

Black carbon (BC) accumulation was highest in fire-excluded plots (10.27 ± 2.141 g/kg), followed by triennial winter burns (6.13 ± 0.474 g/kg). BC content was negatively correlated with pH ($r = -0.384$, $p < 0.001$), with higher BC concentrations observed in plots with lower pH values.

Discussion [Conclusions/Implications]

The significant declines in SOC and TotN stocks with increasing soil depth highlight that the greatest concentrations of SOC and TotN are found in the topsoil, emphasizing the importance of protecting this layer to prevent losses. The greatest SOC in the top 5 cm of soil under annual and biennial burns, particularly in spring, suggests this layer has the greatest capacity for SOC sequestration, supporting findings from similar studies that link moderate fire temperatures with enhanced microbial activity and nutrient cycling (Fynn et al., 2003; Ohrtman et al., 2012).

Low levels of SOC sequestration (measured within a 20-year timeframe) below 5 cm under Triennial burns suggest losses, likely driven by biomass accumulation and shifts in lignin composition, resulting in incomplete combustion. These results challenge the assumption that SOC stocks stabilise within 20 years.

While Fire exclusion appeared to promote BC accumulation, it also appeared in acid conditions, possibly inhibiting nutrient cycling. This is consistent with studies linking fire suppression to the buildup of lignified biomass and coarse BC particles, which stabilise in acidic conditions but limit overall carbon turnover (Agbeshie et al., 2022; Docherty et al., 2012), akin to the 'use it or lose it' principle. The negative correlation between BC and soil pH suggests that acidic soils favour BC retention but hinder the decomposition of organic material, emphasizing the dual role of fire in stabilising and mobilising carbon fractions. The persistence of SOC and recalcitrant carbon forms such as ROC and BC in deeper soil horizons remains an area for further study. These stable fractions, influenced by ash deposition and fire-induced changes in soil, play a vital role in long-term carbon storage and climate mitigation (Lorenz & Lal, 2005).

These results suggest that the interval of prescribed burns must balance carbon sequestration objectives with the maintenance of soil fertility and grassland functionality. Prescribed fire in subtropical grasslands with summer-dominated rainfall, particularly in spring, appears to sustain mesic grasslands as carbon sinks. Annual and biennial burns, particularly in spring, optimise carbon sequestration and nutrient cycling while mitigating soil acidification.

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Woody species composition, diversity and vegetation structure of two rangelands areas along a climatic gradient in Burkina Faso (West Africa)

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Key words: Burkina Faso; Sidéradougou rangeland; Mankarga rangeland; woody species; conservation

Abstract
Climate variability added to anthropogenic pressures leads to habitat fragmentation, degradation and loss of rangelands resources in Burkina Faso. Studying vegetation structure and woody species composition is important in monitoring vegetation dynamics for efficient rangeland management. This study was carried out to characterize woody vegetation along a climatic gradient. Sixty-four quadrats of varying size were laid in each of the rangeland (Sidéradougou and Mankarga). Thus, the inventory unit was 1000 m² (50 m x 20 m) in savannas and 500 m² (50 m x 10 m) in gallery forests. In each plot, all woody species with a diameter at breast height (DBH) ≥ 5 cm were systematically identified and measured. The data were analyzed by using Shannon-Wiener diversity and equitability indices, and the structural analysis was carried out based on frequency, density, DBH, height and basal area/ha-1. A total of 89 forage plant species belonging to 64 genera and 25 families from Sidéradougou and 80 plant species belonging to 57 genera and 23 families from Mankarga was identified. Fabaceae and Combretacea was the dominant family in the two rangelands with diverse population structures. The small trees and shrubs dominated the rangeland suggesting its status under a secondary stage of development. Some woody species require urgent conservation measures. Therefore, local and regional stakeholders should integrate and work together to develop and implement sound conservation and management strategies that encourage the sustainable utilization of rangeland resources.

Introduction
Pastoral ecosystems play a major role in the global climate balance and provide numerous ecosystem goods and services (FAO 2020). They also contribute to socio-economic well-being through the woody and non-woody forest products that they provide. The use of these woody and non-woody forest products makes an invaluable contribution to food production in rural areas (Nacoulma et al. 2011). Woody plants forages provide proteins essential to the dietary balance in livestock feeding strategy on natural pasture during the dry season (Du et al. 2023). Moreover, in Sahelian rangelands, fodder supply from annual fodder species during the dry season or in years of low rainfall remain problematic. In this circumstance woody species

become an important source of forage in the livestock feeding strategy (FAO 2020). Anthropogenic activities are exerting high pressures on natural resources inducing a rapid biodiversity erosion that affects the capacity of ecosystems to provide the goods and services for human uses (Cardinale et al. 2012).

Thus, the current study in the Sidéradougou and Mankarga rangelands in Burkina Faso is critical due to a lack of documentation on the diversity and structure of the woody forage plants. Specifically, it seeks to answer the following research questions: (i) What is the species richness and diversity of woody vegetation in the Sidéradougou and Mankarga rangelands? (ii) How are rangelands structured in terms of tree density, basal area, and diameter class distribution?

Materials and methods

Study area

The research was carried out in the Mankarga and Sidéradougou sylvopastoral zones, located respectively in the Sudanian and Soudano-Sahelian zones of Burkina Faso. Mankarga's rangelands cover an area of 6,270 hectares and lie between latitudes 11°59' and 12°06' North, and longitudes 00°53' and 00° 59' West. The Sidéradougou area covers 51,500 ha and lies between latitudes 10°30' and 11°104' North and meridians 3°55' West and 4°50' East (Fig.1).

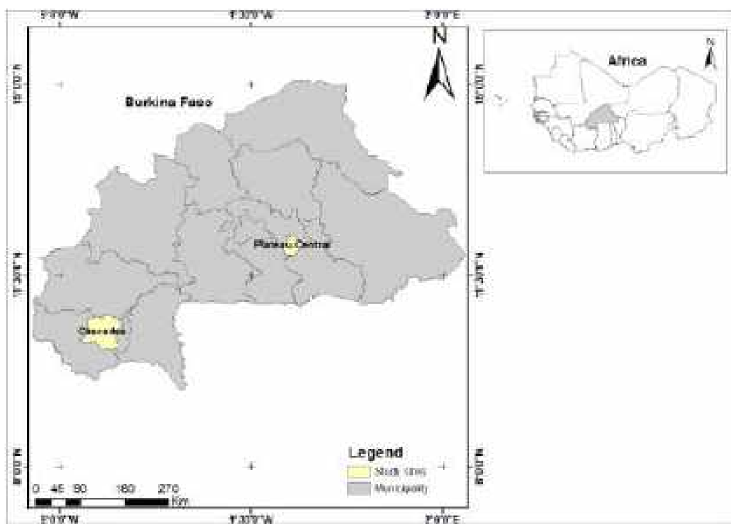

Figure 1: Map showing the study sites.

Data collection

Floristic inventories were conducted at two study sites at the onset of the dry season (November to December 2023) when the plots were readily accessible. A total of 128 plots were established, comprising 64 plots per site within homogeneous stands of plant formations. The inventory unit was 1000 m² (50 m × 20 m) in Savannas and 500 m² plots (50 m × 10 m) in gallery forests. Within (Thiombiano et al. 2016) each sampling plot, phytosociological methods were employed to assess woody plant.

Vegetation data analysis

Diversity indices

The Shannon diversity (H') and evenness (J) indices are used to measure both species richness and species evenness (Kent, 2012). The Shannon Wiener diversity index (H') was computed for each plant community types using the equation:

$$H' = -\sum_{i=1}^{s} pilnpi \quad (1)$$

where S = total number of species in the community (richness) and pi is relative abundance of the i^{th} species in a sample plot. The Shannon evenness (J) was calculated from the ratio of observed diversity to maximum diversity using the equation:

$$J=H'/Hmax=H'/lns \quad (2)$$

Where Hmax is the maximum level of diversity possible within a given population, which equals ln (number of species). J (species evenness) is normally ranges between 0 and 1, and with 1 representing a situation in which all species are equally abundant (Magurran, 2003).

Structural data analysis

To analyze the population structure of woody plant species, tree diameters were categorized into 5 cm intervals. The diameter class distribution of each vegetation type was fitted to a theoretical value of the Weibull distribution, whose probability density function is defined as follows (Johnson and Kotz, 1970) :

$$f\ (x) = \frac{c}{b}\left(\frac{x-a}{b}\right)^{c-1} exp\left\{\left(\frac{x-a}{b}\right)^{c}\right\} \quad (3)$$

In this equation, x represents the tree diameter; a (threshold parameter) equals 5 cm; b is the scale parameter linked to the central value of diameters; and c is the shape parameter of the structure, also known as the Weibull slope.

Results

Floristic composition and species diversity

A total of 169 woody species, spanning 121 genera and 48 families, were identified across the two rangelands. In the Mankarga rangelands specifically, 80 species from 57 genera and 23 families were recorded, while the Sidéradougou rangelands harbored 89 species across 64 genera and 25 families. In Sidéradougou, Fabaceae emerged as the most represented family (7.86% of species), followed by Combretaceae and Malvaceae (both at 5.61%). In contrast, Combretaceae was the dominant family in Mankarga (10% of species), followed by Fabaceae (7.5%) and Rubiaceae (5%).

The species richness of inventoried individuals varied across pastoral zones, averaging 10.28 ± 2.51 in the Sidéradougou rangelands and 9.61 ± 2.70 in the Mankarga rangelands (Table 1). Considering the species richness, statistical analyses revealed that there was no significant difference between gallery forest and wooded savannas within the same rangeland or between the two rangelands. The diversity indices (Shannon's index, Shannon evenness) exhibited significant variations along the two rangelands ($P < 0.001$) and among different vegetation types (Table 1). The Shannon evenness (J) values for the rangelands of Sidéradougou and Mankarga were 0.87 ± 0.13 and 0.83 ± 0.18, respectively, indicating a relatively equal distribution of species within the communities of both rangelands.

Table 1: Diversity indices by plant formation type in each Rangeland

Rangelands	Index	Gallery forest	Woodland savanna	Overall	Chi-square	p
Sidéradougou	J	0.95±0.02[a]	0.93±0.02[b]	0.87±0.13	70.67	<0.001

	H	2.32±0.18[a]	2.26±0.21[a]	1.95±0.57	83.33	<0.001
	S	11.47±1.76[a]	11.40±2.03[a]	10.28±2.51	78.01	<0.001
Mankarga	J	0.84±0.17[a]	0.85±0.19[a]	0.83±0.18	21.46	<0.001
	H	2.18±1.41[a]	2.01±0.56[a]	1.91±1.04	45.45	<0.001
	S	10.73±2.13[a]	10.46±2.38[a]	9.61±2.70	70.32	<0.001

Values along columns with different letter differ significantly.

Woody forage plant population structure

The diameter class distribution of woody forage species in the two rangelands exhibited reversed J-shape (L-shape) pattern (Fig. 2). The majority of individuals fell within the 5-20 cm diameter class. This indicates that the species frequency distribution peaked in the lower diameter classes and gradually decreased towards the higher classes. The 'c' parameter of the Weibull distribution ranged between 0.72 and 0.82, confirming this trend.

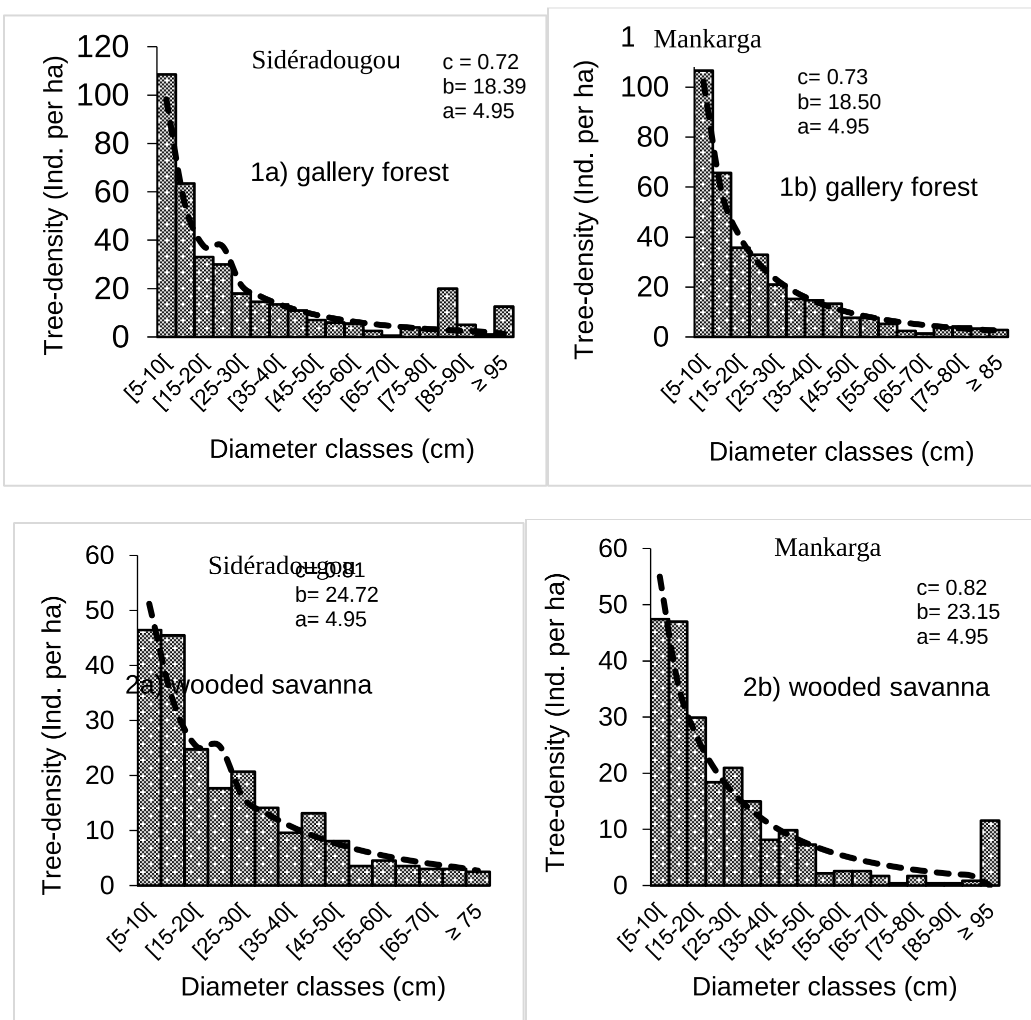

Figure 2: Diameter class size distribution of the two vegetation types in the two rangelands: gallery forest 1a and 1b; wooded savanna 2a and 2b

Discussion

Floristic composition and species diversity

Across the studied rangelands, the Sidéradougou rangeland recorded an average Shannon-Weiner diversity index (H) of 1.95 and an evenness (J) value of 0.87. Similarly, the Mankarga rangeland showed an average Shannon-Weiner diversity index (H) of 1.91, accompanied by an identical evenness (J) value of 0.87. These values are lower than those reported for forest corridor from Burkina Faso (H'= 2.85) (Sanou et al., 2021), but higher than Sahelian woodland formations from Burkina Faso (H'= 1.76; J= 0.55) (Savadogo et al., 2016). Cavalcanti et al. (2004) classify forest diversity into four categories based on the Shannon-Weiner diversity index: high diversity is indicated by a value above 3.0, medium diversity falls between 2.0 and 3.0, low diversity ranges from 1.0 to 2.0, and very low diversity is below 1.0. Therefore, the woody species diversity of the two rangelands falls within the low category, as the estimated value is between 1 and 2. The low value of the Shannon diversity index suggests that there are various factors contributing to these results, including illegal harvesting, agricultural expansion, overpopulation, and livestock intervention (Atsbha et al., 2019). Fekadu et al. (2019) have highlighted that human intervention, overgrazing, and illegal activities pose threats to the diversity and distribution of woody species in rangelands.

The species richness observed in this study is lower than that reported by Sambaré et al. (2011) in similar gallery forests in Burkina Faso. This discrepancy may be attributed to the intensity of disturbance factors and climatic variations that hinder the establishment of certain species in both study sites.

Population structure of fodder trees

The inverse J-shape of the diameter class distribution characterizes tree populations dominated by small diameter individuals. This size class distribution pattern serves as evidence that woody species have young populations with genuine capacities for rejuvenation in these rangelands. However, the absence of trees with large stem diameter in the stands could lead to the regression of the individuals stands because large trees are the best seed producers and thus support the natural regeneration (Tesfaye et al., 2004). The density of plant species decreased with increasing diameter at breast height (DBH) classes, and the lower DBH classes exhibited a greater diversity of species compared to the medium and higher DBH classes. Similar studies have shown that species with a diameter at breast height greater than 30 cm were exploited by local populations for construction and charcoal production (Badji et al., 2014). According to Atsbha et al. (2019), this bell-shaped pattern indicates a low reproductive rate and poor species recruitment.

Conclusions and implications

Assessment of diversity and regeneration status of tree species is crucial for their sustainable utilization, management, and conservation. This study examined the overall population structures of tree species in the Sidéradougou and Mankarga rangelands, revealing significant insights into their contribution to ecosystem health. This study makes a significant contribution to our understanding of tree species diversity and regeneration patterns in African savannas, providing valuable insights for policymakers and conservation practitioners working in similar ecosystems.

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New shoots – Reseeding and planting for rangeland restoration

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Active restoration improved self-restoring ability in extremely degraded alpine meadow

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Key words: Grassland restoration; Long-term restoration; Native plant seeds; Reseeding; Self-recovery ability

Abstract

About 60% of alpine meadow has been degraded, with around 8% considered extremely degraded on the Qinghai-Tibetan Plateau. The natural restoration of extremely degraded land will take more than 200 years and is the biggest challenge for ecological restoration worldwide. To improve the effectiveness of restoration, reseeding native plant seeds has become the main active restoration approach for extremely degraded meadow. However, it is still unclear whether this active restoration approach of native plant reseeding can promote the self-recovery ability and natural regeneration of extremely degraded alpine meadow. To address this knowledge gap, we have conducted long-term active restoration research of extremely degraded meadow on the Qinghai-Tibetan Plateau. Our findings indicate that the meadow vegetation was in an unstable state after active restoration within 10 years. After 10 years of active restoration without meadow management, the plant community degraded again. Soil nutrients also declined significantly after 10 years of active restoration without meadow management, with notable geographical variations. Long-term active restoration did not significantly improve the soil carbon storage. During the long-term recovery process, the vegetation carbon pool was regulated by nitrogen, while the soil carbon pool was primarily regulated by living plant roots. However, long-term active restoration had positive effects on soil seed bank density and species number. Reseeding native perennial grass seeds can improve the soil seed bank and the vegetation-soil system's resilience of alpine meadow. Therefore, for the active restoration targeting the extremely degraded alpine meadow, it is necessary to implement good post-restoration management practice to enhance the meadow's self-recovery ability. Additionally, introducing moderate livestock grazing could promote the ecological restoration's effect and ensure sustainable recovery of alpine meadow.

Introduction

The extensive and severe land degradation worldwide poses a significant challenge to the restoration of Earth's ecosystems, particularly affecting grassland ecosystems. Since the 21st century, approximately 50% of the global grassland area has experienced degradation, with about 5% suffering from severe degradation that makes ecological restoration extremely challenging (Bardgett et al., 2021). On the Qinghai-Tibetan Plateau, the alpine grassland covers an area of 125,000 km², of which 70% has been degraded, and 8% has been severely degraded, referred to as 'Heitutan' degraded grassland by local herders, or 'bare land' degraded grassland (Dong et al., 2020). This severe degradation of alpine grassland results in the disappearance of the topsoil layer (approximately 0-30 cm), the loss of the soil seed bank, the spread of weeds and toxic plants, leading to a loss of biodiversity, the reduction of permafrost, and increased water and soil erosion. This condition is likened to scalp stripping and has been termed the 'ecological cancer' of the Qinghai-Tibetan Plateau. The ecological restoration of severely degraded alpine grasslands on the Qinghai-Tibetan Plateau has been designated as a key mission in China's 'Master Plan for Major Projects for the Protection and Restoration of Important National Ecosystems (2021-2035)'. However, the natural restoration of severely degraded land can take over 200 years or even longer, and in high-altitude areas with cold temperatures and low oxygen levels, the restoration of severely degraded grasslands becomes even more complex and challenging.

We understand that successful ecological restoration requires not only the recovery of a more integrated ecosystem structure but also the restoration of multiple functions, which is a process that takes a long time. Generally, on the Qinghai-Tibetan Plateau, the initial step in restoring severely degraded grasslands is to establish high-coverage vegetation to prevent water and soil loss by reseeding local plant seeds. Subsequently, this approach aims to gradually foster biodiversity and soil fertility, and enhance the ecosystem's self-recovery ability, which is known as active restoration (Dong et al., 2020). However, current studies on active restoration are limited to short-term cases, which do not adequately explain the approach's impact on the recovery process of vegetation, soil fertility, and soil seed banks, nor do they clearly answer questions about the outcomes of long-term restoration (Dong et al. 2020). To address this gap, we conducted field investigations and soil measurements in the laboratory for long-term active restoration projects (over 10 years) in three independent highland counties (elevations is 3900-4200 m a.s.l.). This paper presents the findings of this investigation regarding vegetation, soil nutrients, and soil seed banks, which could provide valuable references for the long-term active restoration of severely degraded alpine grasslands on the Qinghai-Tibetan Plateau.

Methods

The geographical coordinates of the field investigation site are 32°31'-35°40' N and 97°54'-121°50' E, located in the eastern part of Qinghai-Tibetan Plateau. The region experiences an annual average temperature range of -3.5°C to 4°C, with an accumulated temperature of 775 to 2104°C, and receives an annual precipitation of 448.6 to 569 mm, predominantly from May to September. The altitude ranges from 3900 to 4200 m a.s.l., characterized by low oxygen levels, cold conditions, and frequent strong winds and snowfall. The predominant vegetation in the grassland is alpine meadow, with the soil type being alpine meadow soil. The dominant plant species in these meadows include *Kobresia pygmaea, K. humilis, Stipa przewalskyi, Festuca ovina, Poa pratensis, and Elymus nutans*. The severe degraded alpine grasslands originated from overgrazing in alpine meadows, its vegetation coverage of approximately 40-60%, which is now dominated by weeds and toxic plants, with large areas of bare land. All of the long-term active restored grasslands have a history of over ten years and have been managed under traditional grazing practices. The active restoration methods employed were consistent with those used in local government restoration projects conducted more than ten years ago. The reseeding of native plant seeds involved grasses, specifically *Poa pratensis, Elymus nutans*, and *Festuca ovina*, following the same technical standards.

Our field site encompassed three distinct counties (Maqin, Dari, and Gande) with each site being more than 100 km apart from the others, ensuring true replication across similar field types. Within each site (county), we selected three types of grasslands: long-term active restored grassland, undegraded grassland, and severely degraded grassland. This resulted in a total of nine grasslands that were investigated and sampled. In each grassland, we established 20 plots measuring 50cm×50cm to assess plant species, coverage, and species frequency, yielding a total of 180 plots. Additionally, within each grassland, we selected 3 plots to collect soil and root samples from two distinct soil layers (0-10 cm, 10-20 cm). These soil samples were taken to the laboratory for analysis of soil and root carbon and nitrogen content. To assess the soil seed bank, we extracted soil cores (diameter 5 cm) from 20 plots in each grassland, targeting two soil layers (0-5 cm and 5-10 cm). The germination method was conducted in a greenhouse over a period of 7 months, which allowed us to accurately identify the germinable seeds from the soil seed bank.

Results

The three α-diversity indices (Shannon-Wiener index, Simpson index, species Richness) exhibited a consistent trend across the three types of grasslands, generally indicating that undegraded grasslands (UG) have greater diversity than severely degraded grasslands (DG), which in turn have higher diversity than long-term restored grasslands (LR; Table 1). However, at the WSX site, some indices for LR were found to be higher than those for DG (Table 1). Although the DG sites showed higher plant species diversity compared to the LR sites, the majority of species in the DG sites were weeds and toxic plants (Table 1). Community composition analysis revealed that long-term restoration efforts have not resulted in an improvement in the vegetation status of the restored grasslands when compared to both the degraded and undegraded grasslands.

Table 1. Community α-diversity of three grassland types in three sites

Grassland types	Shannon-Wiener index			Simpson index			Richness
	JMC	WSX	QZX	JMC	WSX	QZX	
UG	3.3	3.02	3.31	0.96	0.94	0.96	35.0±3.6
DG	3.27	2.69	3.2	0.95	0.91	0.95	31.7±5.9
LR	3.05	2.96	2.82	0.94	0.93	0.93	28.7±5.1

JM: The study site of Junmuchang in Maqin county; WSX: The study site of Wosai in Dari county; QZX:The study site of Qingzhenxiang in Gande county; LR-Long term active restoration grassland; DG-extremely degraded grassland; UG- undegenerated grassland.

The undegraded grasslands have the highest levels of soil organic carbon (SOC) and total nitrogen (TN), while the severely degraded grasslands (DG) have the lowest levels of SOC and TN (Table 2). There is a significant variation in SOC and TN values among the three sites (Table 2). The changes in SOC and TN across the three types of grasslands are more consistent in the 0-10 cm soil layer compared to the 10-20 cm layer (Table 2). Overall, the long-term active restoration of grasslands has led to an improvement in soil organic carbon and nitrogen content (Table 2).

Table 2. Soil organic carbon and total nitrogen of three grasslands (mean±SE)

Soil layers (cm)	Grassland types	Soil organic carbon (g kg^{-1})			Soil total nitrogen (g kg^{-1})		
		JMC	WSX	QZX	JMC	WSX	QZX
0-10	UG	28.68a±2.66	45.05a±8.20	40.51a±7.42	2.05ab±0.20	2.99a±0.46	2.76a±0.56
	DG	28.22a±1.99	24.33b±1.54	27.74a±2.43	1.81b±0.17	1.84b±0.12	1.91a±0.13
	LR	34.51a±1.09	21.16b±2.49	35.30a±1.05	2.49a±0.12	1.64b±0.16	2.61a±0.09
10-20	UG	23.38b±0.56	32.40a±5.74	30.18a±5.22	1.76b±0.03	2.31a±0.37	1.99a±0.39
	DG	25.64b±3.00	21.47ab±1.31	24.41a±2.06	1.57b±0.23	1.61ab±0.08	1.74a±0.12
	LR	33.68a±2.29	15.93b±1.60	33.40a±1.29	2.58a±0.22	1.31b±0.11	2.43a±0.09

Notes: JM: The study site of Junmuchang in Maqin county; WSX: The study site of Wosai in Dari county; QZX: The study site of Qingzhenxiang in Gande county. LR-Long term active restoration grassland; DG-extremely degraded grassland; UG- undegenerated grassland. Little letter means the significant among grassland types ($p<0.05$).

There is no significant difference in the organic carbon content of both living and dead roots among the three types (Table 3). The total nitrogen content in the living roots is highest in the degraded grassland and lowest in the undegraded grassland (Table 3). The total nitrogen content in the dead roots of the degraded grassland is higher than that in the long-term restored grassland and the undegraded grassland, but the difference is not statistically significant (Table 3). Overall, long-term restored grassland has improved the organic carbon content in living roots.

Table 3. Organic carbon and total nitrogen of grassland root (Mean±SE)

Grassland types	Organic carbon (g kg^{-1})		Total nitrogen (g kg^{-1})	
	Living root	Dead root	Living root	Dead root
UG	518.55a±27.42	474.46a±35.44	7.24b±1.34	10.32a±2.00
DG	509.74a±26.03	487.86a±3.81	12.93a±1.26	14.91a±2.38
LR	511.51a±6.60	450.74a±10.37	10.32ab±1.43	14.07a±0.58

Based on the species composition of the soil seed bank, the degraded grassland exhibits the highest species richness, whereas the long-term restored grassland shows the lowest (Table 4). The soil seed bank of the degraded grassland is predominantly composed of forb species. The long-term restored grassland has a comparable species richness to the undegraded grassland, with gramineous plants being the dominant species in both types of grasslands (Table 4).

Table 4. Species diversity of soil seed bank in three grasslands in three seasons (Mean±SE)

Season	Grassland types	Shannon-Wiener index	Simpson index	Richness
April	UG	2.13±0.21	0.73±0.10	12.56±3.09
	DG	2.30±0.33	0.76±0.18	15.33±2.87
	LR	1.89±0.51	0.63±0.22	13.11±2.57
August	UG	1.96±0.31	0.82±0.06	9.56±2.51
	DG	1.96±0.23	0.81±0.05	12.00±2.60
	LR	1.65±0.22	0.75±0.05	8.11±2.26
December	UG	1.85±0.51	0.78±0.13	10.00±4.47
	DG	2.12±0.26	0.83±0.07	13.44±1.67
	LR	2.01±0.17	0.84 ±0.03	9.44±1.24

The seed density in the soil seed bank across the three types of grasslands follows a similar pattern, with the highest density observed in the undegraded grassland and the lowest in the severely degraded grassland (Table 5). Additionally, the seed density is highest in April and lowest in December (Table 5). The degraded grassland contains several species that produce a large number of seeds, such as the forb *Pedicularis kansuensis* Maxim. The long-term restored grassland has increased the seed density of the soil seed bank, and the plant species composition is now dominated by perennial grasses (Table 5). The soil seed bank is an indicator of vegetation recovery potential, especially in grassland ecosystems. Thus, these findings suggest that long-term restoration efforts can enhance the vegetation recovery ability of this type of grassland.

Table 5. Seed density of soil seed bank of three grassland in three seasons (Mean±SE)

Grassland types	April	August	December
UG	3172.70±1278.08	2386.35±871.62	2173.38±1096.70
DG	9452.57±3362.07	6973.39±2329.87	8731.75±8025.47
LR	7819.80±3473.59	4996.59±3188.58	2506.49±648.29

Discussion [Conclusions/Implications]

Our independent experimental results from the three counties demonstrated that long-term active restoration has a certain positive effect on the recovery of extremely degraded grasslands. However, the lack of post-restoration management may have led to a significant decline, or even the disappearance, of the restoration approach's effectiveness. The typical characteristic of degraded alpine meadows is a marked increase in weed and toxic plant species, which, of course, serves as an effective self-protection mechanism against the grazing pressure on grassland ecosystems (Shang et al., 2016). The increase in weeds and toxic plants also enhances vegetation coverage, soil seed bank density, and soil nutrition, features that have been improved by long-term restoration efforts (Guo et al., 2019).

It is noteworthy that long-term active restoration did not change the degraded status of the grasslands, and there has been a decline in vegetation coverage and biomass. Consequently, the return of plant biomass to the soil system has decreased, leading to more severe soil degradation. As available soil nutrients diminish and the soil becomes more barren, it becomes increasingly difficult to further enhance the grassland's restoration ability. A key reason is that during long-term restoration, the grasslands continue to experience grazing disturbance, a common issue in global ecological restoration efforts (Xu et al., 2023). Our previous studies have shown that active restoration can enhance soil nutrient accumulation, but the restored grasslands should reduce grazing or implement rest-grazing through fencing (Feng et al., 2010; Gao et al., 2019). In this study, all long-term restoration grasslands were not well managed after the restoration measures were implemented. Throughout the long-term restoration process, the grasslands were grazed by local herders, with over-grazing occurring, which reduced the effectiveness of the restoration efforts.

Active restoration with native plant seed reseeding and reduced disturbance, coupled with improved management practices, could enhance the recovery effects for severe degraded grasslands. Furthermore, we advocate against implementing restoration projects without proper subsequent management, as this could lead to more severe degradation, particularly in ecologically fragile areas such as dry and cold regions. Although there is a significant need to restore degraded grasslands on the Qinghai-Tibetan Plateau, the pressure from livestock breeding on these grasslands necessitates a primary reduction in livestock numbers and an increase in protection or conservation efforts (Shang et al., 2014). If the large number of livestock cannot be reduced, the effectiveness of ecological restoration efforts will be greatly limited. Drawing on ecological theory and practice, active restoration with native plant reseeding has a positive effect and can significantly improve grassland recovery, which underscores the importance of post-restoration management (Xu et al., 2019). Local herders should adopt planned-grazing practices on restoring grasslands, which could greatly enhance their recovery. This is because the economic interests of ecological restoration in severe degraded grasslands are ultimately closely linked to the local herders.

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Enhancing rangeland sustainability by reseeding legumes in temperate steppe

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Key words: legumes; reseeding; production; no-tillage; soil nitrogen; soil organic matter

Abstract

Legumes, acting as important fixers of nitrogen (N), are characterized by high forage quality. However, these key species are suffering from substantial declines in rangeland worldwide, especially in degraded ecosystems, with subsequent constraints on livestock performance. There is an urgent need to restore legumes to improve forage quality and quantity. We developed a cutting-edge reseeding technology, and a new re-seeding machine, to introduce legumes into degraded rangeland. Compared with traditional no-tillage reseeding, the new reseeding technology can dramatically improve germination rates of reseeded legumes by creating suitable micro-habitat for seed germination and seedling establishment, e.g., higher soil temperature and moisture. Legume-reseeded rangeland was more productive than non-reseeded rangeland, primarily due to enhanced ecological niche complementarity and compensatory growth through interspecific facilitation. Four years after legume reseeding, soil nitrogen and organic matter content were increased by more than 10%. Beneficial soil microbes, e.g., the abundance of arbuscular mycorrhizal fungi, was significantly increased by 31% after legume reseeding. In general, introducing legumes into degraded rangeland can improve forage production and quality, and simultaneously enhance rangeland sustainability by promoting soil health.

Introduction

Legumes are integral components of rangeland ecosystems, contributing significantly to soil fertility and enhancing the overall nutritional value of forages (Ganjurjav et al., 2024). However, rangeland degradation, driven by climatic change and anthropogenic disturbances, has led to a rapid decrease in diversity and abundance of legumes (Xu et al., 2020; Tognetti et al., 2021). This loss of legumes has profound ecological and economic consequences, for instance, reducing soil carbon sequestration and nitrogen fixation, and decreasing forage quality and quantity (Stagnari et al., 2017). Reintroducing legumes into degraded rangelands has been recognized as a critical strategy for restoration and renewal (Waddington, 1992; Mi et al., 2024). Nevertheless, the successful establishment and persistence of legumes are often hindered by abiotic factors (e.g., drought; light competition) and biotic factors such as competition from native vegetation in rangeland. To facilitate seedling establishment and achieve long-term maintenance of legume proportion in rangeland, there is an urgent need to develop effective agronomic practices. Here we focus on the approach of reintroducing legumes into degraded steppes and then investigate the effect of legume reintroduction on forage production and soil nutrient content. This study aims to provide practical implications for rangeland restoration and ecosystem sustainability.

Methods

Study area and experimental design

The study site is located at a temperate steppe in Hulunbuir, northeastern Inner Mongolia, China (49 ° 20 ′ ~ 49 ° 26 ′ N, 119 ° 55 ′ ~ 120 ° 9 ′ E, altitude 628 ~ 649 m), with an annual average temperature of -3 ~ 0 ℃, and an annual average precipitation of 350 ~ 410 mm. The precipitation is seasonal and mainly occurs from June to September. The study area is moderately degraded steppe. In June 2020, we reseeded yellow-flower alfalfa (*Medicago falcata*) into degraded rangeland using no tillage machine with inverted T-shaped or V-shaped slots, and the un-reseeded area was treated as non-reseeding (NR) treatment. We randomly selected ten 1 × 1 m sample plots for paired sampling, applying both non-reseeding (NR) and reseeding (R) treatments.

Sampling and measurements

After reseeding, we buried button-type temperature and humidity monitors in each slot, which can automatically record data every hour. These monitors recorded soil relative humidity data from July 19th to September 6th, 2020, and soil temperature data from June 17th to September 23rd, 2020. We randomly selected three 1-meter-long slots in each plot, and counted the number of alfalfa seedlings in each slot 7 days after reseeding to calculate germination rate. Aboveground living plants in each plot were harvested and sorted by species in middle August 2024 (peak growth period). All plant species were classified into three functional groups: legume, forb, and grass. We collected soil samples at the depths of 0-15 cm and measured total nitrogen and organic carbon content using an elemental analyser (Vario Macro, elementar, Germany) and a CN analyser (Elementar, Germany), and measured the abundance of arbuscular mycorrhizal fungi (AMF) using phospholipid fatty acid (PLFA) analysis.

Statistical analysis

When investigating the impact of inverted T- or V-shaped slot reseeding on soil temperature and humidity, we performed one-way ANOVA using the *aov* function in the *stats* package. If significant effects were found, we used the *agricolae* package for a Duncan test. We used the *t.test* function in the base *stats* package to detect the difference between non-reseeding (NR) and reseeding (R) treatments. The *ggplot2* package was used for data visualization. All statistics and data visualization were performed in R 4.3.3 (R Core Team, 2024).

Results

The inverted T-shaped slot increased soil temperature and humidity.

We developed a new re-seeding machine using inverted T-shaped slot to introduce legumes into degraded rangeland (Fig. 1). The inverted T-shaped slot significantly increased soil temperature and relative humidity in the ditch by 1.2℃ and 60%, respectively. The increase in soil temperature and relative humidity provided a suitable microenvironment for seed germination (Fig. 2, Table 1), and therefore the inverted T-shaped slot increased seed germination rate by 120%.

Fig. 1 The ditch created by the V-shaped slot or the inverted T-shaped slot.

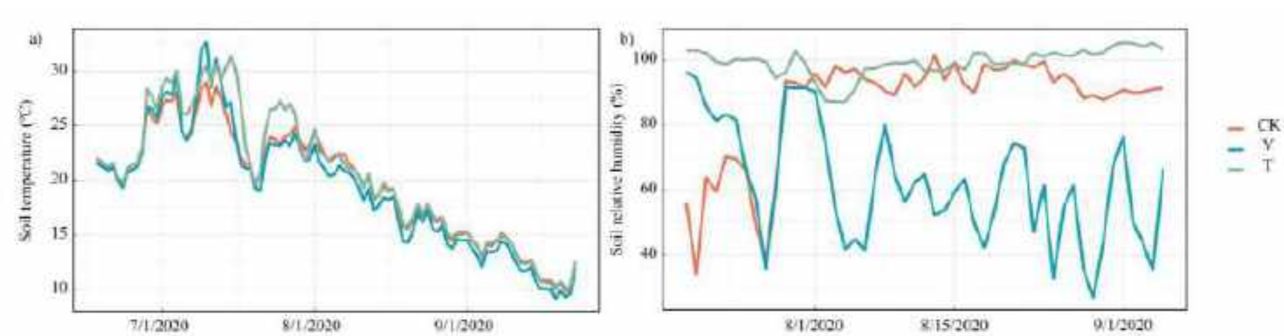

Fig. 2 Effects of the inverted T-shaped slot on soil temperature (a) and humidity (b). CK, control; V, V-shaped slot; T, inverted T-shaped slot.

Table 1 Effects of reseeding method on soil temperature and humidity and gemination rate

Reseeding method	Soil relative humidity (%)	Soil temperature (°C)	Gemination rate (%)
Control (CK)	86.31 ± 2.34 b	19.69 ± 0.51 b	-
V-shaped slot (V)	62.20 ± 2.59 c	19.32 ± 0.57 b	25.41 ± 7.93 b
Inverted T-shaped slot (T)	99.24 ± 0.62 a	20.42 ± 0.60 a	55.96 ± 11.53 a

Note: different lowercase letters following values (mean ± SE) represent significant ($P < 0.05$) differences, while identical lowercase letters indicate no significant differences among or between treatments.

Reseeding legumes increased soil nutrient content and AMF biomass.

Legume introduction increased soil total nitrogen content 14% and increased soil organic carbon content by 7.5% after four years of reseeding legumes (Fig. 3a, b). Reseeding legumes increased the abundance of AM fungi by 31% (Fig. 3c).

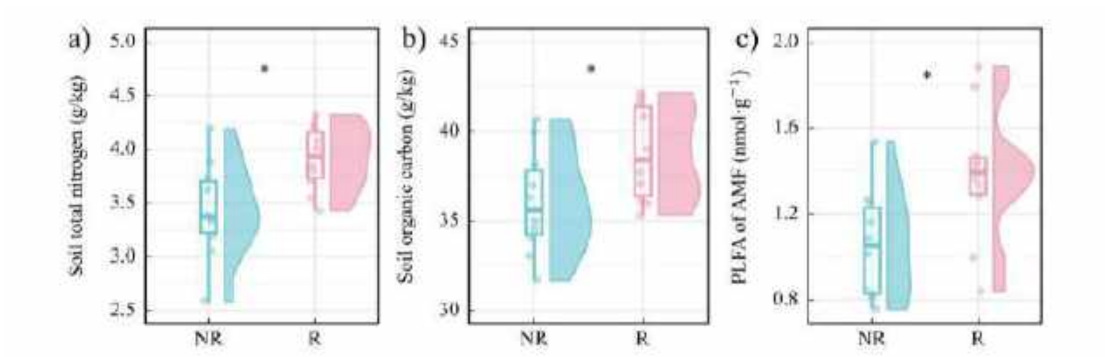

Fig. 3 Effects of reseeding legumes on soil nutrient content and AMF abundance. The difference between the reseeding (R) and non-reseeding (NR) treatments is indicated by asterisks (P < 0.05).

Reseeding legumes increased plant biomass and changed community composition.
Reseeding legumes significantly improved the productivity of degraded rangeland. For instance, total biomass production was increased by 148%, which mainly came from the increase in the biomass of legume functional group (Fig. 4a). After reseeding, the proportion of legume functional group significantly increased, while the proportion of grass and forb has significantly decreased (Fig. 3b).

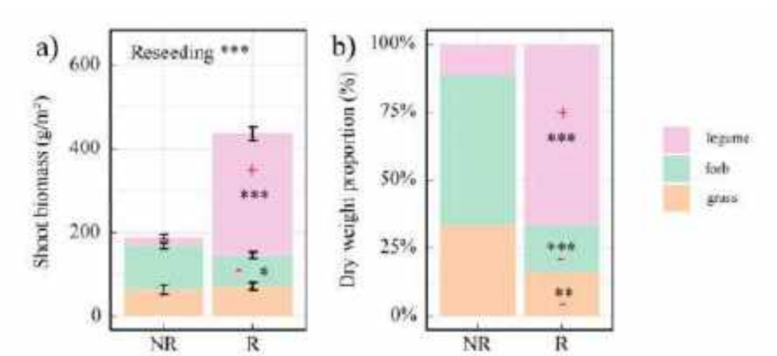

Fig. 4 Effects of reseeding legume on plant biomass and community composition. The difference between the reseeding (R) and non-reseeding (NR) treatments is indicated by asterisks (*, P < 0.05; **, P <0.01; ***, P <0.001). The symbols '+' and '-' indicate a significant increase and decrease by reseeding, respectively.

Discussion
In summary, we have developed an effective solution for restoring temperate degraded steppes through reseeding legumes. The inverted T-shaped slot significantly improved the germination rates of legume seedlings by promoting soil temperature and humidity. The successful establishment of legumes can dramatically improve forage production and simultaneously enhance soil health indicated by an increase in soil fertility and the abundance of AMF. Our study shows that reseeding legumes in temperate steppe can promote forage production and enhance rangeland sustainability.

Reseeding via the inverted T-shaped slot serves as an effective practice for creating favourable microhabitats. Compared to the tradictional V-shaped slot, the inverted T-shaped slot can create a ditch with smaller surface soil cracks and larger underground voids. These attributes not only help reduce soil water loss and maintain soil temperature, but also mitigate the underground competition of native species against the reseeded ones. The improvement of microhabitat could benefit seedling establishment, according to a previous study (Lett and Dorrepaal, 2018). The successful introduction of legumes led to substantial increases in plant productivity, driven primarily by a high proportion of legumes in plant communities. One of our recent studies found that reseeding legumes can further improve the performance of neighbouring species (Guo et al., 2024). This is because the presence of legumes can enhance ecological niche complementarity and promote compensatory growth through interspecific facilitation (Guo et al., 2024). It is well known that legumes can gradually enrich soil nitrogen availability through biological nitrogen fixation. This will stimulate microbial processes that enhance soil organic carbon sequestration (Abalos et al., 2020; Gou et al., 2023; Hu et al., 2024). Our findings align with previous studies, showing significant increases in soil total nitrogen and carbon storage following legume introduction. Additionally, microbial restoration is a critical objective for degraded ecosystems. In our study, the abundance of AMF was increased dramatically by reseeding legumes. The increase in AMF abundance can improve multiple ecosystem functions, e.g., the formation of soil aggregates and plant growth, leading to positive feedback for restoration.

Our study has revealed the multifaceted benefits of legume restoration in improving ecosystem function within degraded rangelands. In the future, efforts should be directed towards harnessing the ecological advantages of legumes to restore degraded rangelands. Furthermore, it is essential to develop appropriate management strategies to maintain the proportion of legumes in plant communities, thereby ensuring ecosystem sustainability.

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Enhancing the resilience of Saharan rangelands by reseeding drought tolerant native shrubs: the case of *Lygos raetam* in southern Tunisia

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Key words: Restoration, Saharan rangelands, *Lygos raetam,* Tunisia.

Abstract

Lygos raetam is a desert and drought-tolerant shrub native to North Africa and West Asia. Goats and camels readily graze its fruits and flowers, and it is well known for its capacity to stabilise mobile sands.

This study was carried out in the communal rangelands of Dhahar, Saharan area of Southern Tunisia, to assess the impact of reseeding *L. raetam* on natural vegetation cover and sand mobility. A sandy rangeland site located at the border of the African Eastern Sand Sea was subjected to three management treatments: two years of rest, reseeding *L. raetam*, and free grazing (control). In all plots, total plant and perennial species percentage covers were determined and monitored for 5 years. Results showed that despite the improvement in the percentage of total vegetation cover recorded, the rest technique seems insufficient and inefficient in cases where vegetation degradation has reached an advanced stage. On the other hand, despite the negative effect of drought, there were considerable positive impacts of reseeding *L. raetam* on vegetation cover and active dune stabilization. The good establishment and survival of *L. raetam* seedlings may encourage rangeland managers and pastoral communities to undertake rehabilitation by reintroducing promising native Saharan species when ecosystems lose their natural resilience.

Introduction

In arid and Saharan areas of North Africa and more specifically in Southern Tunisia, several studies showed that they are subject to human and climate drivers that can result in reduced production and ecosystem functions and services (Jama and Zeila 2005; Ouled Belgacem and Louhaichi 2013). Overgrazing remains the primary anthropogenic factor impacting arid and semi-arid vegetation (Smet and Ward, 2005). Overgrazing is associated with overstocking and drought, further contributing to degradation, and reducing biodiversity and rangeland productivity (Ouled Belgacem et al. 2019).

Several attempts have been made to restore degraded rangelands in dry areas with exotic herbaceous species and shrubs (Zaafouri et al. 1994). Most of these attempts have largely failed due to the inability of the introduced species to adapt to the ecological constraints of the region. As a result, reseeding with native species has become a more attractive option (Aronson et al. 1993).

The irregular annual precipitation and frequent droughts that characterize desert zones affect native plant regeneration and growth, causing land degradation and amplifying desertification. Zaafouri et al. (1994) showed that the success of rangeland restoration depends on the choice of plant species adapted to soil and climatic conditions, adequate sowing techniques, and plant development control. For these reasons, restoration activities in arid zones require the investigation of local germplasms that present good flexibility and adaptation to unfavourable climatic conditions. However, restoration and rehabilitation with endemic germplasm require research into culture conditions and water deficit responses (Zaafouri 1993).

Lygos raetam (Forssk) Heywood is a xerophilic and psammophilic species in the Fabaceae family, common in arid desert ecosystems and widely distributed in North Africa and West Asia where it grows under unfavourable dry conditions. This shrub is well known for its significant role in combating wind erosion and stabilizing dunes and provides an important dietary source for camels. Flowers are well appreciated by small ruminants mainly goats. Additionally, this species represents a viable fuel source for humans (Cheriti et al. 2009) and different therapeutic virtues (Said et al. 2002).

This study is carried out in the El Mahmouda area, in the collective rangelands of Dhahar of Douz in Southern Tunisia, aiming at assessing the impact of rangeland rest and reseeding of *L. raetam*, on plant cover dynamics.

Methods

The experiment was conducted in the El Mahmouda zone, communal rangelands of Dhahar, desert area of southern Tunisia (mean annual rainfall is <80 mm). The zone covers 40000 ha with many micro-reliefs (small depressions, large dunes, etc.). The natural vegetation cover is very sparse and mainly dominated by perennial species such as *Rhanterium suaveolens*, *Haloxylon schmittianum, Stipagrostis pungens*, and *Anthyllis henoniana*. Annual species like *Savigna parviflora*, *Asphodelus tenuifolius*, *Schismus barbatus* and *Matthiola longipetala* are observed during wet seasons.

The study was carried out during the spring (March-April) of five years between 2008 and 2012. The experiment is established as a Completely Randomized Design (CRD) with three management treatments tested: i) strict protection, ii) reseeding *Lygos raetam,* and iii) free grazing (control). Each treatment was replicated three times (3 plots of 2500 m^2 area each).

For each management treatment and within each plot, five transects, 50 m long each, were installed. A fine pin was dropped straight down into the ground every 50 cm along the line. Each of the 100 hits per line was recorded according to the plant species. The results are expressed in terms of percentage vegetation cover (R, %) as:

$$R = (n / N) * 100$$

where n is the number of hits of all plant species and N is the total number of hits.

The data were analysed using analysis of variance (ANOVA) based on the CRD statistical model using SPSS (20.0).

Results

Analysis of variance of total plant cover showed highly significant differences ($P = 0.0001$) between applied management treatments (Table 1). The plots reseeded with *L. raetam* recorded significantly higher total plant cover compared to the protected ones. The lowest values were registered at the freely grazed plots. In these plots most of the plant species were annuals. However, there was also a relatively higher percentage cover of other perennial species in the reseeded plots. Additionally, both total plant cover and *L. raetam* species cover showed a slight decrease with decreasing mean annual rainfall. Given the important contribution of the *L. raetam* seedlings to the total vegetation cover in the reseeded plots, its slight decrease confirms the high adaptation of this species to the harsh environment (Table 1).

Discussion

Lygos raetam species is a dominant perennial shrub in active sand dunes and stabilized sand fields in the Saharan zone of Tunisia. The results of the study confirm the reputation of the species for high tolerance of frequent droughts and water deficits. The establishment and survival of the seedlings seem to be attributed to their excellent root growth (Dhief et al., 2011), which enables plants to exploit a larger volume of soil, which may ensure recruitment success and testify thus an adaptive strategy to deal with drying soils and decreasing soil moisture.

Table 1. Total vegetation and *Lygos raetam* covers (%) with management modes according to mean annual rainfall. Values are means ± SD.

Year	Rainfall (mm)	Control		Rest		Reseed	
		Total	*L. raetam*	Total	*L. raetam*	Total	*L. raetam*
1	163.5	15±1.26	1..90±0.86	13..05±1.45	4.20±1.22	15.80±1.37	8.60±2.26
2	63	13.10±0.92	1.80±0.68	12.79±1.26	4.60±1.38	13.90±1.13	7.60±1.88
3	60.2	9.80±.09	1.20±0.28	10.60±1.50	3.60±1.48	11.52±1.99	6.50±1.78
4	62.8	8.40±0.82	1.50±0.38	10.40±0.47	3.40±0.82	11.02±0.69	6.10±1.69
5	130	8.40±0.35	1.50±0.42	11.70±1.32	3.50±1.66	13.80±1.29	6.18±1.44

On the other hand, the significantly higher total vegetation cover recorded in the plots reseeded by *L. raetam* may be attributed to the improvement of the availability of water and nutrients or the protection against direct irradiance and overheating (Moro et al., 1997) resulting from the small ''islands of fertility'' created around the plants of this Fabaceae species (Barakat et al., 2013).

L. raetam can grow and stabilize mobile sand dunes in conditions of extreme water deficit, and it appears to be suitable for revegetating and restoring degraded Saharan ecosystems. Thus, *L. raetam* can be suggested as one of the best species for the early stabilization of dunes and biomass production for livestock, mainly camels.

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Re-seeding on highly degraded rangeland as strategy for forage production, biodiversity, and carbon sequestration in Ethiopia

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Key words: Ecosystem services; Climate change; Soil water content; Biodiversity

Abstract

Rangeland degradation is becoming a serious problem in semiarid areas affecting rangeland productivity and hence the livelihood of the pastoralists. Degraded rangelands have low levels of soil carbon stock and diminished potential for biomass production. To overcome this problem, a re-seeding strategy is one option that needs to be considered. Accordingly, a study was conducted to examine the impact on biomass production, carbon stock, soil water content and biodiversity of re-seeding highly degraded rangeland with native grasses. Random sampling techniques using quadrats (0.5m x 0.5m) for biomass and species composition assessment were employed on re-seeded and non-seeded plots. Simpson's index of diversity was used to calculate the biodiversity of the vegetation. The soil organic carbon was calculated from soil samples taken at three depths (0-10 cm, 10-20 cm, and 20-30 cm) from re-seeded and non-reseeded plots. The results showed that vegetation composition recovered from the soil seed bank, forage biomass was higher, and carbon stock better on the re-seeded plot. There were sixteen species recovered in addition to *Chloris Gayana* and *Cenchrus ciliaris* on the seeded plots. The Simpson diversity of vegetation on the seeded plots was 0.78 compared with zero on the non-seeded ones. The dry matter yield for re-seeded plot and non-reseeded plots were 3.6, and 0.2 t/ha, respectively. Carbon stock was 15% higher under the restored rangeland compared to non-restored. The overall soil water content was 16.3 and 10.75% for re-seeded plot and non-re-seeded plots, respectively. Options to improve the productivity of highly degraded rangeland for multiple benefits could involve re-seeding with native grasses with integration of appropriate planning and continuous sourcing of grass seeds.

Introduction

Ethiopia's rangelands, covering 62% of the country's land area, provide essential feed for livestock and support the livelihoods of 12-15 million pastoralists (Gina 2015). However, like many other rangelands of the worldwide, Southern Ethiopia's dry land rangelands are facing degradation due to factors such as vegetation loss, increased abundance of unpalatable plants, bush encroachment, conversion to cropland, and overgrazing, exacerbated by climate change (Abdulahi et al. 2016).

Despite these challenges, protected vegetation can recover rapidly. Restoration methods, including reseeding, natural regeneration, and soil and water conservation practices, can address the underlying causes of degradation (Ouled Belgacem et al. 2019). Improved rangeland management can enhance ecosystem services, such as carbon sequestration (Henry B et al. 2024). By implementing appropriate rangeland management rules and successful restoration/rehabilitation practices, it is possible to slow and reverse land degradation, thereby increasing rangeland carrying capacity. This study aims to:

- Determine the capacity of reseeding native grasses on degraded rangelands to enhance ecosystem services, including carbon sequestration, forage production, and biodiversity.
- Raise awareness among development actors about the multiple environmental benefits of specific rangeland management practices.

Methods

Area description and site selection

The assessment was conducted in the rangelands of southern Ethiopia, specifically in the Dugda-Dawa district. This area, located between 4-6°N and 36-42°E, exhibits gentle slopes ranging from 1600 meters above sea level (masl) in the northeast to approximately 1000 masl in the extreme south, bordering Northern Kenya, and reaching 1780 masl in the central vicinity. Rainfall in this region is bimodal, with long rains occurring between March and May and short rains between September and November. The Dugda-Dawa district is a highly degraded rangeland where rehabilitation efforts, including reseeding with native grasses, have been initiated by the Yabello Pastoral and Dryland Agricultural Research Center. Local pastoralists reported that this specific area had been left degraded for over 33 years before the reseeding initiated began.

Data sampling procedures

Sampling was done for reseeded and non-reseed areas. The biomass was calculated using the 50 quadrats (0.5m X0.5m) that each taken from the reseeded area and non-reseeded area. Dry matter yield of grasses was determined after oven drying at 105 °C for 24 hours at Yabello Pastoral and Dry land Agriculture Research Centre.

Six samples of soil were collected from the depth of 0-10cm, 10-20cm and and 20-30 cm, from both reseeded and non-reseeded and bulked together for analysis of organic soil carbon by methods of Black and Walkely method used as described by Sahlemedhin and Taye (2000). Soil bulk density was analyzed following standard procedures (Bashour and Sayegh, 2007). The soil organic carbon stock was calculated using equation (Guo and Gifford, 2002). For soil water content, soil sampling was done using 5mm can from 10 point at depth of 0-10 cm and 10-25 cm within each area. Soil samples were covered and taken to laboratory for gravimetric moisture analysis (Michael 1978). Gravimetric moisture contents were calculated by expressing the percentage moisture on dry mass basis.

Simpson's diversity index was used to quantify the species composition. The data analysed and presented with descriptive methods, like percentage and average of the two areas.

Results

Dry matter yield

This result indicates a high potential for restoring degraded rangelands to support feed production. The previously barren, vegetation-deprived rangelands have shown promising signs of recovery. Although the initial seeding involved a mixture of two grass species with minimal tillage, the subsequent emergence of diverse vegetation has led to a significant increase in biomass in the reseeded area. It's important to note that the average dry matter yield for reseeded was 3.6 t/ha and for non-reseeded area was 0.2t/ha of a single cutting during the growing season. This suggests that the total annual dry matter yield for the reseeded area could potentially be double the value shown above if two cuts for the two seasons considered.

Soil organic Carbon and vegetation composition
Some differences were observed in soil organic carbon (%) content, particularly at the upper depth (0-10 cm) where 1.06 and 0.85 for reseeded and non-reseeded, respectively. The soil bulk density for reseeded and non-seeded areas were 1.21gm cm^{-3} and 1.3 1gm cm^{-3}, respectively. This may be due to the incorporation of root systems, organic matter and some tillage in the reseeded area. When calculating carbon stock (t/ha) for the upper depth (0-10 cm), the reseeded area exhibited approximately 15% higher carbon stock compared to the non-seeded area. This finding suggests that highly degraded pastoral areas can respond to climate change mitigation efforts through measures like reseeding. Such measures can improve rangeland resource management, minimize current vulnerabilities, and enhance resilience to future changes in rangeland degradation. The increased carbon stock in the reseeded area demonstrates the potential of such measures to improve the capacity to respond to climate change. The reseeded area, comprising two grass species, exhibited an increase in plant species diversity to eighteen, including twelve grasses and six non-grasses. Of the twelve grass species, eleven were perennial and highly desirable for livestock feed. The Simpson's Diversity Index calculated a biodiversity value of 0.78 for the reseeded area. The five dominant plant species in terms of percentage composition were *Digitaria melanjiana (*37.78%), *Chloris gayana (25.9%)*, *Indigophera spinosa (4.75%)*, and *Eragrostis capitulifera (3.77%)*.

Soil water content at reseeded and non-reseeded areas
Soil water content significantly influences plant growth and other soil properties. In this study, the soil water content of the reseeded area was found to be higher than that of the non-reseeded area at similar depths. The overall average of soil water content was 16.3 and 10.75% for re-seeded plot and non-reseeded plots respectively. Compared to the non-reseeded area, the reseeded area exhibited a 51.4% and 51.7% increase in soil water content at the 0-10 cm and 10-25 cm depths, respectively.

Discussion
The reseeded area exhibited increased biomass yield and vegetation composition. This improvement can be attributed may be to the long-term persistence of a soil seed bank, which was activated by minimal tillage on the highly degraded rangeland. In contrast, highly compacted, degraded rangelands have limited potential for aeration and water infiltration, hindering vegetation recovery. Amaha et al. (2009) found that degraded rangelands have the capacity to regenerate from existing soil seed banks, demonstrating their potential for recovery. Similar to our findings, Sahar Ezzat et al. (2013) reported enhanced biomass production through reseeding. While various factors influence soil organic carbon, the reseeded area showed promising results. As noted by Lal (2004), increased soil carbon content can improve soil properties and enhance adaptation capacity. Degraded rangelands, whether affected by overgrazing or fire, are susceptible to significant losses of soil organic carbon due to erosion and accelerated decomposition of soil organic matter. However, the increased vegetation cover in the reseeded area may have contributed to higher soil organic carbon content, biomass, and soil water content.

Suliman and Ahmed (2013) reported that reseeding with tillage can increase soil water content. Additionally, Duma (2000) noted that increased vegetation cover can lead to increased soil water content. The higher soil organic matter content in the reseeded area may also contribute to improved water retention

(Kimble et al., 2007). Several factors may contribute to the higher soil water content in the reseeded area, including reduced evaporation due to vegetation cover and increased infiltration rates, as the absence of plant cover in the non-reseeded area can lead to increased runoff and decreased soil moisture (Sadeghi et al., 2007).

Conclusion

It was concluded that reseeding on highly degraded rangelands have positive impacts on forage biomass productivity and protects the land from further erosion and degradation. The increased soil carbon stock and soil water content resulting from reseeding suggest that this practice may be a suitable option for highly degraded environments. The improved vegetation composition following reseeding indicates that this practice can enhance ecosystem stability and thus leading to increased livestock productivity and improved livelihoods in semi-arid environments.

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Development of an environmental decision support system for predicting the natural distribution of Festuca ovina in land restoration efforts

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Key words: environmental decision support system; Festuca ovina; machine learning; multilayer perceptron

Abstract

Anthropogenic activities, species invasions, and ecological factors are rapidly altering rangeland ecosystems, challenging the sustainability of plant species habitats. To address this, reliable prediction models are needed to forecast and map species distribution under varying ecological conditions. This study compares three machine learning methods—Multilayer Perceptron (MLP), Radial Basis Function (RBF), and Support Vector Machine (SVM)—in predicting the distribution of Festuca ovina in Eshkevarat Protected Area eastern Guilan province in Iran. This 30,347-ha mountainous protected area is located in the hills of the Alborz Mountains, ranging from 200 to 3600 m in elevation. We analyzed F. ovina distribution in 305 randomly selected plant sample plots, recording 10 ecological variables in each plot. Three machine learning models were developed to predict the likelihood of F. ovina distribution. Results showed that the RBF model had more misclassifications (11 samples) compared to MLP and SVM models (10 samples), suggesting that MLP and SVM were more accurate for distribution modeling. Additionally, MLP demonstrated a higher R2 value (0.87) compared to SVM (0.85), indicating that MLP was the most precise model for predicting F. ovina distribution. Thus, we developed the F. ovina Distribution Model (FODM) using the MLP model. Sensitivity analyses revealed that soil texture, soil depth, electrical conductivity (EC), pH, and vegetation density significantly influenced F. ovina distribution, with sensitivity coefficients of 0.48, 0.47, 0.45, 0.41, and 0.41, respectively. Based on the finalized FODM, we designed an Environmental Decision Support System (EDSS) tool to assist rangeland managers in mapping F. ovina distribution. The practical application of the EDSS tool demonstrated its effectiveness in using the FODM for decision-making and land management. This tool is a valuable resource for rangeland managers, enabling them to make informed decisions regarding F. ovina restoration and effectively utilize the predictive capabilities of the FODM in real-world applications.

Introduction
Festuca ovina is a perennial, cool-season plant that holds both agricultural and ecological significance. This valuable rangeland species is currently being threatened in Iran's rangelands due to livestock and human activities. Known for its palatability and high nutritional value for livestock, F. ovina also plays a crucial role in soil conservation and fertility through nitrogen fixation (Acharya et al., 2006). Besides its nutritional benefits for wildlife and soil protection, F. ovina is ecologically important due to its excellent drought tolerance, robust bunch-type root systems, and adaptability to various soil types, making it ideal for reclamation projects in areas with 30 to 61 cm of annual precipitation. This stress-tolerant grass thrives in a wide range of soils, including poor soils, and provides effective ground cover in areas with limited precipitation. As we explore the impact of ecological variables on the distribution of F. ovina to model its distribution across the study area, Hulvey et al. (2017) suggested that plant distribution modeling can help identify restoration islands that can eventually be expanded to the entire area. In some state of art studies, MLP models were designed for planning environmental enhancement based on natural condition (Aboufazeli et al., 2021, 2022; Jahani et al., 2023). The main objectives of this study are: (1) to model the distribution of F. ovina in a protected rangeland, (2) to compare various machine learning techniques to identify the most accurate model, (3) to prioritize model inputs (plant and ecological variables) through sensitivity analysis, and (4) to design an environmental decision support tool for the distribution of F. ovina.

Methods
To model the impact of ecological variables on the distribution of Festuca ovina, we utilized machine learning techniques including MLP, RBF, and SVM, prioritizing the ecological factors that influence its distribution. Building on previous research regarding the environmental requirements of F. ovina, the majority of the plot data collection was guided by this prior work. We then determined the quantitative impact of each variable on F. ovina distribution. A graphical user interface was subsequently developed as a decision support system for mapping F. ovina habitats under the ecological conditions of degraded rangelands.

To model and predict F. ovina distribution under varying ecological conditions, a grid network was established to randomize sampling across the entire habitat. The grid dimensions were 1000 × 1000 m within the boundaries of the Eshkevarat Protected Area. During the summer of 2021, F. ovina distribution was recorded within 2 × 2 m sample plots at 305 sampling points. Based on available resources, maps, and the region's ecological conditions, including landform, soil, and vegetation, 10 ecological characteristics were recorded at each sample plot. These included landform variables such as elevation, land slope, and geographic aspect; soil variables like soil depth, soil electrical conductivity (EC), soil pH, and soil texture class; and vegetation variables including vegetation density, vegetation type, and land use. The variables of soil depth, soil EC, and soil pH were recorded as continuous data without classifying their variability.

Annual temperature (ºC) and annual precipitation (mm) also affect species distribution; however, these variables were highly correlated with elevation. Due to the insufficient number of climate stations in the region, they were not included as input variables in the model. The selected variables were then used to build a model to predict F. ovina distribution across the study area.

Results
Based on the accuracy analysis of the three models, the most effective model for predicting Festuca ovina distribution (FODM) was developed using the MLP approach. Although MLP and SVM exhibited similar

accuracy rates (0.967), the MLP model demonstrated a higher R^2 (0.87) and a lower MSE (0.02), indicating that it provides a more precise classification of F. ovina distribution (Table 1).

Figure 1 illustrates the results of the sensitivity analysis, which quantifies the impact of FODM input variables on the model's output. The FODM output classifies F. ovina distribution into two categories: 0 and 1. According to the average sensitivity coefficients, soil texture (0.48), soil depth (0.47), electrical conductivity (EC) (0.45), pH (0.41), and vegetation density class (0.41) are identified as the most significant factors influencing F. ovina distribution (Figure 1).

Table 1. Results of parameter tuning in MLP structure

Structure	10-21-2			
Training function	Scaled Conjugate Gradient			
Activation function	logistic sigmoid -Linear			
Training	**R^2**	0.99	**Precision**	1
	MSE	0.001	**Accuracy**	1
	RMSE	0.03	**FAR**	0
	MAE	0.01	**POD**	1
			Bias	1
Validation	**R^2**	0.76	**Precision**	0.93
	MSE	0.04	**Accuracy**	0.93
	RMSE	0.2	**FAR**	0.07
	MAE	0.06	**POD**	0.98
			Bias	0.96
Test	**R^2**	0.63	**Precision**	0.94
	MSE	0.08	**Accuracy**	0.9
	RMSE	0.28	**FAR**	0.06
	MAE	0.09	**POD**	0.89
			Bias	0.95
All	**R^2**	0.87	**Precision**	0.98
	MSE	0.02	**Accuracy**	0.97
	RMSE	0.14	**FAR**	0.02
	MAE	0.03	**POD**	0.98
			Bias	1

Discussion [Conclusions/Implications]

In this study, we identified the most accurate distribution model for Festuca ovina by analyzing various ecological factors and employing machine learning techniques. An Environmental Decision Support System (EDSS) application was developed to classify degraded lands for F. ovina distribution and to assist in making informed decisions on restoration plans. Ecological evaluation and plant restoration planning often depend heavily on spatial data, making it crucial to link a Decision Support System (DSS) with a Geographic Information System (GIS) containing the necessary thematic layers. This integration of GIS and DSS has become a common approach for addressing decision-making challenges in plant restoration planning and land allocation. Based on the findings of this study and the developed EDSS for F. ovina distribution modeling, we successfully addressed the primary concern of decision-makers in identifying optimal land areas for vegetation restoration through F. ovina planting.

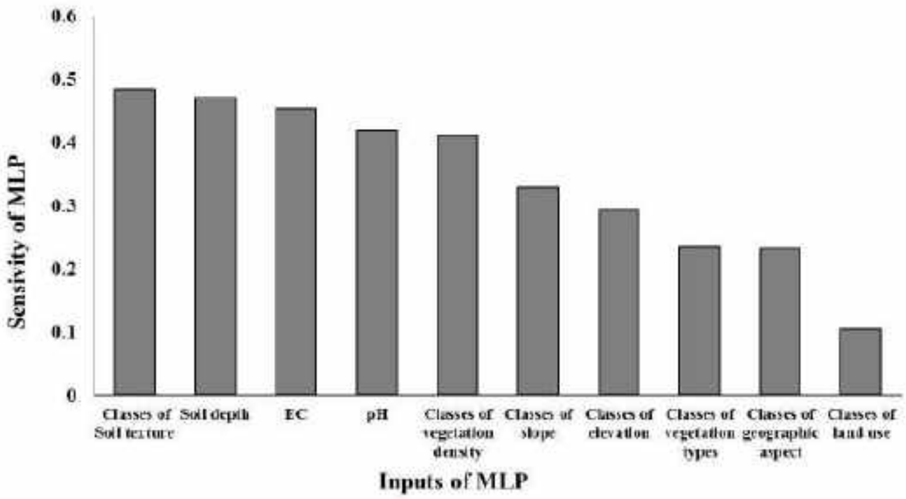

Figure 1. The impact value (0 to 1) of input variables on the FODM outputs in sensitivity analysis of model

One advantage of this research is our use of machine learning models to understand the distribution of F. ovina, whereas previous studies (Hulvey et al., 2017) assessed plant distribution in dryland ecosystems solely by overlaying ecological maps. Initially, we applied three modeling techniques—MLP, RBF, and SVM—to model the distribution of F. ovina in the Eshkevarat protected area, where ecological factors alone influence plant distribution. The results showed that, according to the RBF confusion matrix, there were more misclassifications in the data (11 samples) compared to MLP and SVM (10 samples), making MLP and SVM more accurate in classifying F. ovina distribution. In terms of species distribution prediction models, artificial neural networks (ANN) generally have higher prediction accuracy compared to other methods like regression (Piri Sahragard et al., 2015). While the differences between the studied machine learning models were minimal, these models, particularly MLP, provided satisfactory results in F. ovina distribution classification, making them highly applicable for studying plant communities and rangeland habitats. Overall, it is important to note that machine learning methods offer a more robust approach than spatial statistical methods due to their ability to analyze complex nonlinear relationships between input and output variables.

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Four spinifex species of the East Kimberley

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Key words: Native seed collection, land restoration, spinifex

Abstract
The Kimberley sits in the northwestern corner of Australia, in the state of Western Australia. In the wet season, between December and March, spinifex grass species in the Kimberley flower, set seed and are ready to be harvested for use. Four spinifex species have been selected for discussion; the method of identification, collection and storage will be discussed for *Triodia bitextura, T. bynoei, T. epactia and T. racemigera.* Many spinifex species, such as *Triodia racemigera,* are poorly understood and not enough is known about their habit, habitat and distribution. This impacts revegetation projects as certain plant species protected by legislation cannot be returned through re-seeding. A greater understanding of the spinifex species of the Kimberley will be beneficial for the successful management, conservation and rehabilitation of the northern rangelands.

Introduction
This paper aims to share knowledge and provoke discussion on the collection and use of spinifex seed in the restoration industry in the East Kimberley, focusing on four species: *Triodia bitextura, Triodia bynoei, Triodia epactia* and *Triodia racemigera*. It will outline the species distribution, plant and seed characteristics and habitat. The plant identification, seed harvesting and processing techniques and storage methodology will be discussed. Finally, the future of spinifex seed collection will be discussed as it relates to land restoration in northern Australia.

Spinifex, the common name for approximately 64 species of perennial hummock grasses in the genus *Triodia*, is endemic to Australia and is characteristic of arid and semi-arid rangeland regions (Pitman and Wallis 2012; Jacobs 2004). In the Kimberley region of Western Australia, spinifex is common throughout much of the environment and is well suited to the harsh climate and frequent bushfires that affect country each year (Gamage et al. 2014; Wright and Fensham 2018). Spinifex is important to the local communities of the East Kimberley for several cultural reasons, including hunting, medicinal and food purposes. The book *Kimberley Bush Medicine* states that "decoctions of the leaves or resin (of spinifex) are used as an external medicinal wash to treat the symptoms of colds, influenza and general soreness" (King and Horsfall 2023). According to *Kimberley Bush Food*, the seed of some spinifex species from the Kimberley region were collected to be ground into flour and made into damper (King and Horsfall 2023). The Gelganyem Seed Operation (GSO) works in the East Kimberley region to collect, treat and store native plant seed, including spinifex seed, predominately for use in the rehabilitation of the Argyle Diamond Mine. The cultural significance of spinifex is emphasised in the name of the Gelganyem Seed Operation (GSO); the term Gelganyem refers to a traditional Miriwoong fishing method of crafting fishing nets from rolled spinifex (Gelganyem 2024).

Due to its high cultural and environmental value, the return of spinifex to rehabilitation areas is a critical element of land restoration. Each year the GSO collects the seed of six species of spinifex from a 200km provenance area around the Argyle Diamond Mine (the mine), to be spread on the mine site at the beginning of the wet season. The seed is separated into mixes, based on the suitability of each species for the geographical characteristics of the areas designated and prepared for rehabilitation that year.

The timing of seed collection, as well as the seed cleaning and storage methodology, is critical to maximise viability and subsequent germination of spinifex seeds. Most spinifex species are manually harvested during the wet season using hand sickles. Size, fullness and colour of spinifex seed florets are some of the factors which differ between each species and are indicators of the optimal time for seed collection and of seed viability. Samples of each seed batch collected are sent to Curtin University to test for viability and germination rate, the data of which inform future collections and seeding rates for rehabilitation projects. The spinifex seed collected by the GSO is ‘smoked’ prior to seeding, a process which aims to break the seeds' dormancy mechanisms and increase germination rates (Connolly 2014).

Certain limitations affect the return of some spinifex species to restoration areas, including species protected under the Biodiversity Conservation Act 2016. An example is *T. racemigera*, a Priority One species known to have existed on the mine site before mining began. Due to its protected status, this species will not be reintroduced to rehabilitation areas. The Department of Biodiversity, Conservation and Attractions states that a Priority One species is in urgent need of further survey (Department of Biodiversity, Conservation and Attractions 2016). Further work to understand the distribution and level of threat to priority spinifex species may result in the reclassification of some species and enable restoration practitioners to return those species to areas they inhabited prior to human disturbance.

Methods

Identification

Identification of *Triodia* species is required to collect seed and is undertaken by observing habitat, habit and seed morphology. Online resources, such as Florabase (Western Australian Herbarium, Florabase 1998), Flora of Australia Key (KeyBase 2013) and AusGrass (Lucid Central, Aus Grass 2002) are used to assist with identifying species. The GSO maintains an herbarium of East Kimberley plant specimens, identified by professional botanists with regional expertise to ensure correct plant identification prior to seed collection. Figure 1 shows the East Kimberley distribution of *T. bitextura, T. bynoei, T. epactia* and *T. racemigera*.

T. bitextura is identifiable by its habitat, which can include a variety of soil types, plant habit, and seed morphology. Identifying features include the seeds' light cream colour, long wispy awns, and the plants' curled leaf-blades. *T. bitextura* is widely distributed throughout the East Kimberley and is collected by the GSO in several locations. As this species commonly grows in open fields, there are instances where it can be mechanically harvested, using custom-built native grass harvesters.

T. bynoei is commonly found around Lake Argyle Road and the surrounding regions of Kununurra, often on rocky escarpments and creek beds. Identifying features include the inflorescence structure and awns, which appear similar to those of *T. bitextura* in their feathery appearance.

T. epactia grows in several habitats, including sandy plains and rocky hills. It is hand collected by the GSO in two locations, on rocky outcrops, and is identified by its distinct spikelet and inflorescence morphology, amongst other characteristics.

T. racemigera grows alongside other spinifex species at certain locations and the different species are distinguished in the field by the inflorescences and spikelet morphology. Due to its status as a protected species, *T. racemigera* seed is not collected and subsequently the species will not be returned to rehabilitation areas.

Seed Collection

Spinifex plants which are planned for collection are checked regularly when seed heads develop, to ensure that the seed is collected at an optimal time. This optimal time is when the seeds easily separate from the inflorescence. When ready to collect, gently threshing a seed head into a cupped palm should dislodge a portion of the seed. Issues affecting seed viability and germination rate, such as 'false seeding' events and pest damage, are taken into consideration when collecting seed. Spinifex species can be separated roughly into early, mid and late wet season collections, as the seed of each species matures at a different rate. Factors such as rainfall and temperature affect the development of seed, so seed of the same species will often mature at different rates in different locations. Careful planning goes into seed collection, to ensure that the seed is collected at the optimal time in each location.

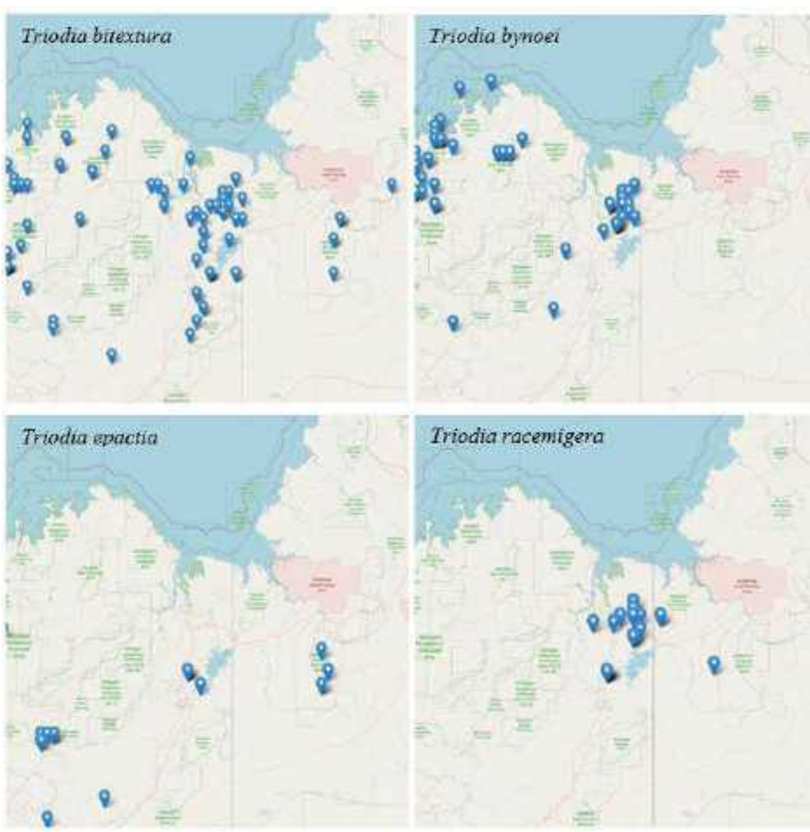

Figure 1: East Kimberley occurrence record maps for four spinifex species (Western Australian Herbarium, Florabase 1998)

Seed Processing
The seed heads collected are laid out in a well-ventilated area, on a flat surface such as a tarpaulin, in a thin layer to dry completely. Once dry, the seed heads are threshed into a container, then 'cleaned' using a sieve, to separate the seed from all other plant material. Correct cleaning allows for efficient storage and reduces the likelihood of pests. Seed which is contaminated with pests is CO_2 treated prior to storage. This is done by placing the clean seed into an airtight bag, which is filled with CO_2, and left for a minimum of 2 weeks. The seed is then re-inspected for pests prior to bagging and placing in storage.

Seed Storage
Anecdotal evidence from seed collectors in northern Australia suggests that allowing spinifex seed a 12 month 'maturing' stage in a non-climate-controlled area increases its germination rate. This is undertaken by the GSO by placing bags of cleaned spinifex seed in a raised, well-ventilated and dry area, prior to cool room storage, where it is kept between 15ºC and 16ºC. This maturing process can be complicated by certain factors such as high humidity and rainfall, especially during the wet season, which increases the risk of seeds absorbing moisture and developing mould. This is managed by ensuring the seed stays in a well-ventilated and dry environment, and by ensuring that the seed is completely dry prior to bagging.

Discussion
Spinifex seed collection is undertaken by the GSO in the East Kimberley region to return species to degraded country. Understanding plant identification, seed collection, cleaning and storage processes are critical for maximising the seeds germination potential and therefore, for the success of rehabilitation efforts involving direct seeding.

Restoring *T. bitextura, T. bynoei* and *T. epactia* to rehabilitation areas in the East Kimberley is a high priority due to their environmental and cultural significance and it is critical to return the country to a level of plant species diversity that closely resembles its pre-mining state.

To progress the native seed industry, it is essential to encourage continuous learning and knowledge sharing across all aspects of seed collection. Enormous rehabilitation efforts will likely be required in the future, and for these to succeed in the Kimberley, the sustainable and accurate collection of seed is of paramount importance. Wild populations of native plants are not capable of sustaining unethical seed harvesting methods, where the quantity of seed collected impacts the survival of plant populations. This fact highlights the need for correctly identified and collected seed, which has the highest possible germination rate, and which therefore reduces the overall volume of seed required to achieve successful rehabilitation outcomes.

There are many difficulties surrounding the collection and use of native seed, including storage, germination and legislative limitations. These challenges often lead to a reduced species diversity in rehabilitation areas compared to baseline levels. Whilst managing potentially at-risk species is crucial, further study of these species could better inform their management and potential reintroduction to former habitats. Improving our understanding of all Kimberley spinifex species will improve restoration, conservation and management outcomes.

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Poster presentations – Theme 4

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Determination of browse production, browsing capacity and implications on bush encroachment and livestock feed resources in rangelands of Southern Ethiopia

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Key words: Leaf biomass; canopy volume; browsing height, Goat, Kudu

Abstract

Rangelands covering about 61 to 67% of the total land area of Ethiopia have herbaceous and woody vegetation layers. Browse production, browsing capacity and implications on bush encroachment and livestock feed resources have not been investigated in the Borana rangelands of Ethiopia in contrast to the many studies of biomass production and grazing capacity of the herbaceous layer. Thus, the objective of this research was to determine browse production and browsing capacity and the implications on bush encroachment and livestock feed. Eighty-six rangeland sites were identified to collect data on woody vegetation species, density, plant height, heights of maximum canopy diameters, heights of first leaves or potential leaf bearing stems, and maximum and minimum canopy diameters using plots of 20 m x 20 m or 10 m x 10 m at each site. The browse production and browsing capacity were analysed using biomass estimation from canopy volume model and browsing capacity equation. The mean browse production at peak of the growing season varied from 516 to 14,914 kg ha^{-1} with a browsing capacity ranging from 8.27 ha and 0.21 ha BU^{-1} (browser unit), respectively. The mean woody vegetation density varied between 783 to 8,800 plants ha^{-1} while the mean evapotranspiration tree equivalent (ETTE), which is a measure of the status of a woody community in terms of potential moisture use, ranged from 2,421 to 58,951 with a high degree of bush encroachment with increasing ETTE. The woody plants that contributed more to browse production and bush encroachment were mainly the acacia species. While the increase in the woody vegetation results in higher browse biomass production, the high degree of bush encroachment, which lowers the production of the herbaceous layer affects the grazers. Thus, appropriate bush management needs to be implemented while taking into consideration the feed needs of the browsing and grazing animals

Introduction

Rangelands, which are usually defined as uncultivated land that will provide the necessities of life for domestic and wild grazing and browsing animals, include grasslands, savannas, shrublands, woodlands, wetlands, and deserts. They are among the most important terrestrial ecosystems in the world, occupying 54% of the world's terrestrial area (ILRI et al. 2021). Globally, rangelands contribute about 70% and over

95% of the feed needs of domestic and wild ruminants, respectively (Holechek et al. 2014). Likewise, Ethiopia has a vast area of rangelands, 61-67% of the total land area, which is primarily used for extensive livestock production and the rangelands in Ethiopia are also rich in biodiversity, mineral, water, energy resources, cultural heritages, untapped tourist attractions, and socio-anthropological values (Getachew et al. 2024). The vegetation structure of the Ethiopian rangelands includes 50% woody-browse plants; 35% open grasslands, and 15% open bush-grassland savanna. These rangelands particularly in southern Ethiopia are experiencing increasing bush (Ibrahim, 2019). Bush encroachment, which is the spread of woody vegetation into grass-dominated areas, has led to changes in the livestock species the pastoralists keep. The number of browsing animals like camels and goat is increasing while the number of grazers like cattle and sheep is decreasing (Hassan et al. 2023). Compared to the research undertaken to determine the production and grazing capacity of the herbaceous layer, the studies undertaken to determine browse production and browsing capacity is scant. Thus, the objective of this study was to determine browse production, browsing capacity and implications of bush encroachment and on livestock feed resources.

Methods

As the Borana rangeland is very vast, the woody vegetation assessment was undertaken following a road transect sampling technique. The effect of the roadside was avoided by moving more than 50 meter from the edge of the road. Data was collected from 86 rangeland sites throughout the three sub-basins of the Borana zone, and the woody vegetation data was collected in most instances at an interval of 10-20 km. The woody vegetation was assessed at the peak of the growing season using a plot of 20 m x 20 m or 10 m x 10 m at each of the sites, and all live woody plants within the 400 or 200 m^2 plots were counted by species to determine density.

All live plants rooted in the plot were counted, and multi-stemmed plants were counted as a single plant. The measurement consisted of the following: (i) maximum height, (ii) height where the maximum canopy diameter occurs, (iii) height of first leaves or potential leaf-bearing stems, (iv) maximum canopy diameter (2 dimensions), and (v) base diameter of the foliage at the height of the first leaves (2 dimensions). The canopy volume of each woody plant was calculated using the Biomass Estimates from Canopy Volume model (Smit, 1989,1996). The number of evapotranspiration tree equivalent (ETTE) ha^{-1} was subsequently calculated from the leaf volume estimates (1 ETTE mean leaf volume of a single-stemmed tree with a height of 1.5m = 500 cm^3 leaf volume, Smit, 1989). The ETTE is a measure of the status of a woody community in terms of potential moisture use. To measure the heights and diameters of the woody plants, two calibrated aluminium poles of 2 and 4m were used. Dimensions of those woody plants too tall to measure with poles were taken using a dimension meter (Smit 1996). Estimates of the browsing capacity for the most important woody plants based on leaf DM were made from the leaf DM estimate, using the formula proposed by Smit (1999).

$$\text{ha BU}^{-1} = \frac{\text{DM x p x f}}{\text{r}}$$

BU = Browser unit defined as the metabolic equivalent of an average kudu with a mass of 140 kg (Dekker 1997)
DM = Total leaf DM yield ha^{-1}
p = Phenology (0= no leaves, 1.0 = peak biomass)
f = Utilization factor
r = Daily browse DM required per BU (3.5 kg day^{-1})

The estimated leaf phenology for the various plant groups can theoretically vary from 100% (p= 1) in the case of evergreen to 0% (p=0.0) during winter for the early deciduous group. However, there are indications that browsers may utilize the tips of shoots and twigs even if no leaves are present. Accordingly, the allocated leaf phenological values ranged from 0.2 (lowest leaf yield) to 1 (maximum leaf yield).

Furthermore, each woody plant was assigned a leaf carriage score to determine leaf phenology: where, 0= no leaves, 1= 1-10% of full leaf carriage, 2= 11-40 % of the leaf carriage, 3= 41-70% of the full leaf carriage, 4 = 71-100% of full leaf carriage (Smit 1994). A utilization factor ranging from 0.1 to 0.3 depending on the palatability of each of the woody species as perceived by the pastoralists was used in this study.

Results

The woody vegetation density (plants ha^{-1}) ranged from 700 to 11,200 with an average range of 783 to 8,800 while the ETTE ha^{-1} varied from 2,271 to 73,425 with an average value ranging from 2,421 to 58,951. The results clearly indicate a high degree of bush encroachment in the sampled sites. The higher the ETTE value, the higher the degree of bush encroachment. The browse production (kg ha^{-1}) at the peak of the growing season varied from 503 to 22,766 with an average value ranging from 516 to 14,914. The browsing capacity varied between 8.47 ha BU^{-1} and 0.003 ha BU^{-1} with a mean range of 8.27 to 0.21 BU ha^{-1}. Generally, the results indicate that with an increase in the amount of browse production, the land size required to support a browser unit for a year will decline. Removing the unpalatable woody plants, the browse production and the associated browsing capacity will decline. Acacia species are the most important woody species contributing to browse production and bush encroachment, and they varied from site to site.

Discussion/ Conclusions/Implications

Bush encroachment, one of the major problems in Sub-Saharan Africa, leads to an increase in plant cover by woody species and a decrease in grass cover, grass production, and the grazing capacity of the rangelands which corresponds with the findings of previous studies in the study area (e.g., Ayana, 2007; Chaun et al. 2018). The availability of forage/browse that can support the different livestock species is the most important factor influencing habitat selection by large herbivores (McNaughton, 1987). However, there is variability from locality to locality in terms of browse production and browsing capacities (Jarman and Sinclair, 1979). Different bush control techniques are applied by government and non-government organizations in the area. The pastoral communities own both grazers and browsers, and the number of browsers has increased in recent years. While the increase in the woody vegetation results in higher browse biomass production, the high degree of bush encroachment lowers the production of the herbaceous layer, and decreases forage for grazers. The study implies that appropriate bush management needs to be implemented while taking into consideration feed needs of the browser and grazers animals.

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Pasture land use and planning: An example from the Mogod soum of Bulgan province, Mongolia

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Key words: Pasture use; pasture land planning; pasture carrying capacity; pure pasture; pasture irrigation; affected pasture land; soum, bag

Abstract
The pressure on soil and vegetation of pastureland has drastically increased in recent years and the tendency to desertification has increased due to overgrazing and non-rotational grazing. We aimed to evaluate the possibility of developing a pastureland use plan based on suitabiliy assessment and citizens' survey of pasture use and its future, as well as an assessment of the current condition of the pastureland, in Mogod soum[6] of Bulgan province. Our study shows that as of 2020, Mogod soum contains a total of 243,789 ha of pastureland that includes 1,073 camps. Camp registrations show that these comprise 366 camps used for winter, 402 for spring, 272 for winter-spring, 28 for summer-autumn, 2 for autumn and 3 all-season camps. Some 28,500 ha of pastureland (11.7 per cent of the toal) is affected or changed of which 68.7 % is affected moderately and 31.3% strongly; rodents are widespread on 6,499 ha, overlapping both moderately and strongly affected pastures. Over the total soum pasture area the total number of livestock exceeds the carrying capacity by 3.7 times, indicating the dire need to take immediate actions to improve pasturelands in the region. It is planned to use 19.8% of the total pasturelands in summer and autumn, 18.6% in spring, 51.3% in winter and spring and 10.3% in winter under a rotational use scheme, with livestock numbers reduced to the approproiate seasonal carrying capacity. For improvement of affected areas, we plan 3.6% for fallowing, 7.8% for rotational use only, 2.6% for rodent control, and 88.6% for seasonal rotation without exceeding the carrying capacity.

[6] A small administrative unit within a province, further divided in 'bag', the smallest administrative unit.

Introduction

Since the last century, land that was used solely for agricultural purposes is now being used for various purposes. In recent years the pressure on the soil and vegetation of agricultural land has increased dramatically due to overgrazing on pastureland, with negative effects of grazing including pastureland degradation and increased tendency for desertification.

Therefore, we need a plan that balances the two factors: (i) increase the economic benefits of using the land and livelihood improvements of the residents and (ii) encouraging appropriate use of land based on the natural resources and conditions of the area and their relationships. Right balance aimed at maintaining the sustainability will ensure creation of wealth in the area and better life quality for the residents.

Methods

The current situation of the Bulgan province of the Mogod soum's pasture land was determined, and pasture land plan was developed based on the land suitability assessment and local citizens' opinion. We used the methods outlined in the Methodical Instructions for Monitoring the State and Quality of Pastureland (MoCU, Order 34 of 2019) as well as reports related to Mogod soum's pastureland use, unified land fund, land cadastral database, surface water inventory, pasture condition and its state quality control and photo monitoring activities.

Results

The "2020 report of the United Land Fund" shows that Mogod soum has pasture land totalling more than 237,000ha, which is 97.3% of the total agricultural land. The report further indicates that 35.6% or 84,533.4 hectares of pasture lands belong to summer-autumn pastures, and 64.4% or 152,750.5 hectares of pasture lands belong to winter-spring pastures as shown in Figure1. There is a difference of 6,037.7 hectares compared to the result of the study of the unified land fund report. In this study, pasture area was calculated as pure pasture used by livestock.

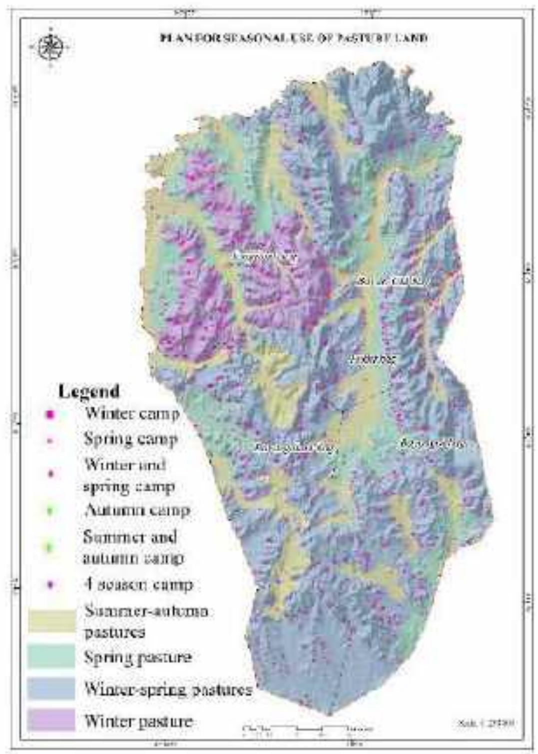

Figure 1. Plan for seasonal use of pasture land

Pasture lands affected by use: Based on the analysis and quality comparison of the Mogod soum's pasture land pasture quality inspection reports, as well as the survey of soum citizen opinions, 28,500hectares of pasture land were affected (11.4 percent of the total pasture land). The degradation of pastureland in Mogod soum is related to the rapid growth of animal husbandry and non-rotational use throughout a year. About 68.7% or 19,558.2 ha of changed or affected pasturelands are moderately grazed, and 31.3% or 8,899.0 ha are strongly grazed and rodents are spread in 6,498.5 ha of pastures, which coincides with moderately and strongly grazed pastures as shown in Figure 2.

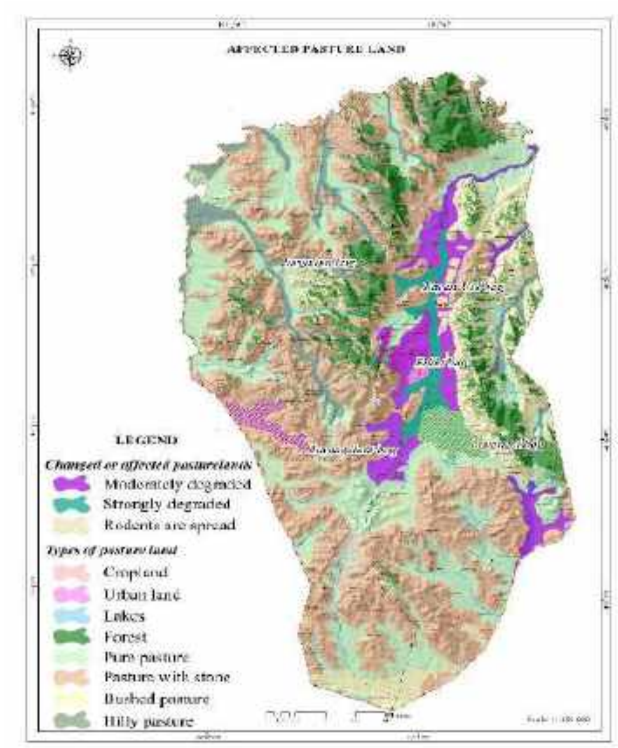

Figure 2. Affected pasture land

Carrying capacity of pasture in Mogod soum: The carrying capacity of pasture was calculated by the "Integrated method for calculating the carrying capacity of livestock pastures", which was approved in 2019, and is being implemented nationwide.

The total number of livestock is compared with the total soum pasture area, the carrying capacity of the pasture is exceeded 3.7 times the maximum limit. Taking further actions to improve pasture lands in Mogod soum is necessary.

Pasture land improvement, and conservation plan: As the number of livestock increases in Mogod soum, traditional types of grazing pastures are lost, and the number of winter and spring shelters increase dramatically.

Therefore, based on the suitability assessment of the pastures and citizens' opinion and features of the surface landscape, seasonal pastures are planned for 4-year use, that allows the use of 19.8% of total pasture lands in summer and autumn for all 4 years, 18.6% in spring only in year 1 and 3, 51.3% in winter and spring in year 2 and 4, and 10.3% in winter for year 1 and 3. In this way, it is possible to use the pasture with seasonal rotation and reduce the carrying load of the pasture to maintain the appropriate number of livestock for that season.

Plan for affected pastures: In accordance with regeneration capacity of pastures, measures like summer and autumn pastures to be alternated between months and seasons, rest periods, taking improvement measures, and fighting rodents in the pastures are planned.

Table 1. Modified Pasture

№	Measures to be taken on the pasture	Area, ha	Normal condition	Affected degree		
				Overgazed strongly	Overgrazed moderately	
1	Rest pasture	11,659.7		8,899	2,760.7	
2	Rotational timely grazing	16,797.5				16,797.5
3	Seasonal rotation according to carrying capacity	221,369.3	221,369.3			
4	Destroy pests and rodents	6,498.4		3,737.7	2,760.7	

It is planned to take measures to improve pastures covering all soum pasture land. For rest pastures 3.6%, for replacement pastures 7.8%, for rodent control 2.6%, and for seasonal rotational pastures 88.6% of total grazing measures are planned as shown in Table 1.

Measures for seasonal rotation according to carrying capacity: This measure is planned for 221,369.3 hectares of pastures in normal condition. To sustainably use and protect pasture land for a long period of time, it is necessary to herd animals suitable for the carrying capacity of the pasture, and to use it with seasonal rotation and sell the surplus animals to the market. Thus, it is advisable to introduce to the herders the right practices and methods to use pastures in groups under contract and ensure its proper practices. The following actions are required:

- Adjusting the number of animals to the carrying capacity of the pasture;
- Optimizing the herd structure;
- Separating long legged animals and male animals into remote herds;
- Improving the quality of animals and intensifying the sale of male and female animals.

Rest measures: Rest pastures are planned 2,556.5 hectares of spring pastures in the area of Suuj Ukhaa, which is a strongly overgrazed pasture, 6,342.5 ha of pastures along the Khulj, which is summer and autumn pasture, and 2,760.7 hectares of pastures in Ikh Khujirt and Suuj khundii are moderately overgrazed spring pastures.

It is necessary to calculate the load to be 10 percent lower than the possible bearing capacity, and it is necessary to make a long migration to rest when visiting the pasture. When making a long distance migration, we planned to move along the Bumbat river and Rashaantyn khoshuu.

Alternative use measures: Total of 1,679,765 hectares of moderately degraded pastures, so these pastures will be released from use during the growing season until the vegetation cover recovers. The load should be calculated at less than 10% of the potential capacity and should be used during the growing season of plants for 2 years in a row.

Measures to control pasture pests and rodents: Total of 6,498.5 hectares of pastures are planned to be controlled by voles. During the implementation of the measure, it is planned to use many methods, such as poison spraying, biological control, fumigation, and water pouring, based on the characteristics and capabilities of the ammunition.

Discussion

By implementing the above plan for 5-7 years, the following results are expected:

1. Herders in Mogod soum will adapt the rotational use of pastureland.
2. By letting 3.6% of pasture rest as per plan, and 7.8% used by rotation, and fight against rodents on 2.6% of the pasture, the floral cover of the pasture will be rehabilitated causing more types of plants to emerge, thus the pasture will be restored naturally.

3. At the end of the implementation period, a study on affected pastureland conditions and quality shall be conducted and compared to the data before the implementation of the plan.
4. AS a result of implementation of the plan, severely degraded pasture conditions should be restored bringing its level up to medium level of degradation.
5. Implementing the plan requires close cooperation of the loval government and herders to reduce the number and types of animals and keep it suitable to the carrying capacity of the pastureland.

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Developing a national kangaroo strategy

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Key words: Macropod; kangaroo; wildlife management; policy.

Abstract

Macropods are important and treasured Australian animals. Several kangaroo species have increased due to land changes since European settlement, and overabundant populations require management to conserve biodiversity, production, and to protect human safety and property. Management is also necessary to avoid boom-bust cycles which have extremely poor animal welfare outcomes with mass starvation events and road trauma.

Current management practices, however, can also result in animal welfare, conservation and waste issues. A National Statement: Improving Kangaroo Management was developed from the symposia of two 2019 conferences, supported by a special edition of *Ecological Management & Restoration: Optimum management of overabundant macropods* (Read et al. 2021b). The key recommendation was for a National Kangaroo Taskforce to work with stakeholders to develop a National Kangaroo Strategy which will improve animal welfare, human safety, sustainability and reduce waste.

This research project, commencing March 2025, will expand on recommendations outlined in the National Statement to develop the case for a National Kangaroo Strategy. It will include consultation and engagement to integrate Indigenous, animal welfare, industry and conservation stakeholder priorities, set unified objectives, along with analysis of population dynamics, identification of appropriate foraging densities, steps to prevent extreme population cycles, non-lethal management options where appropriate, ethical standards to be maintained and included in a single National Code of Practice, opportunities to better integrate kangaroos into rangeland production systems, and recommendations to overcome barriers associated with regulatory limitations, lack of unified practices, and resource constraints.

Introduction

Conservation and management of macropods, particularly kangaroos, is complex with varying objectives across jurisdictions and diverse views amongst stakeholders.

In some developed areas kangaroo populations are under threat due to loss of habitat and safe connectivity. This can result in a range of animal welfare and human-wildlife conflict issues including morbidity, road strikes and problematic individuals in places where dispersal opportunities are limited, such as golf courses and schools.

Across much of Australia, kangaroos have benefited from land use changes in the past 200 years with additional grazing habitat and watering points, reduction in dingo numbers and reduced traditional hunting. In these areas boom-and-bust cycles can occur, with periods of almost exponential growth in favourable conditions followed by mass starvation events in times of drought (see Figure 1). An overabundance of kangaroos can result in overgrazing, damage to vegetation and pastures, competition with other fauna and livestock, and an increased risk to road safety, food security and property damage.

Population management is therefore required to avoid animal welfare impacts in starvation events, conserve biodiversity, protect agricultural land and human safety.

A Joint National Statement was prepared by scientists experienced in applied ecology, conservation biology, primary production, veterinary science and environmental policy advocating for a coordinated national approach to management (Read et al. 2021a). Motivation for this was a shared belief that current kangaroo management is leading to detrimental consequences for kangaroo welfare, landscape sustainability, biodiversity conservation, resilient agricultural production and cultural values. They asserted that there is a need for a credible, collaborative approach to represent diverse stakeholders and challenge the viewpoint that commercial harvesting of overabundant macropods is contrary to welfare, conservation and cultural values, while acknowledging that treating kangaroos as pests to meet management objectives limits the values of managing kangaroos as a resource. The key recommendation was for a National Kangaroo Taskforce to work with ecologists and stakeholders to develop a National Kangaroo Strategy to support government and other stakeholders in decision-making.

A suite of other issues and topics are canvased in the 2021 paper including the implication for managers that overabundant kangaroo populations, along with other herbivores, must be managed to conserve minimum forage resources, such as grass cover, and to enhance conservation, production and for animal welfare outcomes. Where dingoes are not compatible with other land uses, regulated and accredited harvesting of overabundant macropods (as a resource) is preferable to culling (and wasting) or death by starvation. Kangaroo populations are best managed by informed, proactive and adaptive management at property, regional and national scales, so that waste is minimised and resources are used sustainably.

This research project aims to develop the case and considerations for a National Kangaroo Strategy.

Methods

This research program, supporting the development of a National Kangaroo Strategy, commenced in March 2025 and seeks feedback from attendees at IRC XII as priorities, scope and questions are refined. The options are numerous, and not all can be included. Potential topics include:

- Engaging with Indigenous, animal welfare, industry and conservation stakeholders to integrate the priorities of all stakeholders, establish unified objectives and practices, and build on existing successful initiatives.
- Analysing population dynamics including harvest quotas and factors contributing to population fluctuations over time (Figure 1), investigating foraging densities and thresholds to maintain healthy populations and landscapes.
- Identifying steps to prevent extreme population cycles including objectives, roles and responsibilities of stakeholders.

- Identifying when non-lethal management options are practical and appropriate.
- Detailing ethical and humane standards during harvesting/culling for a single National Code of Practice.
- Identifying opportunities to better integrate kangaroos into rangeland production systems in a complementary way with domestic stock as a low carbon, healthy protein with low impact on soils and vegetation. This climate-friendly income stream could mitigate income fluctuations by participating in programs for emissions reduction, soil carbon sequestration, and biodiversity stewardship. Sustainable harvesting can also limit future demand for intensive, factory-style farming practices which often have poor animal welfare outcomes. These opportunities could be promoted through a public awareness campaign.
- Identifying barriers to be addressed including regulatory limitations, lack of unified practices, and resource constraints, with recommendations for overcoming them.

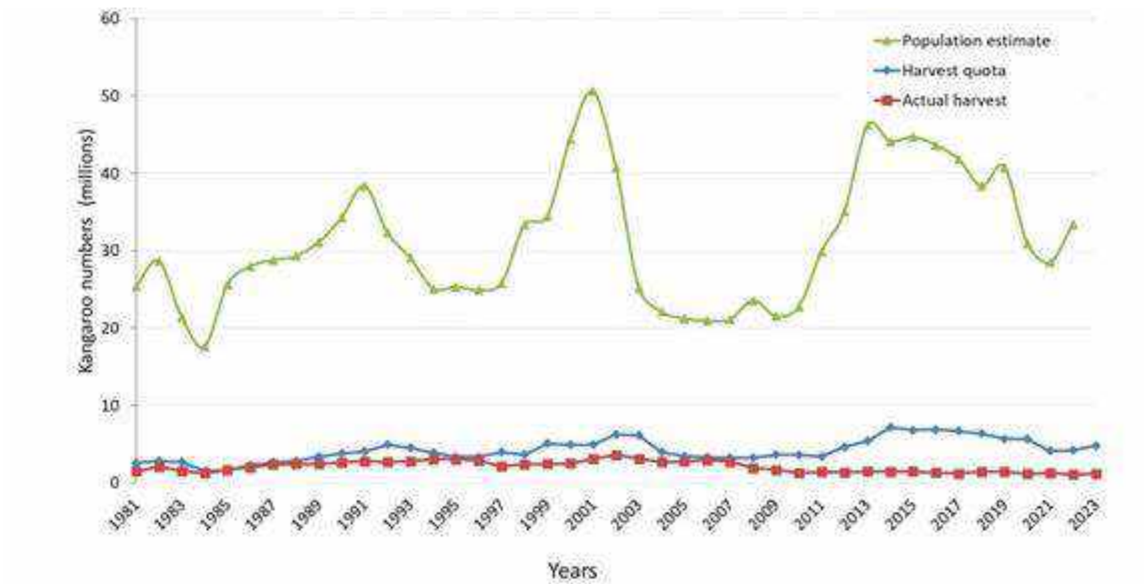

Figure 1 National Kangaroo Population and Harvest Statistics (Edwards & Wilson 2023).

Discussion

This research will contribute to a National Kangaroo Strategy integrating all stakeholder needs and objectives to enhance consistency, efficiency, ethical standards and sustainability in kangaroo management across Australia. Contributions by a broad range of government and non-government stakeholders will be critical to the success of the project. A national, collaborative approach, featuring evidenced-based decision making and education of the public is needed to build a broad social mandate for improved management of kangaroos in Australia.

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Local flora for ecological restoration: the FLoRE project

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Key words: native seeds; restoring nature; Mediterranean region

Abstract

The territories of south-western Europe are still recognised as a biodiversity hotspot. However, it is very much subject to the dangerous consequences of the intensification of human activities, climate change, wild fires and the abandonment of the agricultural and forestry activities in marginal land areas, with the consequent degradation of the land, vegetation and the ecosystems. There, the Interreg SUDOE FLoRE project, started in January 2024, is being implemented to test, analyse and scale-up the implementation of different ecological restoration solutions based on native and locally sourced herbaceous plant seeds. We develop: a) practical tools adapted to the current needs of the target groups; b) create a network of pilot projects in sites with diverse environments and land degradation (due to wildfires, overgrazing, mining, invasive vegetation); and c) lead a multi-stakeholder participatory process to design and test new models of economic cooperation, aimed at the self-production of seeds by users or the supply of products and services to sector players. The project will engage public authorities, non-profit private organization and private companies with the ambition of introduce this type of species into their restoration processes and organise dissemination days for the general public.

Three working groups (WG) were created: WG1 - Operationalise and disseminate existing knowledge on ecological restoration using local seeds, to facilitate the information and learning process by stakeholders, and encourage their commitment and the implementation of good practices.; WG2-Test, monitor and evaluate different ecological restoration solutions from local seeds; and WG3-Develop a strategy to involve all the stakeholders in large-scale actions to support the sustainability of the ecological restoration solutions tested, and formulate recommendations for professionals and decision-makers on the different means of action available to them.

Introduction

Our lives depend on nature, but we are degrading it, and it is imperative that we reverse this trend. A number of factors are putting pressure on ecosystems and species populations, including: pollution, climate change, habitat loss and invasive species (80% of habitats are in poor condition, 10% of bee and butterfly species are in risk of extinction and 70% of soils are in an unhealthy state) (European Council 2024). Soil degradation represents a major threat to ecosystem services and biodiversity conservation. In addition, degradation processes are continuing and worsening (EC 2023).

The semi-enclosed nature of the Mediterranean Sea and the complex topography result in unique physiographic and ecological features. The latest IPCC results show an increasingly arid future for the Mediterranean, with less rainfall and more frequent and longer heat waves (Ali et al. 2022). Some of the consequences of climate change are: reduction of river low flows and annual runoff by 5-70%; yields of rainfed crops may decrease by 64% in some places; desertification will affect more areas, especially in the south and south-east.

The EU Environmental Council adopted the Nature Restoration Law (NRL). They intend to intervene in at least 20 per cent of the EU's land and sea areas by 2030. Restoration plans are intended to cover the period up to 2050. One of the measures envisaged is to restore of at least 30% of the habitats that are in poor condition.

In this context, the FLoRE project was created as part of the INTERREG-SUDOE programme, which aims to consolidate South-West Europe as an area of territorial cooperation in the of innovation, competitiveness and environmental protection. The major challenge of the FLoRE project is to ensure the preservation of the quality of life and the attractiveness of rural areas by demonstrating the economic and organisational viability of scale-change in the implementation of various ecological restoration techniques aimed at valuing native and local wild herbaceous species.

Project Workplan

The Interreg SUDOE FLoRE project, started in January 2024 and will finish in December 2026. The consortium is made up of eight partners (three in France: Conservatoire d'Espaces Naturels d'Occitanie (project leader), FAB'LIM - Le Labo des Territoires Alimentaires Méditerranéens, Conservatoire d'espaces naturels d'Auvergne; three in Spain: Comunidad Autónoma de la Región de Murcia, Asociación Forestal de Soria, Cámara Oficial de Comercio, Industria y Servicios de Badajoz and two in Portugal: National Institute of Agricultural and Veterinary Research, MORE CoLAB on mountain regions. Three groups of tasks were drawn up into three working groups (WG 1, WG 2 and WG 3); all the beneficiaries will take part in each WG, but one beneficiary is responsible for coordinating each WG.

WG 1 - Operationalisation and dissemination of existing knowledge on ecological restoration

Here, the focus is disseminating and applying existing knowledge on ecological restoration techniques using native and locally sourced wild herbaceous species, to facilitate their use by stakeholders (professionals in the sector, landowners, managers, national bodies), in order to encourage their involvement in changing practices and identify the remaining gaps in technical and socio-economic knowledge. To do this, we will update the current state of knowledge on initiatives, scientific publications and public policies aimed at supporting ecological restoration. Then, to facilitate access to information, the most frequently asked questions by stakeholders will be identified and answered, along with other types of dissemination actions. The deficits and gaps in knowledge identified will be revealed and addressed at a later stage of the project. (INIAV is the responsible beneficiary).

WG 2 - Experimentation and evaluation of different solutions for seed production and ecological restoration

A network of demonstration sites is being set up in different environments to publicise different solutions (including different restoration and seed multiplication techniques). Most of our pilot sites are already in place and are located in:

- Occitanie: representing altered agricultural systems and highly anthropized environments and Auvergne: representative of wetlands, meadows and pastures in Auvergne (France)
- Soria: captures truffle farms, recently cleared environments and forest environments and Murcia: degraded natural spaces and eroded areas (Spain)
- Serra da Estrela: I an example of mountain burnt areas in the centre of Portugal and the left bank of the Guadiana river- south-east Portugal represent grasslands (Portugal). This last pilot site is the responsibility of INIAV.

Based on the mapping of grasslands of ecological interest carried out, different techniques for obtaining and recovering seeds will be developed (brushing, mowing, hay transfer). Transnational co-operation will enable us to provide a range of restoration solutions adapted to the regulatory contexts of each country and the realities of each territory, given the diversity of environments representative of the SUDOE area[7]. The experiments carried out and their monitoring (based on indicators developed by the consortium) will make it possible to consolidate protocols and identify the relevant adaptations to be made depending on the contexts and restoration objectives. We will also measure the real benefit or added value, as well as the possible impacts of the restoration operations carried out. (*Asociación Forestal de Soria* is the responsible beneficiary)

WG 3 - Development of a strategy to involve stakeholders in a large-scale action

A medium/long-term strategy (from three to eight years) will be developed jointly based on the sharing of results from the multi-stakeholder group animation work at a transnational level, i.e., from the workshops involving different types of stakeholders (from scientific researchers and public decision-makers to seed vendors and farmers) from various countries, specifically from the SUDOE European region (southwest of France, Spain, and Portugal). Its main objective will be to guide professionals (landscapers, consultants, public and private buyers, scientists, local development associations, site managers) and decision makers (elected representatives, company managers, etc.) towards the means of action available to them supporting long-term viability of the technical solutions tested during the project (collection, planting and monitoring of native and locally sourced wild herbaceous species, etc.). This strategy will define realistic objectives (taking into account the constraints of these stakeholders) but ambitious enough to support the development of the proposed solutions. This may be broken down into several action plans, tailored to each type of public concerned and their respective areas of competence. We will identify a number of economic and public policy levers that can support this strategy. To facilitate its implementation, the strategy will be accompanied by a number of resources available in open access e.g. training modules for field workers and decision makers, awareness-raising content, a letter of engagement, feedback from multi-stakeholder groups, etc. (*FAB'LIM* is the responsible beneficiary).

Goals to be achieved

By carrying out the different tasks (WG1-3), we aim to achieve the following goals:

-1.Obtain commitment from: (i) the managers of the pilot ecological restoration fields to guarantee the sustainability of the solutions tested, (ii) the professionals to collectively implement the economic and organisational models co-constructed in accordance with the initial ethics, (iii) the beneficiaries of the multiplied seeds for use in projects of collective interest and (iv) the communities and companies to introduce this type of seed in their ecological restoration processes in favour of biodiversity.

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[7] Interreg Sudoe is a European Union funding programme to support regional development and cohesion in the regions of south-west Europe.

-2.Training organisations that adopt the tested solutions to manage them independently over time.

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Characterization of pastures legumes with potential for biomass production and for mediterranean pastures restoration

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Key words: Pastures; Pré-breeding; Genetic resources

Abstract

True extensive livestock systems - those based on the use of permanent pastures and grazable agricultural co-products, with low use of external production factors, and which promote ecosystem services, combat desertification and create economic conditions for the population to settle in the territory - are probably one of the most vital ecosystems in the world, particularly in the Mediterranean. These agrarian systems provide us high quality products, fodder, ecosystem services and harbour a great plant and animal biodiversity, both above and below the soil surface.

In some regions of the world, the area of permanent pasture has decreased and changes in land use continue to threaten its extent. In Portugal, many of these pastures (which occupy > 50% of the utilised agricultural area) need to be restored, preferably using nature itself, and thus increase agricultural productivity and soil health, as well as improving land management.

INIAV-Elvas (southern Portugal) has morphologically and phenologically characterised a collection of 66 ecotypes belonging to the genera *Ornithopus* and *Trifolium* genera. The aim is to evaluate ecotypes of native legume species of mainland Portugal which have the potential to successfully establish and develop under very limiting agro-ecological conditions. Descriptors developed by INIAV-Elvas, based on those developed by "Bioversity International" and UPOV-International Union for the Protection of New Varieties of Plants for species in the same group, were used to characterise this plant material. High winter growth and early flowering are important descriptors for the improvement of the Mediterranean agro-sylvo-pastoral sector. So, the ecotypes considered to have the best potential are: Ornitopus compressus 15692 e 15682; Ornithopus pinnatus 13563; *Trifolium cherleri* 15710; *Trifolium glomeratum* 15648 and *Trifolium lappaceum* 14174.

Introduction

Permanent pastures are a key feature of the European rural landscape, representing not only a significant agricultural resource but also supporting multiple non-provisioning ecosystem service. However, this vital farming system is at risk of loss or degradation due to changes in agricultural land use and management practices (Elliot et al., 2024). Schils et al. (2022) emphasize that, despite apparent shifts in the dietary preferences of the European population, prioritizing the protection of permanent grasslands in Europe is essential to prevent further losses in area and to safeguard the provision of ecosystem services. In Portugal, 52% of agricultural land consisted of permanent pastures. Meadows and permanent pastures covered approximately 2 million hectares, 68% of which consisted of unimproved pastures, lacking interventions such as sowing, fertilizing, watering, or drainage (INE, 2019). Many of these pastures are either natural (characterized by low and irregular yields) or degraded. It is necessary to intervene in permanent pastures to enhance their productivity and quality, enabling increased stocking densities and reducing the need for supplemental feed.

When faced with the challenge of restoring poorly productive or degraded permanent pastures, sustainability must be a central consideration. One effective strategy to enhance pasture functionality involves improving its floristic composition. This can be achieved through appropriate grazing management and/or the introduction of seeds from species well adapted to the specific environmental conditions. The introduction of new plant genetics, particularly legumes offers numerous benefits, including increased biodiversity, improved grass yield and quality, reduced dependence on fertilisers, lower greenhouse gas emissions, and enhanced landscape aesthetics. The addition of legumes, in particular, plays a crucial role in improving soil fertility by enriching it with mineral elements (especially nitrogen) and organic matter, creating conditions that support the development of other high-quality species.

For many years, INIAV-Elvas has been developing programs focused on the conservation and improvement of various legume species suitable for grasslands. These programs aim to contribute to the economic and environmental sustainability of Mediterranean farming systems.

In this study, we aimed to evaluate ecotypes of native legume species from mainland Portugal that have the potential to successfully establish and develop under highly limiting agro-ecological conditions.

Methods

The Portuguese ecotypes used were collected in the wild, in uncultivated fields; the prospecting and germplasm collection missions followed the rules laid down in the 'Seed Collecting Manual for wild species' published by the 'European Native Seed Conservation Network' (ENSCONET 2009).

Caraterizaram-se um total de 66 ecótipos, pertencente aos géneros *Ornithopus* e *Trifolium*. As espécies consideradas foram: *Ornithopus compressus*-Ocom ((90% Hard seeds; Deep root system; Well adapted to light-textured, acidic soils), *Ornithopus pinnatus* (Opin), *Trifolium cherleri* (Tche), *Trifolium glomeratum* (Tglo) e *Trifolium lappaceum* (Tlap).

Each ecotype was characterised for 2 consecutive years. To characterise this plant material (10 plants/access/year), several descriptors developed by INIAV-Elvas were used, based on those of Bioversity International and UPOV (International Union for the Protection of New Varieties of Plants) for species in the same group: Winter vigour; Spring vigour; No. of days to flowering (Flo-I); No. of days to end of flowering (Flo-F); Duration of flowering (Durflor); Plant size; No. of internodes; Longest stem including flower head; Leaf colour; Length; No. of internodes; Stem pubescence; Length of longest stem including flower head; Stem thickness; Stem anthocyanin colouration; Leaf colour; Length (normally developed centre leaflet immediately below terminal flower; Frequency of plants with coloured leaflet markings; Centre leaflet length; Centre leaflet width; Flower colour; Seed colour; Seed weight 1000 seeds and seed yield.

The data were analysed by numerical taxonomy techniques, using the NTSYS-pc (Numerical Taxonomy and Multivariate System) programme.

Results

A wide range of variation was registered among the ecotypes of the five annual herbaceous legume species, particularly in flowering period and cycle duration.

O. compressus is the earliest species, requiring approximately 152 days from transplanting to the start of flowering, whereas *T. lappaceum* is the latest, taking an average of 170 days. Regarding flowering duration, *O. pinnatus* exhibited the longest average flowering period (42 days) but showed the weakest vegetative vigour. The species characterised exhibited significant differences in their cycle duration. For example, the average cycle duration of *O. pinnatus* is 50 days, while that of *T. lappaceum* is only 19 days (Table 1). Additionally, there is substantial intraspecific variability.

Discussion and Implications

The species evaluated in this study exhibit the characteristics of pioneer species, meaning they are plants capable of growing in inhospitable environments with unfavorable conditions, being the first to colonize areas where many other plants cannot survive. When analysing the results, it is important to consider that the long-term goal is to identify and select species and ecotypes with the ability to adapt to challenging soil and climatic conditions (e.g., light-textured, shallow soils with acidic pH, and a Mediterranean climate characterized by increasingly shorter and warmer springs).

The ecotypes identified as having the greatest genetic potential were: Ocom_15692, Ocom_15682, Opin_13563, Tche_15710, Tglo_15648, and Tlap_14174. These ecotypes demonstrated the most stable performance over two years of characterization and exhibited reproductive and vegetative cycles suitable for Mediterranean dryland farming, including high winter vegetative vigor and an early growth cycle.

INIAV should continue to develop programs for the conservation and characterization of plant genetic resources in consistent way, given the extensive collection of forage accessions that have been preserved and which hold significant potential. This approach will enable the identification of new solutions capable of addressing the needs of diverse national agricultural systems in the face of constant environmental changes.

Table 1 - Limits of variation and coefficient of variation for some of the descriptors evaluated

	Opin				***Ocom***			
	Min	Max	Mean	CV(%)	Min	Max	Mean	CV(%)
Winter vigour*	9	3	4	13,4	5	3	6,19	27,7
Spring vigour*	8	2	7	17,8	9	5	4,55	34,8
Number of days to flowering (no. of days)	142	168	156	5,9	134	165	152	6,2
Duration of flowering (no. of days)	17	50	42	22,4	25	61	31,61	37,7
Cycle duration (no. of days)	24	60	60	22,9	42	80	40,64	31,7

**1: Very vigorous to 9: Very little vigorous*

Table 1 - Limits of variation and coefficient of variation for some of the descriptors evaluated
(continuation)

	Tglo				***Tche***				***Tlap***			
	Min	Max	Mean	CV(%)	Min	Max	Mean	CV(%)	Min	Max	Mean	CV(%)
Winter vigour*	7	3	5,01	15,7	7	3	4,52	20,1	9	1	5,09	44,8
Spring vigour	8	3	5,99	21,7	7	3	5,27	22,5	7	2	3,89	38,6
Number of days to flowering (no. of days)	152	183	167	4,6	146	176	161	5,5	150	181	170	5,4
Duration of flowering (no. of days)	13	44	26,01	29,5	42	47	34,86	20,6	12	28	19,25	30,1
Cycle duration (no. of days)	26	58	41,55	18,9	37	63	51,45	16,3	24	46	35,05	17,2

**1: Very vigorous to 9: Very little vigorous*

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Physiological advantages observed in a C_3 grass invading C_4 grasslands

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Key words: *Nassella tenuissima*; Mexican feathergrass; shortgrass prairie; invasion mechanisms

Abstract

Mexican feathergrass (*Nassella tenuissima* (Trin.) Barkworth) is a C_3 bunchgrass native to the Trans-Pecos region of West Texas and south-central New Mexico in the United States but has been planted as an ornamental in many other regions. *N. tenuissima* can escape from landscaping areas and become a weedy species on disturbed rangelands. To understand any physiological advantages this species may over native species, we surveyed three *N. tenuissima* colonies throughout a remnant 54-ha native shortgrass prairie within the limits of Lubbock, Texas, USA in the summer of 2022. We selected *N. tenuissima* from three locations within the colonies: inner, edge, and outer for physiological (i.e., leaf-level gas exchange) and morphological (i.e., basal area) measurements. We also monitored two 'companion' native grasses adjacent to *N. tenuissima* in the outer location: blue grama (*Bouteloua gracilis* (Kunth) Lag. ex Griffiths) and purple threeawn (*Aristida purpurea* Nutt.). *N. tenuissima* photosynthesis rates were greater than those of *A. purpurea* and *B. gracilis*, while stomatal conductance and transpiration rates were similar among species. No significant differences were seen in photosynthesis, stomatal conductance, or transpiration rates across the three colony locations for *N. tenuissima*. *N. tenuissima* cover and biomass was greatest in inner locations and decreased with distance away from the center of colonies. In contrast, warm-season grass and forb cover increased with distance away from the center of colonies. N. *tenuissima* appears to exhibit physiological and morphological advantages over native warm-season grasses, which likely contribute to its expansion in the local region, particularly at degraded and overgrazed sites.

Introduction

Mexican feathergrass (*Nassella tenuissima* (Trin.) Barkworth) is a perennial C_3 bunchgrass native to the Trans-Pecos region of West Texas and south-central New Mexico in the United States (Shaw et al. 2011), Mexico, Argentina, and Chile (Jacobs et al. 1998), but has been planted as an ornamental in many regions. *N. tenuissima* is escaping landscaping plantings and becoming a weedy species in shortgrass and midgrass prairies in western Texas and the Texas panhandle (Russell and Rector 2017). In South America where the species is native, overgrazing of desirable forage species and fire suppression are attributed to its spread (Distel and Boo 1996). Additionally, leaf litter of this species has high amounts of lignin, a high C:N ratio, and is slow to decompose (Moretto et al. 2001), further exacerbating competition with native grass and forb species. *N. tenuissima* has been reported since 1998 to be a potential threat to biodiversity in Australia (Jacobs et al. 1998).

N. tenuissima has long, narrow, tightly-rolled leaves (Jacobs et al. 1998). The foliage is considered to be unpalatable due to low N and P content, high lignin (Moretto and Distel 2002), and high amounts of silica (Russell and Rector 2017). At the field site used in this study, wildlife seem to prefer other grass species to *N. tenuissima*. Horticultural guides advertise the species as "deer resistant" (Chapman and Salwitz 2017). Additionally, a lack of grazing or prescribed burning contributes to large amounts of *N. tenuissima* litter on the soil surface. *N. tenuissima* is drought tolerant and adapted to hot and dry regions (Hillock et al. 2022), with a shallow root system well adapted to capturing soil moisture close to the soil surface following intermittent rainfall events (Humphries and Florentine 2021). The species germinates readily in vegetation gaps (Moretto and Distel 1998) and prefers full sun (Hillock et al. 2022). It also seeds freely, and a single plant can produce up to 100,000 seeds annually (Humphries and Florentine 2021).

Little is known about *Nassella tenuissima*'s physiology. In West Central Texas, the majority of its growth occurs in the late spring through early summer, with seed set continuing into the fall (Russell and Rector 2017). In the Texas High Plains, *N. tenuissima* retains a considerable amount of green tissue into late November. Though it is a C_3 species, its life cycle suggests that it behaves similarly to warm-season C_4 grasses in many ways (Russell and Rector 2017).

Our study was conducted due to a lack of information on *N. tenuissima*'s invasion mechanisms and effects on native warm-season species in the shortgrass prairie of the Texas High Plains. Objectives were to assess: 1) the relationship between *N. tenuissima* cover and biomass and those of native warm-season grasses and forbs, 2) *N. tenuissima* physiognomy relative to location within a colony, 3) leaf-level physiological characteristics of *N. tenuissima* relative to common native warm season-grasses.

Methods

This study took place at a ~53-ha remnant shortgrass prairie located within the city limits of Lubbock (33.60327 N, -101.9003 W) and used for research and teaching by Texas Tech University. Historically, the dominant vegetation was short grass prairie. Today the site has some shortgrass prairie species such as blue grama (*Bouteloua gracilis* (Kunth) Lag. ex Griffiths), and buffalograss (*Bouteloua dactyloides* (Nutt.) Columbus) but with high densities of encroaching honey mesquite (*Prosopis glandulosa* Torr.) and annual Chenopodiaceae forbs (Jackson et al. 2020). The region is semi-arid, with hot summers and mild winters. Local temperatures range from –2.8°C in January to 34.4°C in July, with an average annual precipitation of 466 mm. The site has not been grazed by livestock in ~20 years, though overgrazing occurs via high populations of cottontail rabbits (*Sylvilagus* spp.) and black-tailed jackrabbits (*Lepus californicus*). *N. tenuissima* has been planted in many locations in Lubbock and is thought to have established on the site following escape from planted locations nearby.

We selected three *N. tenuissima* colonies at the site. Colonies ranged in size from ~10 to 20 m in diameter. From the center of each colony, three transects were established in random directions to well beyond the colony margin. Total transect lengths ranged from 20 m at the smallest colony to 40 m at the largest. In November 2024, beginning at the 5 m mark, canopy cover was measured in a 0.1-m^2 frame every 5 m along each transect. Cover was classified into bare ground, litter, *N. tenuissima*, warm-season grasses, and forbs. On the opposite side of the transect from where we collected cover, we measured the height and diameter of the nearest *N. tenuissima* plant. Heights were measured to the nearest cm and diameters to the nearest 0.5 cm. If no *N. tenuissima* plants were within 2.5 m, no *N. tenuissima* morphology measurements were taken there. For analysis, data were pooled from the four to eight locations along a transect into three colony zones: 1) *inner colony* consisting of distances nearest the colony center to 1x the distance of the colony radius, 2) *mid colony* which contained locations > 1x the colony radius and < 3x the colony radius, and 3) *outer colony* which contained locations > 3x the colony radius. The number of locations varied in each zone across colonies, but this method provided a standardization for colonies of different sizes.

In summer 2022, we selected three *N. tenuissima* plants from the three colony locations for physiological (i.e., leaf-level gas exchange) measurements. We also monitored three adjacent plants of blue grama and purple threeawn (*Aristida purpurea* Nutt.) in the outer location of each colony. Leaf-level gas exchange [photosynthesis (*A*; µmol CO_2 m^{-2} s^{-1}), stomatal conductance (g_s; mol H_2O m^{-2} s^{-1}), and transpiration (*E*; mol H_2O m^{-2} s^{-1})] was assessed using an open-flow infrared gas analyzer system (LI-6800, Li-Cor, Lincoln, NE, USA). Measurements were taken in May 2022 at midday. Due to the number of colonies, gas exchange measurements were conducted over three consecutive days with similar cloud-free weather. During gas exchange measurements, three fully expanded leaves of each plant were placed parallel in the chamber. Other studies assessing gas exchange of narrow-leaved grass species have used sections from multiple leaves simultaneously as well (Ramirez et al. 2008, Perez-Anta et al. 2024). Following the gas exchange measurement, we measured and recorded the width of each leaf section in the chamber. Widths were multiplied by the length of the chamber cuvette to calculate leaf areas which were then used to normalize gas exchange data. Due to the rolled nature of *N. tenuissima*'s leaves, we were required to use the projected (rolled) leaf area to determine leaf-area corrected gas exchange rates (Haase et al. 1999, Perez-Anta et al. 2024).

Linear mixed models (SAS 9.4) were used to test the effects of colony location on *N. tenuissima* height, basal area, and leaf-level physiological parameters. The interaction of colony location and cover type was tested on canopy cover in colonies. In the outer colony location, the effect of species was tested on leaf-level physiological parameters. Differences were considered significant at $P \leq 0.05$ and tendencies assumed at $0.10 \geq P > 0.05$. Means separation of significant effects and interactions were performed using Tukey's HSD.

Results

N. tenuissima photosynthesis rates, 11.8 µmol CO_2 m^{-2} s^{-1}, were greater than those of *A. purpurea,* 4.1 µmol CO_2 m^{-2} s^{-1}, and tended to be greater than those of *B. gracilis*, 5.8 µmol CO_2 m^{-2} s^{-1} ($P = 0.06$). Stomatal conductance and transpiration rates were similar among species. No significant differences were seen in photosynthesis, stomatal conductance or transpiration rates across the three colony locations for *N. tenuissima*.

N. tenuissima basal area tended to be related to colony position, with plants in inner colony positions tending to have greater basal areas ($P = 0.052$). *N. tenuissima* height was greatest at inner colony locations. Colony position interacted with cover type to influence ground cover. *N. tenuissima* cover was greater in inner colony locations (40.4%) than mid (10.8%) and outer (3.8%) locations. In contrast, cover by native warm-season grasses and litter was lowest in inner colony locations. Forb cover and amounts of bare ground were not affected by colony position and were low in all colony locations. In every colony location, litter comprised a large portion of the cover, 55.6 – 75.2%. Within inner colony locations, *N. tenuissima* comprised a larger portion of cover (40.4%) than warm-season grasses (1.5%) and forbs (5.2%). In mid colony positions, *N. tenuissima*, warm-season grasses, and forbs had similar cover. In outer colony positions, however, warm-season grasses (17.6%) had greater cover than *N. tenuissima* (3.8%).

Discussion, Conclusions, and Implications

Though *N. tenuissima* is a C_3 species, it maintains actively growing tissue throughout the summer and fall, directly competing with warm-season native shortgrass prairie species during their active-growth period. Gas exchange measurements suggested that, at least early in the summer, *N. tenuissima* had greater intrinsic water use efficiency than warm-season native species at the site. *N. tenuissima's* drought tolerance and low water consumption has been reported in other studies (Asin et al. 2021), though we did not observe lower transpiration rates or stomatal conductance in *N. tenuissima* than *B. gracilis* or *A. purpurea*. The summer of 2022 was exceptionally dry, which limited our ability to measure gas exchange accurately following May 2022 measurements. Thus, further tests are needed to assess *N. tenuissima*'s gas exchange rates relative to the C_4 grasses under a wider range of soil moisture conditions.

We believe that the combination of the large quantities of durable litter produced by *N. tenuissima* in addition to the live cover from this species results in the suppression of the local warm-season grasses. Following honey mesquite invasion across much of the site, warm-season species have been restricted to areas of low mesquite cover. Those areas are now experiencing encroachment from *N. tenuissima* despite *N. tenuissima* being reported to be a poor competitor against native species in well-managed locations (Amme 2003, Mapaura et al. 2020). Stress from overgrazing by wildlife coupled with the unpalatable nature of *N. tenuissima* and build-up of litter appears to have resulted in warm-season species being displaced in the areas of low mesquite density. Further studies are needed to assess the effects of woody canopy cover on *N. tenuissima* growth and the degree to which it can tolerate high cover of summer-active shortgrass prairie grasses and forbs.

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Rangeland Management Practices Used to Increase Usable Habitat Space: A Case Study with Greater Sage-Grouse

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Key words: Sagebrush, Forb and Grass Response, Shrub Canopy, Spike, Dixie Harrow, Lawson Aerator

Abstract
Greater sage-grouse (*Centrocercus urophasianus*) need forbs, and the associated insects, for chick diet and growth in sagebrush habitat. In some cases, sagebrush cover may limit the abundance of forbs in the understory. Sage-grouse require sagebrush and large-scale shrub treatments are detrimental to sage-grouse populations. We implemented small (40.5 ha) shrub-management treatments of Dixie Harrow, Lawson Aerator, and Tebuthiuron (Spike) in a replicated plot design with control and monitored the response of herbaceous cover and grouse. We found that spike treatments demonstrated the strongest forb response, especially forbs that are known to be consumed by sage-grouse, and greater grouse use. This long-term response of forbs and grouse shows that small-scale shrub management may provide rangeland managers with methods to improving sage-grouse brooding habitat when needed.

Introduction
Greater sage-grouse (*Centrocercus urophasianus*; hereinafter sage-grouse) depend upon sagebrush-dominated rangelands throughout western North America (Connelly et al. 2000). Sage-grouse populations have been experiencing declines due to loss or degradation of sagebrush (*Artemesia* spp.) communities (Braun 1998, Schroeder et al. 2004). Additionally, in some big sagebrush (*A. tridentata*) communities shrub canopy cover has increased and can limit herbaceous understory cover and diversity, which may negatively impact sage-grouse brooding habitat. For brood-rearing habitat, sage-grouse prefer more open shrub canopy cover (~15% cover) with plentiful grasses and forbs, which typically provide arthropods - an important component of chicks' diet - and an indication of high-quality brood-rearing habitat (Connelly et al. 2000).

The scale of habitat management is critical to predicting whether an action would be positive, negative or neutral. Sage-grouse are a landscape species, dependent on large expanses (i.e., thousands of km^2) of sagebrush-dominated rangelands (Connelly et al. 2000). However, more information is needed regarding the appropriate management techniques and scale of management activity within these areas to improve specific seasonal habitats, such as brooding areas, for sage-grouse. Within the context of a large intact sagebrush landscape, small-scale habitat manipulations may provide an effective rangeland management tool for improving herbaceous cover and associated arthropod resources, while not adding large-scale fragmentation that is known to be detrimental to sage-grouse.

Our objectives were to assess the vegetation and sage-grouse response to small-scale sagebrush canopy reduction treatments in mountain big sagebrush communities (*A. t. vaseyana*) in a replicated (i.e., n=4) and controlled design. We predicted that treated areas would exhibit improved brooding habitat conditions and sage-grouse would select for treated areas more than controls.

Methods

Study Area

Our study occurred on Parker Mountain, south-central Utah, USA. Parker Mountain is a 120,000-ha high elevation (~ 2500 – 3000 m) plateau dominated by sagebrush, with Wyoming big sagebrush (*A. t. wyomingensis*) at lower elevation, black sagebrush (*A. nova*) at mid-elevation, and mountain big sagebrush at higher elevation (Dahlgren et al. 2006). The study area has one of the largest and relatively stable populations of sage-grouse in Utah. There is relatively little to no development on Parker Mountain, except for some graded gravel and two-track roads. The study area typically receives 400-500 mm of precipitation annually, primarily in the form of winter snow and late-summer monsoons.

Shrub Removal Treatments

In 2000 and 2001, we implemented small-scale (n = 16, 40.5-ha square plots) shrub canopy reduction treatments with three methods – mechanical treatments of Dixie Harrow and Lawson Aerator, a chemical treatment of Tebuthiuron (i.e., Spike), and control plots (Figure 1). The Dixie harrow is dragged behind a large tractor and has connected pipes with alternating harrows that rip up sagebrush and scarify the bare soil when dragged in two opposing directions (i.e., double harrow treatment). The Lawson aerator is a large drum aerator dragged behind a tractor that crushes larger, woodier sagebrush without impacting the soil. The 40.5-ha plots were square and delineated to contain as much mountain big sagebrush cover as possible, but each plot also contained areas of black sagebrush. Only mountain big sagebrush was treated. Mechanical treatments were completed in a mosaic design to leave some intact big sagebrush adjacent to treated areas (Figure 2). Spiked plots received 0.75 lbs. per ha active ingredient resulting in a mosaic of varying levels of defoliation and kill to the mountain big sagebrush due to varying soil depths and other conditions within the plots.

Vegetation and Grouse Monitoring

From 2001 to 2009, we sampled n = 5 randomly placed permanent 20-m vegetation transects in each plot and measured shrub and herbaceous canopy cover using a variation of the line intercept method (Canfield 1941) and Daubenmire frames (Daubenmire 1959) centered on every meter, respectively. We recorded genus and species, when known, of shrubs, forbs, and grasses. To evaluate sage-grouse use of plots, we used trained pointing dogs to locate, point, and flush grouse using the plots from mid-July to the end of August (Dahlgren et al. 2006). A handler would cast the dog through the plots to search the entire plot. Each plot was sampled at least twice per field season.

Results

Sagebrush canopy cover was relatively high (~ 40%) in our plots pre-treatment (Figure 3). All treatments reduced sagebrush cover and increased grasses and forbs the first couple years post-treatment. However, spiked plots showed the strongest long-term herbaceous response to treatment (Figure 4). When we separated forb species into those known (i.e., reported in the published literature) to be consumed by sage-grouse we found the strongest long-term treatment response. Sage-grouse responded positively to all treatment plots, with more use (grouse flushed per plot) compared to control plots. However, grouse had nearly double the flush rate in spiked plots when conducting pointing dog surveys than the mechanical treatments (Figure 5).

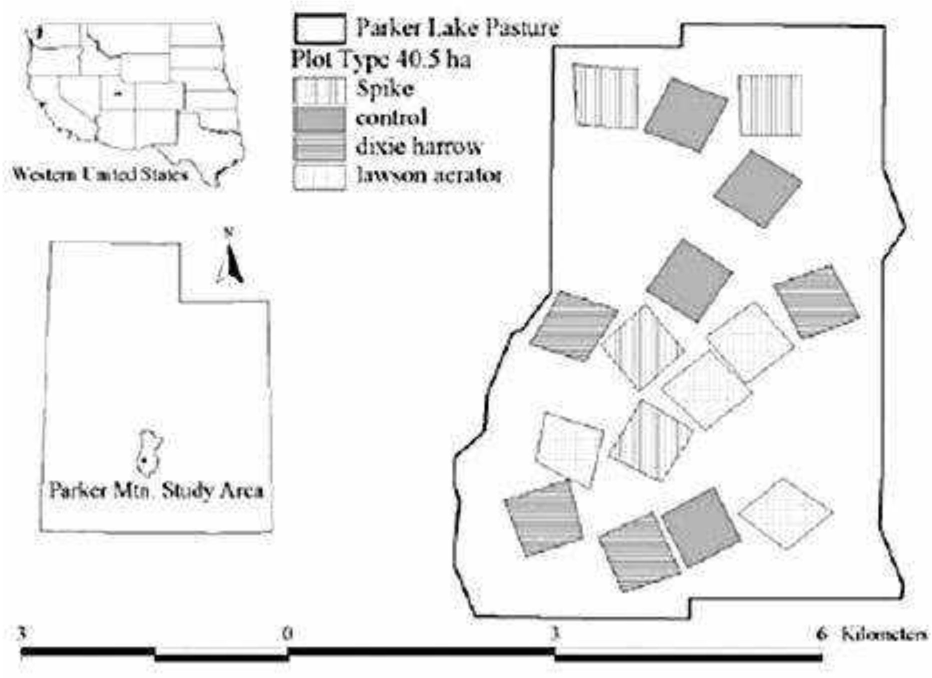

Figure 1. Parker Lake Pasture study design, Parker Mountain, Utah, USA.

Figure 2. Example of a mosaic design shortly after the Dixie Harrow treatment was implemented, Parker Mountain, Utah, USA, 2002.

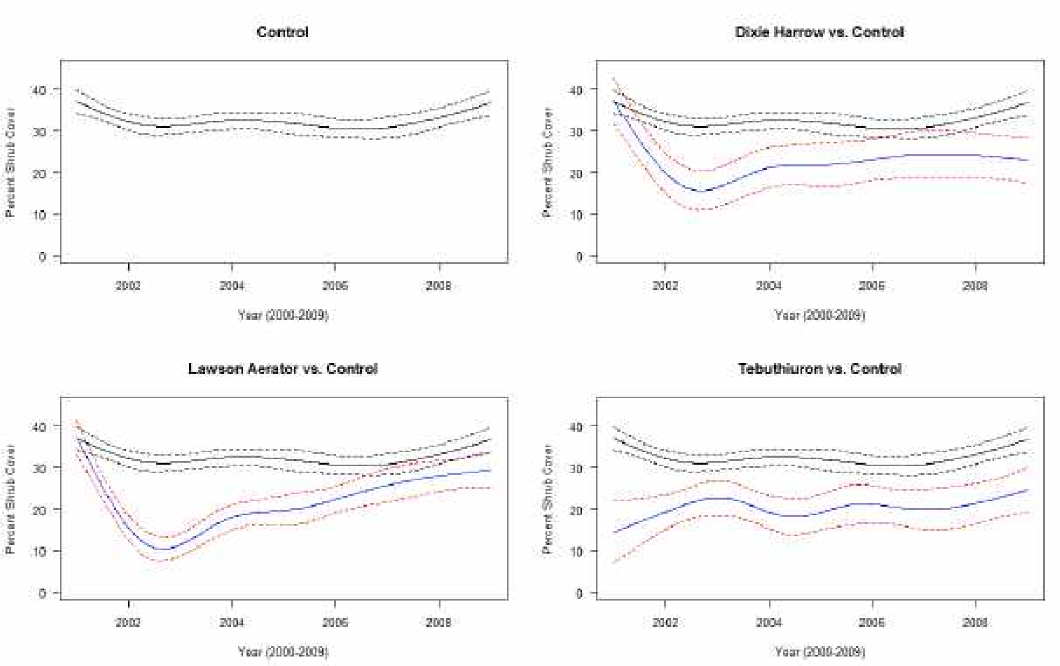

Figure 3. Response of shrub cover to treatments of Tebuthiuron, Dixie Harrow, and Lawson Aerator, mean percent canopy cover and 95% confidence intervals, Parker Mountain, Utah, USA, 2000-2009.

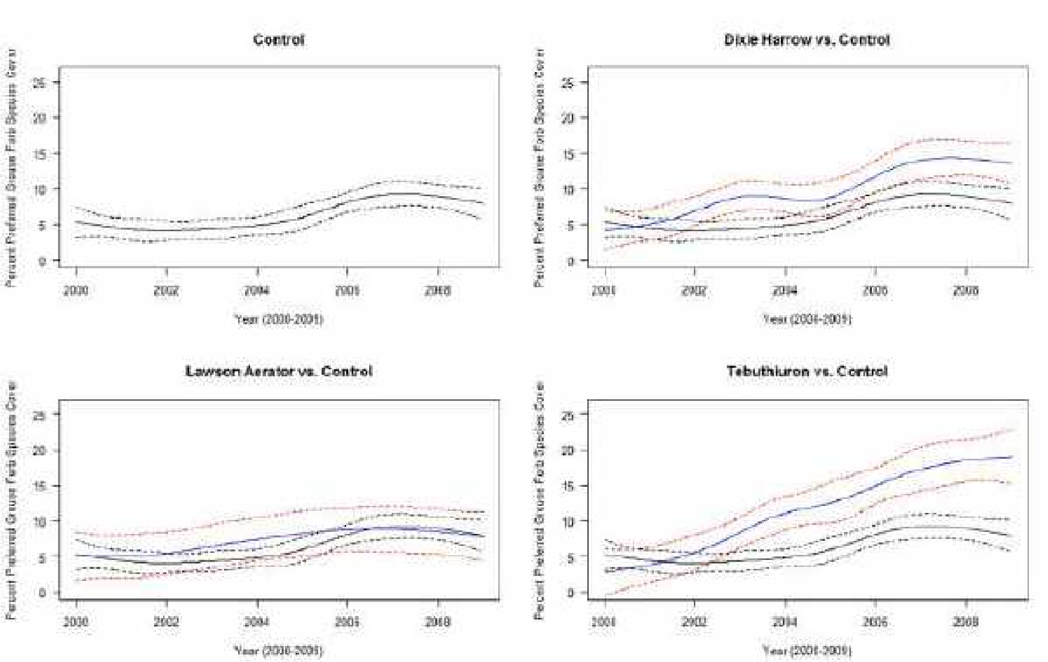

Figure 4. Percent canopy cover of perennial gras and forbs, mean percent canopy cover and 95% confidence intervals, Parker Mountain, Utah, USA, 2000-2009.

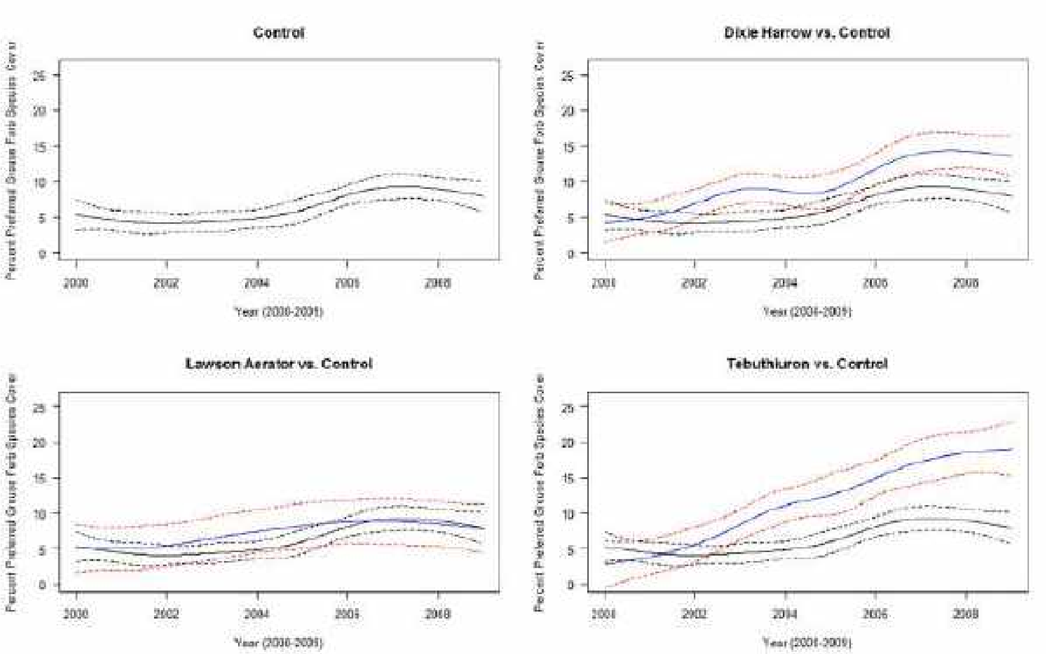

Figure 5. Response of forbs consumed by sage-grouse (in published literature) to sagebrush canopy cover treatments, mean percent canopy cover and 95% confidence intervals, Parker Mountain, Utah, USA, 2000-2009.

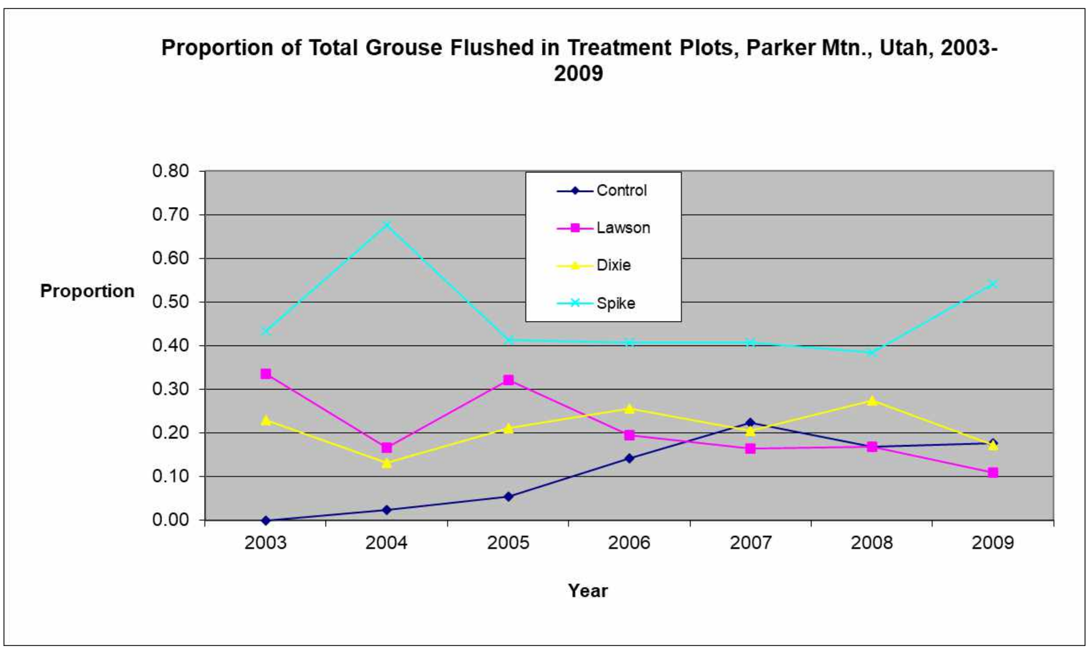

Figure 6. Response of sage-grouse to sagebrush canopy reduction treatments using pointing dog surveys, Parker Mountain, Utah, USA, 2003-2009.

Conclusions and Implications

All treatment types reduced shrub canopy cover and mechanical treatments showed a small herbaceous response for the first few years post-management. Spike treatments demonstrated a long-term increase in herbaceous cover, especially forbs that sage-grouse eat. Sage-grouse use, especially broods, was correlated with the strong forb response in spiked plots. Spike plots also demonstrated a longer recovery period for sagebrush canopy cover, likely associated with the long-term increase in herbaceous cover. The Dixie harrow and Lawson aerator plots initially showed a significant decrease in shrub canopy cover, but they also returned to pre-treatment shrub canopy cover levels within our 10-year study period.

Spatial and temporal scales are critical to consider when planning and implementing sagebrush canopy cover reduction treatments (Connelly et al. 2000). Our small (40.5 ha) treatment areas were placed within a large intact sagebrush landscape. Such prescriptive small-scale rangeland treatments may provide an opportunity for managers to address seasonal habitat needs for sage-grouse, such as forb and grass cover in brood-rearing habitat, and other sagebrush-associated species. Shrub canopy reductions conducted at large scales (100's to 1000's of ha) have been shown to be detrimental to sage-grouse. Sagebrush canopy reductions would not be advisable in sage-grouse habitat that is highly fragmented or within landscapes with limited sagebrush dominated areas (Braun et al. 1977). Additionally, we placed these treatments in high-elevation mountain big sagebrush known to be brooding habitat. Sagebrush canopy cover reduction in nesting or wintering habitat, and/or in lower-elevation Wyoming big sagebrush, have been shown to have only neutral or detrimental impacts to sage-grouse habitat and populations. The recovery time frame of treated sagebrush communities is another important consideration when it comes to how often an area might be treated and predicting potential impacts to sage-grouse.

Our results may seem somewhat counterintuitive. We provide novel findings concerning how, when, and where sagebrush treatments may benefit a sagebrush obligate species to help them meet specific seasonal habitat conditions, such as increased forbs during the brooding period. While sagebrush treatments have become highly discouraged over time as the sage-grouse conservation issue has grown since the mid-1990s, our study offers a way to continue to manage sagebrush rangelands, even potentially increasing forage for livestock and other species, while continuing to conserve and support sage-grouse populations into the future.

Acknowledgements

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Cacti biocontrol in the South Australian Arid Lands

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Key words: cacti; biocontrol; cochineal; arid

Abstract

All Opuntioid cacti species in Australia are introduced and are Weeds of National Significance (WONS) and declared under the Landscape South Australia Act 2019 (except *O. ficus-indica*). Significant time, money and effort has been spent trying to control infestations using herbicide and physical removal. Despite this, Opuntioid cacti have resisted control efforts and continued to infest rangelands.

Since 2016, with the support of Biosecurity Queensland (Queensland Department of Primary Industries), we have developed an Opuntioid cacti biocontrol program. The biocontrol agent we use is cochineal, species of mealybugs that are cactus specific. As a result, we have biocontrol agents that assist in controlling 12 of the 15 species of Opuntioid cacti found in the SAAL LB region (Map of infestation locations included). Cochineal has been a game changer in helping to get on top of some of the worst infestations of Opuntioid cacti in our region. Before and after photos in this paper demonstrate how successful this biocontrol has been.

Biosecurity Queensland have provided cochineal species, that SAAL LB previously didn't have, that were suited to many species of Opuntioid cacti in our region. In return, we have provided samples of cactus and cochineal that they have used to further develop their Opuntioid cacti biocontrol program through trials and DNA testing of cochineal.

The SAAL LB have also been supported by the Port Augusta City Council who agreed to house the SAAL LB Cochineal Nursery on their Australian Arid Lands Botanic Garden site. The Cochineal Nursery was established in 2021 and breeds four species of cochineal, which work on six species of cacti. Cochineal from this facility has been used on infestations on numerous properties in SAAL and other Landscape Boards.

Introduction

Many cacti are invasive species globally, posing a risk to native species via competition, impeding access to natural areas, and causing harm to animal and humans due to physical attributes such as sharp spines. In Australia, Opuntioid cacti in particular, are Weeds of National Significance (WONS), with many declared species under the Landscape South Australia Act 2019 (except *O. ficus-indica*), requiring control. Opuntioid cacti are mainly found in low rainfall areas, such as the South Australian Arid Lands Landscape Board (SAAL LB) region which covers more than half of South Australia, and shares borders with three other States: New South Wales, Queensland and the Northern Territory. The vastness of this region with inaccessible terrain and a sparse population, poses a challenge to the logistics of implementing chemical control and follow-up treatments. Biocontrol is an effective management tool for cacti and entails the use of a plants' natural enemies to control populations in introduced ranges. There are several varieties of Opuntia species present in our region, including Wheel cactus (*Opuntia robusta)*, Prickly pear *(O. stricta),* Engelmann's cactus (*O. engelmannii)*, Devil's rope (*Cylindropuntia imbricata),* jumping cholla (*Cylindropuntia prolifera*), Coral cactus (*Cylindropuntia fulgida var. mamillata)* and Red-flowered prickly pear *(Opuntia elatior)* for which there are effective biocontrol agents available.

Methods

The SAAL LB initiated an Opuntioid cacti biocontrol program in 2016. The biocontrol agents we use are collectively called cochineal (*Dactylopius sp.)*, of which there are several species of mealybugs belonging to the genus *Dactylopius*. Research has identified which *Dactylopius* species to release on targeted cactus species (see table 1). Biosecurity Queensland's Cacti Biocontrol Research program has provided support through the provision of suitable cochineal that the SAAL LB didn't previously have, but that were suited to many species of Opuntioid cacti in our region (*e.g.* Jumping Cholla (*Cylindropuntia prolifera*) and Coral cactus (*Cylindropuntia fulgida var. mamillata).*

In return, we provided samples of local cactus plants and cochineal that they have used to further develop their Opuntioid cacti biocontrol program through trials and DNA testing of cochineal.

Another aspect to ensure the success of any biocontrol program, is the mass-rearing of suitable agents to ensure a smooth supply-demand cycle. This involves distribution of cochineal to new plant populations infield, and collection and replenishing of fresh plant material for agents to feed on. In partnership with the local Port Augusta City Council, a cochineal nursery was established at the Australian Arid Lands Botanic Garden property in 2021.

Results

Cochineal has been a game changer in helping to get on top of some of the worst infestations of Opuntioid cacti in the SAAL LB region. (See Fig. 1 for an example of a Before and after image that demonstrates how successful biocontrol has been). We now have cochineal released against 12 of 15 Opuntoid cacti present in the region. In the 2023-2024 financial year alone, cochineal was released at 23 sites in the SAAL LB region, targeting seven cacti species. Thirteen of these were new release sites (see Table 1).

This cochineal nursery is crucial to the success of the biocontrol program, four strains are bred at the facility that are specific to six cacti species found in region: Wheel cactus (*Opuntia robusta*), Red-flowered prickly pear (*Opuntia elatior*), Engelmann's cactus (*Opuntia engelmannii*), Devil's rope cactus (*Cylindropuntia imbricata*), Coral cactus (*Cylindropunta fulgida var. mamillata*) and Jumping cholla (*Cylindropuntia prolifera*).cacti. Cochineal from this facility has been used on infestations on numerous properties in the SAAL LB and other Landscape Board regions. Maintaining the nursery to ensure adequate stock is a shared responsibility amongst many SAAL LB staff (See Fig.2 below).

Table 1. Cochineal release across different Districts in the SAAL LB region in the 2023-2024 Financial year

Cactus Species	Cochineal species	District	Release Date
O engelmannii	*Dactylopius opuntiae* - Mexican lineage	GR	03-Aug-23
O engelmannii	*Dactylopius opuntiae* - Mexican lineage	GR	04-Sep-23
C imbricata	*Dactylopius tomentosus* - Imbricata biotype	NEP	28-Sep-23
O elatior	*Dactylopius opuntiae* - Mexican lineage	Kin	29-Sep-23
O engelmannii	*Dactylopius opuntiae* - Mexican lineage	PA-Q	29-Sep-23
C fulgida var. mamillata	*Dactylopius tomentosus* - Cholla biotype	Kin	05-Oct-23
C fulgida var. mamillata	*Dactylopius tomentosus* - Cholla biotype	M-O	06-Oct-23
C. prolifera	*Dactylopius tomentosus* - Californica biotype	M-O	06-Oct-23
C fulgida var. mamillata	*Dactylopius tomentosus* - Cholla biotype	Kin	14-Oct-23
C imbricata	*Dactylopius tomentosus* - Imbricata biotype	NF	24-Oct-23
C fulgida var. mamillata	*Dactylopius tomentosus* - Cholla biotype	M-O	30-Oct-23
C. prolifera	*Dactylopius tomentosus* - Californica biotype	M-O	30-Oct-23
O. engelmannii	*Dactylopius opuntiae* - Mexican lineage	GR	10-Nov-23
O. stricta	*Dactylopius opuntiae* - USA lineage	PAQ	17-Nov-23
O. stricta	*Dactylopius opuntiae* - USA lineage	PAQ	20-Nov-23
C. imbricata	*Dactylopius tomentosus* - Imbricata biotype	PA-Q	29-Nov-23
C. prolifera	*Dactylopius tomentosus* - Californica biotype	NF	01-Nov-23
O. robusta	*Dactylopius opuntiae* - Mexican lineage	NF	13-Nov-23
C. prolifera	*Dactylopius tomentosus* - Californica biotype	NF	04-Dec-23

O. elatior	*Dactylopius opuntiae* - Mexican lineage	Kin	02-Feb-24
O. robusta	*Dactylopius opuntiae* - Mexican lineage	NEP	23-Feb-24
C. prolifera	*Dactylopius tomentosus* - Californica biotype	NF	16-May-24
O. robusta	*Dactylopius opuntiae* - Mexican lineage	NEP	13-Jun-24


Fig. 1 Fountain Spring in the Flinders Ranges, before (LEFT) in 2008, and in 2018 (RIGHT), 10 years after cochineal release against prickly pear cactus.

Fig. 2 Cochineal Nursery, established at the Australian Arid Lands Botanic Garden in January 2021, as a joint project between SA Arid Lands Landscape Board and the Port Augusta City Council.

Discussion

The SAAL LB prides itself in harnessing partnerships that benefit the landscape, and this is evident through the delivery of many collaborative natural resource management projects in the region, possible through a combination of internal (levy) and external (project) funding. The SAAL LB Opuntioid cacti biocontrol program is a prime example of this. This project has been a success so far, due to the building and maintaining of partnerships, including with landowners, volunteers, and other stakeholders who participate in collaborative planning and also distribution and spread of cochineal.

For example, landholders and volunteers were engaged to map out control work that had already been completed and the scale of remaining cactus infestations, coming up with a plan of when and where to use cochineal versus chemical control. This led to the Northern Flinders Opuntia control strategy and bringing a group like this together allowed for better cross-property collaboration. Volunteers made up of 4WD, bushwalking and cycling clubs have also played a crucial role in spreading cochineal in the North Flinders for over a decade (~4,000 hours of volunteer hours annually).

Biocontrol agents are able to establish and spread by themselves infield, reducing time, effort and capacity required. Human-aided spread of agents can enhance the success of such programs, which have minimal costs involved. However, biocontrol should not be viewed as a stand-alone "golden ticket" and is often required to be used as a management tool in conjunction with other treatment methods *e.g.* herbicide control. Integrated pest weed and animal management reaps benefits, and biocontrol can be used for example, in reducing populations sizes to a more manageable level for a targeted chemical control program to reduce costs.

The Opuntioid cacti biocontrol program is directly linked to at least three SAAL LB Board priorities; Sustainable land management, Protecting and enhancing biodiversity, and People and partnerships. It is envisaged that this program will expand in future years to include a more structured post-release monitoring protocol, and collection of more in-field population data to demonstrate its effectiveness over time.

Acknowledgements
Queensland Department of Primary Industries Port Augusta City Council

Staff, volunteers and landholders in the SAAL LB region

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The Koonamore Project: 100 years of research in a short-term rangeland ecology study

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Key words: LTER; Chenopod shrublands; stock exclusion, long lived plants.

Abstract
The Koonamore project is based at the Osborn Vegetation Reserve, located in arid lands of South Australia, 350 km NNE from Adelaide. The site was established in a badly degraded corner of a paddock that was fenced off to exclude stock and rabbit grazing in 1925. A series of permanent plots and photopoints have been established at the site and resurveyed regularly.

The data collected (which is available for research on request) include location and sizes of trees and long-lived shrubs in several permanent plots, and sequences of photographs for over 40 permanent photopoints.

The accumulated information provides important insights on the changes that occur in rangelands when stock and feral grazers are excluded. It also informs us on the dynamic associated to weather fluctuations and trends of climate change.

To our knowledge this is the longest running ecological study of rangelands in Australia and one of the oldest in the world. However, as the data shows, this period encompasses just a few generations of several species (e.g. *Maireana sedifolia*, *Sena artemisifolia*) and even less than one generation for some of them (e.g. *Acacia aneura*, *Myoporum platycarpum*). Given the long life span of key species in the system, and the long term nature of climatic variation, we argue that a century is a relatively short term, and that the project warrants to be continued for at least another 100 years.

Introduction
The Koonamore Project was started in 1925 with the aim of obtaining information about the recovery of rangelands in extremely degraded conditions, when stock grazing was removed. This objective was framed within Clement's recently formalised ideas about ecological succession. The project was started by Professor T.G.B Osborn by fencing off a 4 km^2 of a heavily degraded paddock in Koonamore station (between 30º07'S, 139º20′E, in the centre of the Koonamore Station) (Figure 1). This area is now the TGB Osborn/ Koonamore Vegetation Reserve (KVR). Several permanent plots and photopoints continue to be monitored (albeit with some temporal gaps) to this day, which make this project (to our knowledge the oldest Long Term Ecological study in Australia, and one of the oldest in the world.

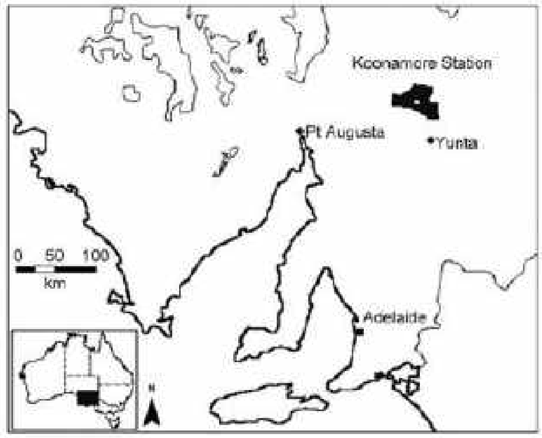

Figure 1: location of the T.G.B Osborn Vegetation Reserve, where the Koonamore Project is based.

The System

The whole area can be described as an open woodland with chenopod understorey, comprising a combination of low sand dunes alternating with sand plains and harder loam soils with travertine limestone at various depths on the intervening flats (Osborn, 1925). The annual rainfall, averages 200 mm, but shows substantial variability (between 50 and 850 mm during the period of the project). Vegetation is predominantly low open-woodland, with an sparse tree storey dominated by *Acacia aneura*, *Myoporum platycarpum* and *Alectryon oleifolius*. The tall shrub stratum include *Eremophila* spp., and *Senna artemisioides* (various subspecies). The low shrub stratum is dominated by *Atriplex vesicaria*, *Maireana sedifolia*, and *Maireana pyramidata*. Other shorter-lived chenopod shrubs grasses and ephemeral vegetation make up the lower stratum.

Central to the Koonamore Project are permanent plots where individuals of long lived plant species are mapped (x & y coordinates recorded) and, since the 1970's, dimensions of the canopy (diameters in N-S and W-E directions, and height) recorded. The main quadrat are four 100 m x 100 m areas representing the main types of vegetation (as understood when the site was established). (For more details see Sinclair and Facelli 2019). The data collected is in the public domain (currently through AEKOS (http://www.aekos.org.au/), and we are in the process of enhancing accessibility and ease of use. The data is particularly valuable since not only covers the recovery of the rangelands after de-stoking, but also the response of the system to variability in climate as the data covers several El Niño and La Niña events. It also includes several decades of important changes in climate driven by human activities.

Discussion and Conclusions

Previous recent publications (Sinclair 2005, Sinclair and Facelli 2019) report changes in population sizes, organization of the community (Lawley et al. 2013), persistence of dead logs and their effects in the creation of microsites (Bowman et al. 2014), and models of growth for the most abundant tree (*Myoporum platicarpum*) (Boland and Sinclair 2014). These publications, in our opinion, only cover a small fraction of the possible areas of research that could be explored using the massive data set accumulated. Here we present some of the areas of possible research we consider worth pursuing.

The data should allow studies of the life span of several species. The presence of species with highly contrasting life history strategies is well documented. The KVR data provide opportunities to assess several aspects of their demography. For example: is there a demonstrable trade off between life span and how often conditions conducive to recruitment occur? Because several species in permanent quadrats are mapped from establishment to death, the data base provides excellent opportunities for such studies. Equally, the role of density dependence in establishment and recruitment (a contentious issue in arid lands) can be effectively addressed with the data available. The site also provides unique opportunities to explore population genetics. The recording of date of establishment together with genetic information that can be obtained with molecular techniques could shine a light on genetic dynamics of plant populations recovering after undergoing a strong reduction in the number of individuals

The second important point we want to make is questioning whether, having reached the 100 years mark, is it worth continuing the project. It could be argued that data covering 100 years should contain ample information on the dynamics of these rangelands. Two issues are relevant. Firstly, we need to consider whether (still thinking within the Clementsian conceptual framework}, successional changes have reached a stable state. An inspection of the age population structure of some of the key species suggests that this is not the case. Indeed, populations of species such as *Myoporum platicarpum* and *Acacia aneura*) show sparse numbers of old individuals and relatively large numbers of juveniles, with no individuals in intermediate age classes. This suggest that these key populations have not reached a stable state. Further, as these species are likely to act as ecological engineers, it can be expected that as young individual mature, changes in soil and microhabitat will trigger further changes in ecosystem dynamics and in other populations. Secondly, to the successional consideration it must be added the influence of climate change. Indeed, this project has run during critical times for the climate of the planet. During the period global temperatures have risen by almost 2ºC. These changes, along with associated changes in rainfall patterns, have occurred as the vegetation and the ecosystem underwent recovery from extreme degradation. Compounding this, is the possibility of time lags in responses. Time lags are pervasive in ecological systems, and may be particularly important in rangelands, They may include responses of various species to changes in the soil, either produced by organisms, or by geological processes leading to soil formation. Microbial changes in the soil are also candidates to produce time lags. As soil changes through biotic and abiotic processes, soil microorganisms respond at different rates, which in turn through can lead to further vegetation changes.

These considerations highlight that various processes can occur in short periods of time, while others can take much longer times. Even when considering population dynamics only, species with relatively short life spans may complete several generations in a couple of decades, while species with long life spans may have not completed a single generation turnover in the 100 years of the project. Indeed, *Atriplex vesicaria*, with a life span of ca. 30 years may have have some 3 or four population turnovers. On the other hand species like *A. aneura* or *M. platycarpum*, with life spans of 150-250 years have not completed a single generation turn over. Thus, while for short lived species this project can be considered a long term study, for the later mentioned species this 100 year is a short term study documenting mortality of old individuals present at the site when the reserve was established, and establishment and recruitment of new individuals in episodic events, providing a simple snapshot of how the populations change. A corollary of this is that defining long term ecological studies require explicit identification of the variables of interest, and the identification of relevant time scales. Potentially, sampling intervals could also be defined in the same study at various intervals for the different variables.

Thus, in view of the importance of long lived trees in modulating the function of ecological systems, the required long time for changes to eventuate in rangelands, and the urgent need for better understanding of the effects of climate changes, we conclude that the Koonamore Project should be continued for at least another 100 years. Achieve this will not be easy, as several issues difficult the continuity of LTERs, Under most granting programs obtaining funds for this type of project is not feasible, so alternative sources of funding must be achieved (through establishment of specific funds to support the project via fund raising bequests, etc.). Secondly, the leading of such project do not always get the recognition they deserve, both at the institutional and global academic level. Finally, it is often difficult to ensure continuity requires academic succession planning. Given the importance of this type of studies there should be enough incentive to overcome these obstacles.

Acknowledgements
Ove the century of the project numerous volunteers have contributed enormously to the continuation of this project. Particularly we thank undergrad and graduate students of the Departments of Botany, Environmental Biology and Ecology and Evolution (this reflects organizational changes over time). The School of Biological Sciences of the University of Adelaide has supported the project, as have the Rasheed family, in charge of Koonamore station, where the project is located.

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What limits seed-based restoration: seeding methods or environmental constraints?

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Key words: seed-based restoration; seedling survival; seed pelleting; soil moisture

Abstract
Drylands worldwide face severe degradation, requiring restoration efforts that often rely on native plant species. However, the small seed size of some species poses challenges for conventional seeding machinery. In Western Australia, the "Comm Veg" seeder is commonly used, creating furrows to improve seedling establishment.

To address limitations in seed distribution and sowing speed, seed pelleting technology was explored to increase seed size, enabling the use of a crop seeder (Aitchison). A field experiment in Eganu, WA (July 2024), compared seedling emergence and survival of four native species (*Eucalyptus oldfieldii, Melaleuca cordata, Eremaea pauciflora*, and *Acacia pulchella*) sown as bare seeds using the Comm Veg and as pelleted seeds using the crop seeder. Seedling emergence was measured in early (September) and mid-spring (November). A glasshouse experiment assessed germination rates of bare versus pelleted seeds.

Glasshouse results showed similar germination rates for bare and pelleted seeds across species. In the field, seedling emergence was higher with the Comm Veg seeder, likely due to greater soil moisture storage in the deep soil layer (7–15 cm) in furrowed areas. Alive *Acacia* seedlings exhibited significantly longer roots than dying seedlings, indicating deeper moisture access. However, seedling mortality was high for all species by mid-spring (<2% survival), likely due to late sowing and frequent droughts. Although crop seeder showed lower effectiveness in conserving soil moisture and supporting seedling survival, integrating agricultural machinery with seed pelleting technology remains promising for cost-effective, large-scale restoration. Refining sowing techniques and pelleting methods is essential to improve restoration success in degraded drylands.

Introduction

Drylands worldwide face severe disturbances from grazing, land-use changes, fire, and drought. Vast areas with low plant productivity making large-scale restoration in drylands costly and challenging. Direct seeding of native plants is widely regarded as a cost-effective and essential approach for large-scale restoration (Merritt and Dixon, 2011). However, less than 10% of seeds typically establish successfully due to various edaphic and biotic constraints (Ceccon et al., 2016). Additionally, handling and precision seeding of multispecies mixes with diverse seed sizes and shapes present logistical challenges, requiring specialized equipment and often resulting in low seedling establishment rates (Masarei et al., 2019).

In Western Australia, the "Comm Veg" seeder is commonly used for creating furrows during seeding. While effective, this approach could be enhanced with improved seed distribution and faster sowing speeds. Adapting agricultural machinery capable of sowing seeds over large areas at higher speeds and precise soil depths could benefit large-scale restoration efforts. However, the extremely small seed size of many native plants, such as gum trees, poses a significant challenge for using conventional crop seeders.

Seed enhancement technologies, initially developed for precision seeding in agriculture and horticulture, are increasingly being applied to ecological restoration (Madsen et al., 2016). One such technique, pelleting, involves adding materials to seeds to create an oval or spherical shape, making the original seed shape indiscernible (Pedrini et al., 2020). This process increases propagule size, enabling their use with agricultural machinery.

Effective restoration requires deep ecological knowledge to create restoration niches that support seed germination and seedling establishment, emphasizing the need for cost-effective, ecologically sound, and scalable methods. This research aimed to compare the effectiveness of two seed-based restoration methods: sowing bare seeds using the commonly used Comm Veg machine and sowing pelleted seeds of the same species with a crop seeder (Atchison). We hypothesized that the crop seeder would provide more precise seed distribution, while the slower-moving Comm Veg machine, which creates furrows, would offer more favourable recruitment restoration niches for seed germination and seedling establishment.

Methods

We tested seedling emergence and survival of four native plant species and a mixed-species treatment, comparing bare and pelleted seeds sown using two different seeder machines . The species included *Eucalyptus oldfieldii*, *Melaleuca cordata*, *Eremaea pauciflora*, and *Acacia pulchella* var. *pulchella* (DBCA 2024) (henceforth we refer to them using their genus names). Seeds of all species were pelleted using azomite as the coating medium and polyvinyl alcohol (PVOH, 8% solution) as the binder (Pedrini et al., 2020), resulting in pellets with a diameter of 1.5–2 mm, similar to canola seeds.

Bare seeds were mixed with perlite and sown using a Comm Veg direct seeder (North Stirling Pallinup Natural Resources). This seeder, designed for restoration applications in Western Australia, allows simultaneous sowing of fine and coarse seeds in four separate rows, while creating deep furrows to enhance rainwater catchment. Pelleted seeds were sown using an Aitchison drill seeder (Aitchison Seed Drills, New Zealand). This machine is optimized for sowing varying size crop seeds.

Seed sowing was conducted from July 22–24, 2024. Seedling emergence and survival were assessed 60 days after sowing (September 20, 2024) and 103 days after sowing (November 5, 2024). The final rainy week of the season occurred in early September, placing the assessments approximately three weeks and two months into the dry season, respectively. Soil moisture was measured by collecting soil samples from two depths: 0–5 cm (topsoil) and 7-15 cm (subsoil). Additionally, morphological growth parameters, including root and shoot biomass, seedling height, and maximum root distribution, were measured for six *Acacia pulchella* seedlings (both alive and dead).

The experiment followed a completely randomized block design with two seeding types (bare and pelleted) and four plant species as the main factors. Each seeding type was replicated in blocks, with each block containing five rows randomly assigned to one of the four species or a mixed-species treatment. This design resulted in 30 experimental units, encompassing two sowing types, five plant treatments, and three replicates. In a glasshouse experiment, seeds of the same species were sown as either bare or pelleted, and their emergence and survival were monitored over 45 days. This allowed us to confirm that observed differences in emergence between plant species in the field were attributable to factors other than seed pelleting and dormancy.

Results

Seedling emergence and survival in glasshouse

The glasshouse experiment showed species-specific differences in seedling emergence (Figure 1). *Acacia* (58%) and *Eremaea* (52%) had the highest emergence rates for bare seeds, while *Eucalyptus* (44%) and *Melaleuca* (23%) had lower rates. Pelleting reduced emergence in *Melaleuca* (8%) and *Eremaea* (29%) but did not affect *Eucalyptus* or *Acacia*. Seedling survival from day 20 to 45 was similar for both pelleted and bare seeds.

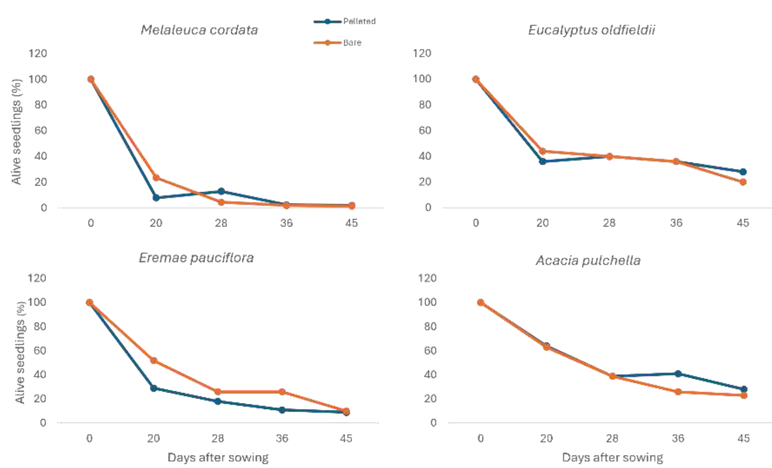

Figure 1: Seedling emergence and survival of four native species sown as bare or pelleted seeds under glasshouse conditions, means were compared by Tukey test at P<0.05).

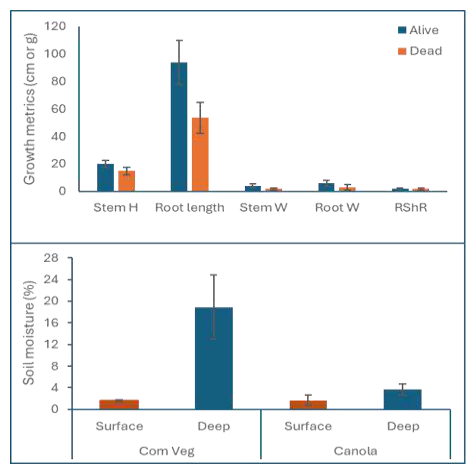

Figure 2: Comparison of growth metrics for Acacia seedlings (top) and soil moisture content across different seeding methods and soil depths (bottom), means were compared by Tukey test at P<0.05).

Soil moisture and growth metrics

Living acacia seedlings had root lengths approximately twice as long as those of dead seedlings, although their stem height and stem and shoot weights were similar. Soil moisture in the deeper soil layer (7-15 cm) was significantly higher in furrows created by the Comm Veg method compared to those created by the crop seeder, while no difference was observed in the topsoil layer (0–5 cm) between the treatments (Figure 2).

Seedling emergence and survival in field

For three of the four species (*Acacia*, *Eremae*, and *Melaleuca*), early seed emergence was significantly higher under the Comm Veg treatment, which used bare seeds sown in deep furrows, compared to the crop seeder treatment, which used pelleted seeds sown at the soil surface. In contrast, early seedling emergence for *Eucalyptus* was extremely low (<5%), with no clear difference between the methods. All species experienced severe mortality as drought intensified by mid-spring, with no difference in survival between the Comm Veg and crop seeder treatments.

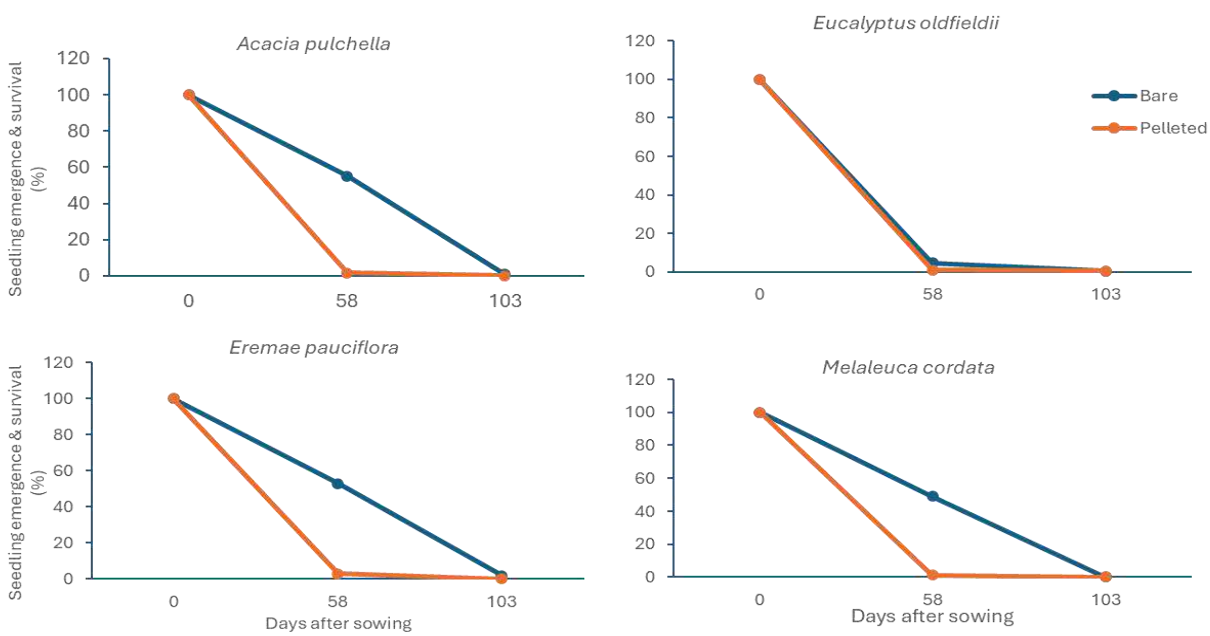

Figure 3: Seedling emergence and survival of native plant species sown as bare seeds in furrows using the Comm Veg method or as pelleted seeds using a crop seeder.

Discussion

Seed-based revegetation is widely regarded as a cost-effective and scalable solution for dryland restoration. Pelleting seeds into larger sizes offers the advantage of enabling the use of more sophisticated agricultural machinery in dryland restoration However, the results of this short-term trial highlight the pivotal role of major environmental factors—such as rainfall, soil moisture availability, and soil properties—in determining the success of restoration efforts. Late sowing and an unexpected 20-day drought in early September worsened moisture stress and led seedling mortality that was intensified by mid-summer.

Our glasshouse experiment corroborates previous studies (e.g., Pedrini et al., 2020) showing that seed germination rates were generally similar between pelleted and bare seeds. Therefore, the reduced seedling emergence observed in the field suggests that other factors, such as mechanical sowing methods, may have contributed to this outcome.

Field results demonstrated significant soil moisture retention in the deep soil layers of treatments using the Comm Veg machine, which creates deep furrows for seed placement. These furrows facilitated better moisture storage, which proved critical for seedling survival, especially under drought conditions. Morphological analysis showed that *Acacia* seedlings with longer root systems had a distinct advantage in accessing stored soil moisture within these furrows. This suggests that Comm Veg furrows, combined with the inherent root growth characteristics of *Acacia* species, enhance plant survival in water-limited environments.

In conclusion, our findings emphasize the critical importance of soil moisture storage around the root zone for seedling survival during dry seasons. Sowing techniques and timings that promote root elongation toward available moisture in the deep soil layers can significantly enhance seedling survival during dry seasons. While this small-scale trial indicated lower effectiveness of crop seeders in conserving soil moisture and improving seedling survival, the integration of agricultural machinery with seed pelleting technology remains a promising avenue for cost-effective, large-scale restoration. Further research and development on optimizing sowing techniques and machinery adjustments are warranted to enhance the efficiency and reliability of these methods.

Acknowledgements
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Insights into spinifex (*Triodia* species) pastures and their management

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Key words: interviews; hummock; livestock; fire

Abstract

Interviews about various aspects of spinifex pastures were conducted with 21 pastoralists, five Traditional Owners, and seven rangeland scientists from the Pilbara, Kimberley, and central Australia regions. Interviews sought to provide insights into spinifex pastures and covered topics such as plant identification, burning, grazing systems, tree/grass balance and Indigenous uses of spinifex and burning practices; knowledge gaps were also identified.

The interviews made it clear that fire plays a significant role in spinifex pastures and is frequently used to enhance grazing productivity by removing old or moribund spinifex and allowing palatable new growth to replace it. Additionally, fire is used as a tool for wildfire mitigation by creating different-aged fire scars and subsequent variations in fuel levels across the landscape. The amount of non-spinifex material in the diet of grazing animals was also commonly discussed where, after rain, cattle primarily grazed on a non-spinifex diet by selecting the soft fresh growth of annual and perennial grasses and forbs where available.

At the conclusion of each interview, interviewees were asked what additional information they would like regarding spinifex pastures and their management. The most common request was for accurate identification of spinifex species. Interviewees also wanted more information on the nutritional value of spinifex seed heads and leaves; specifically, how nutrient content and digestibility change throughout the year and between fire intervals. Additionally, they expressed interest in comprehensive information on various aspects of spinifex biology, including growth habits, reproduction, response to fire, and the formation of spinifex rings.

Introduction

Spinifex is the common name for a group of native perennial grasses (*Triodia* species) that are found in all Australian mainland states (Australian Virtual Herbarium 2024) and cover more than 25% of the Australian continent (Allan *et al.* 2002). Spinifex plants grow predominantly on soils with low nutrient levels and low water-holding capacity. The genus *Triodia* consists of 65 species, all of which are endemic to Australia (Australian National Botanic Gardens 2024). A notable feature of many *Triodia* species is their ability to form a ring. A hummock is formed as the plant expands outwards via above-ground stolons. At some point the central growth may die and disappear leaving a distinctive ring surrounding a bare area.

Although spinifex covers a significant proportion of Australia (Fig. 1), there is limited readily available information on spinifex plants or the management of spinifex pastures in a pastoral context. The purpose of the interviews was to consolidate the collective knowledge on spinifex pastures and make this information available to land managers, pastoralists, Traditional Owners, extension officers, researchers and other interested stakeholders.

Methods

A total of 33 interviews were completed in April and May 2024; 21 with pastoralists, five with Traditional Owners, and seven with rangeland scientists. Due to the large distances and time constraints, all central Australian and rangeland scientist interviews were conducted by phone. Pastoral and rangeland scientist interviewees were asked a standard list of questions. In a small number of cases, interviewees chose not to respond to certain sections because of time constraints or their perceived lack of qualification. Of the five Traditional Owners interviewed, two were asked all interview questions, while the other three focused only on the aspects of spinifex and fire as relevant to Traditional Owners.

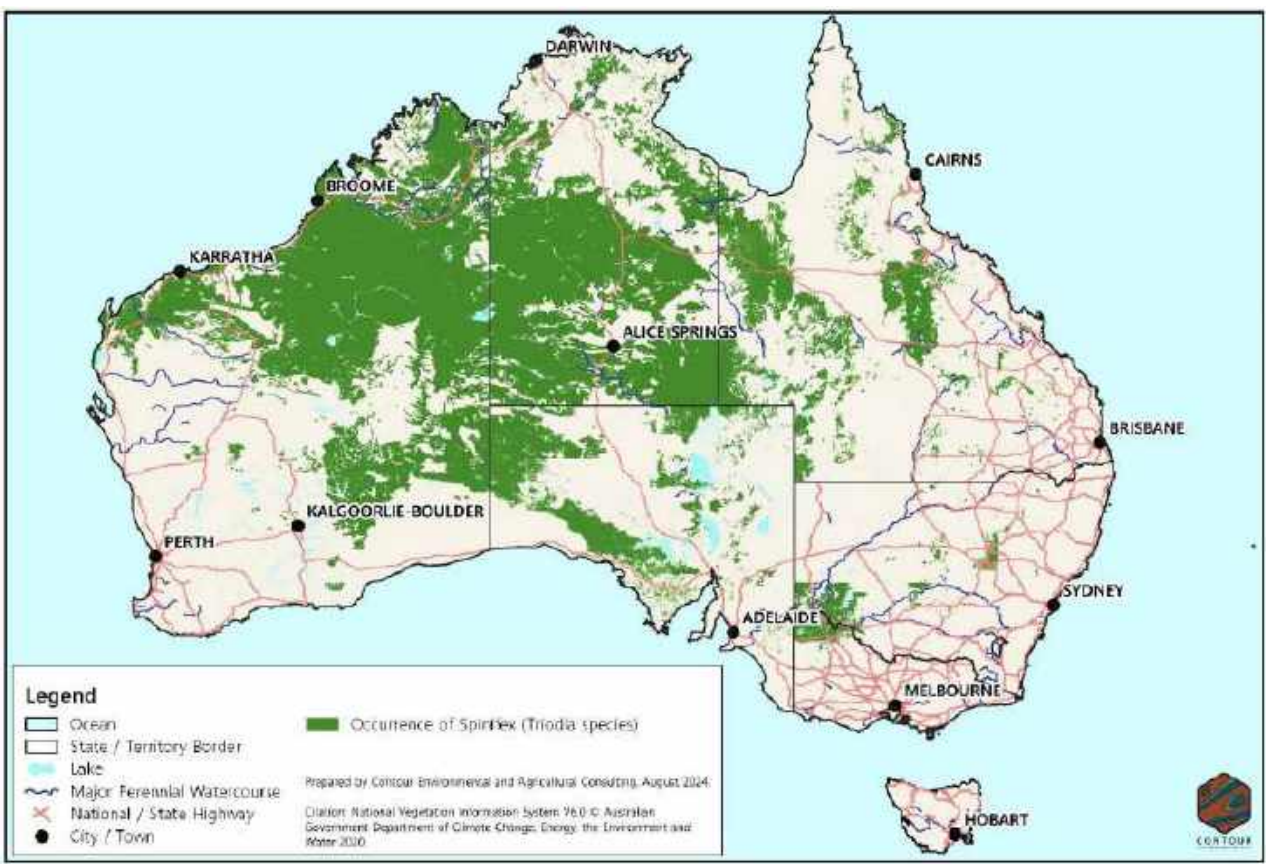

Fig. 1. Occurrence of spinifex (*Triodia* species) in Australia.

Results and Discussion

Interviewees generally referred to spinifex as being either hard or soft. Hard spinifexes included *Triodia basedowii*, *T. intermedia*, *T. irritans*, *T. secunda* and *T. wiseana* and soft spinifexes included *T. epactia*, *T. pungens* and *T. schinzii*. Hard spinifex foliage was generally considered unattractive to livestock at all stages of growth. In contrast, soft spinifex foliage is grazed by livestock and remains palatable for 3–4 years after fire, after which the feed quality deteriorates.

Spinifex and fire

Most of the interviewees preferred cool fires and emphasised the need for adequate soil moisture prior to burning. Burning after rain, when the soil and spinifex are well hydrated, is desirable because fire intensity is reduced. Importantly, pre-existing soil moisture also enables rapid regrowth of spinifex and any other perennial grasses that have not been killed by fire, typically within a week or two. Humidity was another key requirement for a cool fire. With high humidity, the fuel (particularly of cured pasture plants) absorbs moisture from the air. This increased moisture content renders the plant more difficult to ignite and slows down the rate at which it will burn. Consequently, fire intensity and its rate of spread is reduced.

In general, interviewees emphasised that they do not deliberately ignite hot fires; however, they often encountered them as a result of lightning strikes or unauthorised fires. Hot fires were typically associated with east/southeast winds, low humidity, dry fuel, and high temperatures from September to December and throughout the summer until sufficient rainfall has occurred. Many interviewees made efforts to avoid hot fires because areas affected by hot fires often take years to recover. The effectiveness of hot fires in killing spinifex, shrubs, and trees was frequently discussed.

The primary tool utilised for wildfire mitigation in spinifex is mosaic/patch burning. Creating variation in fuel levels through different-aged fire scars is considered the most effective method for mitigating wildfires. Not only does this practice minimise the risk of wildfires, it also rejuvenates the spinifex pastures by replacing old, dense spinifex with new growth. Essentially, to prevent wildfires, one must 'combat fire with fire'.

Spinifex and grazing

Cattle congregate on burnt areas. The early growth is nutritious but not abundant, so cattle also need access to other bulk feed. Getting the proportions right around how much to burn or not burn is crucial. Burning areas that are too small can lead to excessive localised grazing, while burning too much can deplete feed reserves and affect areas that should be reserved for burning in following years.

There are more annual grasses and forbs present 1–3 years after fire compared with longer time frames of four or more years, and it seems the presence or absence of these species significantly influences productivity. Similarly, young spinifex plants aged 1–3 years contain a higher concentration of nutrients compared to older plants, aged four or more years. Additionally, the leaves are more digestible when actively growing than when dormant. Interviewees were aware of the benefits to animal performance provided by increased amounts of annual grasses and forbs and appreciated the importance of varying nutrient concentrations and digestibility of spinifex.

The practice of patch burning enables cattle to have access to spinifex at various stages of regeneration. This way, cattle may never need to graze pastures that are considered rank (4–6 years old), as there are always some available areas that have been burnt more recently (in the last 1–3 years). As a result, cattle may only graze areas of rank spinifex for a short time; grazing the seed heads for a couple of weeks each wet season.

Beef production

All pastoralists keep breeders in their spinifex country; mainly older cows that have had at least two calves. Where possible, weaners, steers, and heifers are moved onto the more productive buffel (Cenchrus spp.) and Mitchell grass (*Astrebla* spp.) pastures. Some interviewees can grow their cattle out on the more productive pastures of their lease, while others have farms in the agricultural areas of Western Australia, where all growing and sale cattle are transferred for finishing. A common response from those interviewed was that dry or spayed cows will fatten on spinifex, however wet cows or growing cattle will not.

Additional information needs

At the end of each session, interviewees were asked what further information they wanted on spinifex. While some were satisfied with their current knowledge, others had many unanswered questions. The most common areas of interest were spinifex identification, understanding nutrient mobilisation between rainfall and fire events, and a basic '101' introduction covering growth habits, reproduction, response to fire, and the formation of rings.

There was also interest in exploring whether non-spinifex species form the bulk of an animal's diet through faecal DNA sampling. Additionally, interviewees were keen to learn about cattle movement patterns across different aged fire scars and between seasons and the potential of high-density, short-duration grazing strategies to manage rank growth without relying on fire.

Conclusion

This work provides insights into spinifex pastures and their management and is based on 33 interviews with experienced practitioners from the Pilbara, Kimberley and central Australia.

Notably, fire plays a significant role in spinifex pastures and is frequently used to enhance grazing productivity by removing old or moribund spinifex and allowing palatable new growth to replace it. Additionally, fire is used as a tool for wildfire mitigation by creating different-aged fire scars and subsequent variations in fuel levels across the landscape.

The amount of non-spinifex material in the diet of grazing animals was a commonly discussed topic. Interviewees reported stock preferences for available annual and perennial grasses and forbs as well as browse species – predominantly wattles.

Many of the interviewees would like more information on spinifex identification, and nutrient levels relative to time of year as well as time since fire. There was support for developing a '101' of spinifex dealing with spinifex biology, response to fire, and other plants found in spinifex pastures. Over the next 3–4 years, the Kimberley Pilbara Cattlemen's Association proposes to address identified knowledge gaps and produce a more comprehensive and in-depth document outlining spinifex ecology and best practices for managing spinifex pastures.

It is envisaged that this report will provide industry, industry bodies, and government agencies with information to guide future research, extension, and development activities to benefit all those working with spinifex pastures.

Acknowledgements

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A book on the rangelands of Libya

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Key words: Agricultural systems; steppe; desertification; rehabilitation

Abstract

Our book cut across all aspects of arid Libyan rangelands. It addresses climate – bioclimates with statistical analysis on climate change trends and droughts recurrences, geomorphology and landforms, soils, vegetation types and landscapes, rangeland production and stocking rates, livestock systems, traditional rainfed barley cropping and Australian ley-farming implemented on large scale, common water use and valorisation by water harvesting and flood farming, forest - afforestation and charcoal manufacturing, past and present wildlife, historical tribal rangeland use, degradation and desertification, restoration and rehabilitation techniques applied to large areas all over northern Libya from passive rangeland protection to fodder shrubs /trees plantations, and agro-ecological zoning to identify land capability and suitability for rainfed barley and olive trees without encroaching current land use.

Our monograph is unique and without equivalent from Morocco to Mongolia. It is relevant to the challenges affecting the arid rangelands of North Africa, the Middle East and Central Asia. It explains the transition from subsistence arid rangeland systems to current trends in livestock feeding with imported and subsidized feed stimulating rangeland degradation and desertification. We explain rangeland degradation and recovery, and agro-ecological zoning using the most up-to-date remote sensing and GIS techniques. It covers arid rangeland rehabilitation and afforestation projects with appropriate plant material, operations unfortunately failing most time due to lack of rangeland communities' involvement.

Our Libyan book is abundantly illustrated with 759 photos including 561 photos of 220 plants with their description and pastoral use, 48 figures, 37 tables and 35 original maps. The bibliography covers Mediterranean arid zones publications with some 630 references in English, French, Arabic, and Latin.

We expect that our book will encourage pastoralists colleagues, decision makers and politicians of North Africa, the Middle East and Central Asia to act wisely before it is too late.

The Libyan Rangelands Under Siege

The Libyan rangelands, inhabited by nomads and livestock, are facing significant challenges from land clearing, hazardous rainfed cropping, unsustainable irrigation projects, expanding human and livestock populations, urbanization, and modernity, particularly in the 100-500 mm rainfall zones, leading to degradation and desertification (Fig. 1).

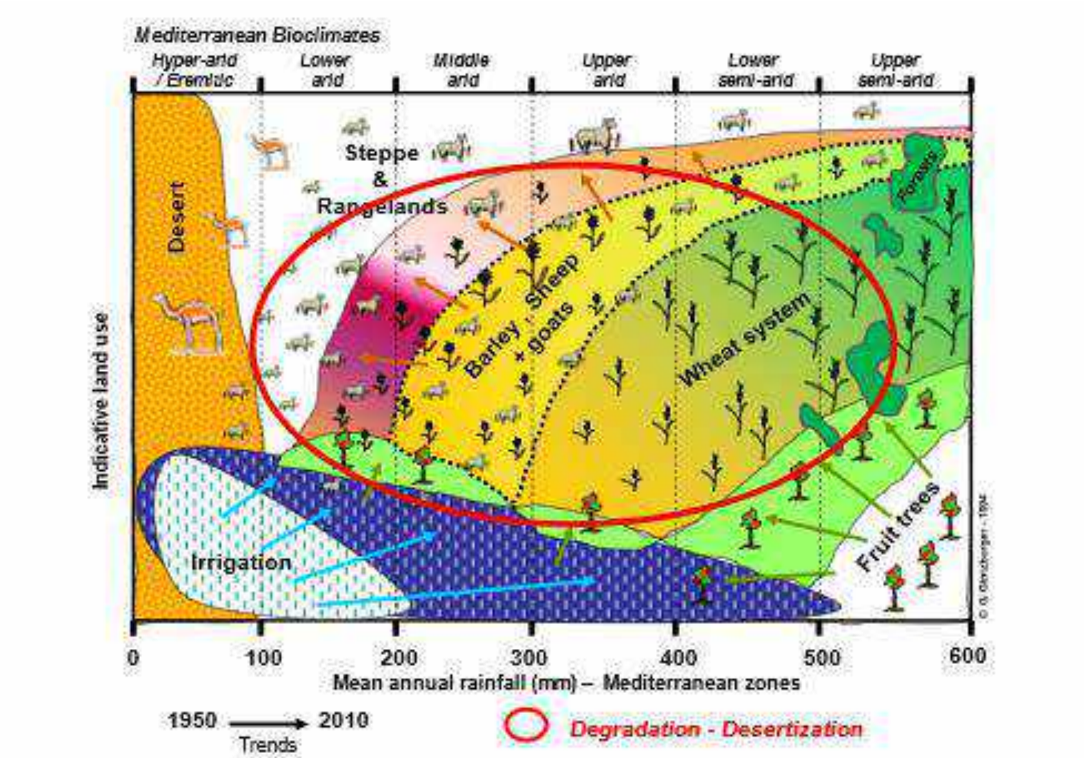

Fig. 1. Land use trends in West Asia and North Africa (Gintzburger, 1996)

Climate, Bioclimates And Droughts

Our study analyses Libyan climatic data from 1945 to 2010, revealing differences in spring rainfall between the northwest and northeast regions and rainfall variability. It examines climatic factors affecting native vegetation and rainfed cropping. Libya was not immune from long-past climatic oscillations, with evidence from paleoclimatology and archaeology.

Geomorphology And Landforms

Geomorphology is crucial for understanding arid zones' ecology and vegetation distribution. Northern Libya is dominated by Cretaceous limestone altered over millions of years. The Sirte region results from long-past marine transgressions. Quaternary terraces, saline coastal endoreic depressions, thick loess deposits, and sand deposits are common features. Wind and water erosion, along with land clearing and overgrazing, continue to alter and chisel landforms and soils.

The Libyan Soils

Based on research in southern Tunisia, we identify and classify the main Libyan soils based on the topsoil and upper horizons supporting native vegetation. Our soil description and classifications remain easily accessible to rangeland ecologists and land developers. It provides for easy soil interpretation and identification from vegetation type, ecological group, plant association, or presence of specific indicator plants. We produced a synthetic soil map of Northern Libya based on our classification and field experience.

The Vegetation Types
Libyan landscapes are shaped by geology and geomorphology, resulting in various vegetation types, and ecological groups modelled by climate, soil types, and land use, creating specific plant associations altered by land use and grazing pressure. Vegetation surveys require detailed phyto-sociological studies necessitating a deep understanding of environmental parameters and plant taxonomy. It necessitates incessant field trips and surveys, herbarium collection and accurate plant identification, complemented with local knowledge collected from shepherds and farmers.

The Most Common Libyan Rangeland Plants
We illustrate 262 plants from 51 families commonly found on Libyan rangelands with their scientific and vernacular names, life form, description and morphology, reproduction, pastoral importance, palatability and fodder value, toxicity, economic interest, habitat, distribution, and endemism.

From Rangeland Vegetation Standing Biomass To Stocking Rates
Sustainable rangeland management necessitates biomass field measurements, Rain-Use-Efficiency evaluation, satellite imagery processing and GIS. However, grazing decisions based on western concepts of carrying capacity and stocking rates are not suitable for shepherding in arid zones due to logistical constraints, water availability, flock management, and land tenure issues.

The Rainfed Ley-Farming System On Rangelands In Western Libya
The Australian ley-farming system, implemented from 1973 to 1984 on 50,000 hectares of Western Libyan rangelands, improved rainfed cereal yield and sheep production compared to the traditional system as long as annual rainfall was about 250-275mm. However, the Australian system was difficult to manage due to low erratic rainfall and required constant Australian expertise and Libyan colleagues' training. The technology transfer to private farmers failed due to lack of community participation, small farm size, and complexity of the input system. It was abandoned for more profitable irrigated vegetable and fruit tree production or reverting to free rangeland grazing.

Livestock On Libyan Rangelands
For centuries, Libyan rangelands have been home to herded small ruminants and dromedaries supported by native vegetation and scanty water resources, both limiting livestock numbers. Droughts would occasionally reduce their numbers, taking years to restock. Today, degraded Libyan rangelands are not producing the necessary feed to sustain rocketing livestock numbers. Feed and barley grain production are insufficient despite expanding rainfed cropping targeting the best rangelands. Livestock are now mostly artificially fed under open-air feedlots using subsidised imported barley grain. With overstocking causing desertification, it also stimulates the spread of infectious diseases barely controlled. The livestock situation is dire and cannot be solely attributed to climate change.

Water On Rangelands
Water availability is vital for arid rangelands communities. Since antiquity, they dug shallow wells, built cisterns and developed efficient water harvesting and flood farming. Widely spaced watering facilities was the norm up to the end of WWII, but perceived as a limitation to modern rangelands management, hence uncontrolled implementation of legal and illegal wells and cisterns. Modern drilling and pumping stations accessing deep aquifers with hauling water to the most remote rangelands accelerated rangeland degradation. Without strict control and policing water resources, Libyan rangelands will be totally degraded, leading livestock to be exclusively fed on stationary open-air feedlots.

Tribes And Territories

Berber and Arab Libyan tribes managed their rangelands despite endless battles, invasions and colonisations, fiercely defending and controlling their territories. Each tribal territory covers a diversity of landscapes and rainfall zones allowing for balanced resources and sustainable land management. Tribal rules about territory and shared resources are reviewed with examples from the West, Sirte and the East extending deep into the southern desert. With the discovery of oil reserves by 1959, the Libyan tribal system and economy gradually evolved, leading impoverished nomads and semi-nomads to quit the rangelands for financially secure but humble employment. Yet, the *esprit de corps*, traditions and rules within and between tribes remains strong to these days. The weaving art composing the elements of the customary bedouin tent is portrayed as steadily disappearing.

Forests, Afforestation, Fuelwood And Charcoal

Libya still benefits from a wealth native trees and shrubs. The use of fuelwood and charcoal is a part of Libyan culture. Native forests, woody shrubs, and afforestation are relentlessly threatened from illegal logging and charcoal manufacturing. Current forestry and rangelands legislations are inefficient. Without policing, accurate mapping and monitoring, fuelwood resources will continue to be plundered. Alternatives to fuelwood harvesting and charcoal manufacturing are reviewed. Afforestation projects must be encouraged using native and appropriate exotic species. Without immediate actions to remedy illegal logging and charcoal manufacturing, Libya will soon see its native forests, exceptionally drought resistant trees, and forestry plantations decline, widening already rampant rangeland desertification.

Past And Present Wildlife On Libyan Rangelands

Wildlife is an essential element of rangelands and forests, and a sign of good health of the ecosystems. These days, in Libya, even in the most desert remote areas, native herbivores, carnivores and birds are mercilessly hunted. Hunting, not anymore a vital necessity, is replaced with indiscriminate illegal sport hunting leading to wildlife massacres. We review, describe and illustrate the Libyan wildlife from prehistoric to modern time.

Assessing Rangeland Recovery, Degradation And Desertification

Rangeland bio-physical recovery, degradation or desertification are azonal and affect all arid Libyan rangelands. The anthropogenic reasons are well known with climatic high variability and possible climate changes. We review the methods and tools to assess rangeland health from simple site- and date-specific measurements to the most advanced complex satellite imagery time-series processing allowing monitoring and mapping trends over large areas. Rangeland degradation, often over emphasised in media, is not inescapable as many examples confirm rangeland recovery. Libyan rangeland managers, decision makers and scientists could benefit from these technologies to accurately identify, locate rangelands recovering and prioritise treatments of degraded areas under threat of desertification.

Recovery, Restoration And Rehabilitation Of Degraded Rangeland

Rangeland rehabilitation techniques were implemented on tens of thousands of hectares in Northern Libya. Rangeland passive protection and deferred grazing remain the cheapest and most efficient techniques well accepted by shepherds. Active means of rehabilitation, such multipurpose shrub plantations combined with water harvesting techniques and phosphate fertilization may be necessary. Reseeding with native rangeland species remains to be explored, especially with annual *Medicago* sp. (Medics) pods. Reallocating the best rangelands to fodder shrubs plantations is labour-intensive, and expensive, and is neither valued nor accepted by rangeland communities. Rangeland protection, multipurpose shrubs plantations, reseeding, low-cost water harvesting techniques, and minimal fertilisation produced satisfactory technical results on Libyan rangelands. They remain doomed unless supported by local communities.

Agro-Ecological Zoning Of Libya: The Case Of Barley And Olive Tree

Considering the barley grain deficit and current plans to expand olive tree production, is there some agricultural land still available for rainfed farming in Libya ? We developed an agro-ecological zoning methodology based on algorithms and GIS mapping filtering limiting climatic, soils, and barley and olive tree agro-ecological and agro-biological factors. We produced maps of western and eastern Libya excluding current land use and accurately locating suitable land for the two crops. The methodology could be improved providing up-dated land use map and refined limiting factors. Cropping, planting new trees on additional suitable land would have to remain with identified communities, property rights and traditional laws.

Overall Conclusions

Despite their apparent monotony, the Libyan rangelands are ecologically extremely diverse due to a rich geology and climate shaping landscapes supporting various soil types, in turn defining plants associations. For centuries, plant associations provided free feed and wildlife resources to rangeland communities. There was a fragile equilibrium between resources and demand. This equilibrium, often broken by droughts or unrest, tilted towards creeping land degradation past WWII and accelerated by 1970 with the oil discovery, increasing human and livestock population, wealth and urbanisation. The Libyan rangelands are these days in a crisis, unable to sustain the current livestock numbers. This is unsustainable without importing vast quantity of complementary subsidized feed, illegally drilling wells and constructing countless new watering places, all contributing to more rangeland desertification. The culprit is not climate change, but simply the man.

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Grassland restoration in the face of invasive species: A British Columbia, Canada case study

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Key words: invasive species management; spotted knapweed; grassland restoration; temperate grasslands

Abstract

The preservation and ecological integrity of temperate grasslands globally are under threat, making the effective control of invasive species crucial. The spread of spotted knapweed (*Centaurea stoebe,* spp. *Micranthos*) endangers native plant biodiversity and the functioning of grassland ecosystems in British Columbia, Canada, where temperate grasslands cover less than 1% of the province's total area but contain more than 30% of the province's threatened species. To combat this threat, a project was launched in 2022 on Red Hill within Lac du Bois, the second-largest protected grassland area in British Columbia, to test various knapweed treatments and evaluate grassland restoration success. This project employed a randomized block design to compare six treatments: a control, hand pulling, mowing using a weed whacker, spraying Milestone^{TM} (broadleaf selective herbicide with active ingredient aminopyralid) at high (0.5 l/ha) and low (0.29 L/ha) concentrations during the bolting (just prior to flowering) stage of knapweed, and spraying Milestone^{TM} in the fall at a high (0.5 L/ha) concentration. Percent cover data were collected and analyzed using a nonparametric Kruskal-Wallis test, with a post hoc pairwise comparison to further investigate differences between treatments. Variables examined included the cover of knapweed, bare ground, native and non-native forbs, native and non-native grasses, native shrubs, and species richness. Spray treatments proved highly effective in eliminating spotted knapweed, significantly decreasing both non-native and native forbs while increasing native grass cover. Hand pulling and mowing were less effective in reducing knapweed and had limited effect on native grass cover. These findings offer valuable insights for efforts to restore native grassland by managing invasive species. Ongoing data collection at this site will continue, making it an effective demonstration site for raising awareness about grassland restoration.

Introduction

Invasive plants pose significant threats to British Columbia's landscapes, particularly its native grasslands, which account for less than 1% of the province’s land area (GCC 2017). Lac du Bois, a protected area adjacent to Kamloops, is a vital grassland reserve but faces numerous threats, including recreation, overgrazing, climate change, and invasive species. Among these invasives, spotted knapweed (*Centaurea stoebe spp. micranthos*) is of major concern. Originally introduced from Europe in the 1890s, this aggressive plant spreads easily and forms monocultures that outcompete native species (Marrs et al. 2008), reducing biodiversity, forage availability and resulting in other negative impacts (Sheley et al. 2001, Tyser and Key 1988). Despite its protected status, Lac du Bois is at high risk of further knapweed invasion, exacerbated by disturbances like overgrazing and climate change.

Efforts to control spotted knapweed at Lac du Bois, specifically in the Red Hill Demonstration area, involve a range of methods, including herbicide, hand pulling, weed whacking, and seeding. Each technique has its own advantages and challenges, with herbicides being necessary for large infestations and hand-pulling effective for smaller ones. Integrating these control methods is essential for successful long-term management. Restoration is also key, with strategies focusing on reintroducing native plants and managing competition from weeds. The current project aims to compare six treatments, evaluating their effects on knapweed cover, native vegetation, and species richness in order to inform future management practices in the region.

Methods

The study was conducted in the Thompson-Pavilion grassland region, specifically at Red Hill in the Lac du Bois protected area. This region is influenced by a dry climate due to the rain shadow from coastal mountains, with cold winters and hot summers. Red Hill, located in the Bunchgrass Nicola Very Dry Warm (BG xw1) biogeoclimatic zone, represents middle grasslands with an elevational range of 700-1000 meters. Dominant plant species in this zone include bluebunch wheatgrass (*Pseudoroegneria spicata*), rough fescue (*Festuca campestris*), and flowering plants such as mariposa lily (*Calochortus macrocarpus*) and yarrow (*Achillea millefolium*). Red Hill is known for its distinct reddish soil and rocky terrain, and prior to protection, was heavily impacted by motorized vehicles. The area, which also serves as grazing land for cattle, has been the focus of various restoration efforts, including invasive plant removal and grassland enclosures to monitor recovery.

The experimental plots for the Red Hill project were established in the summer of 2022, and treatments were applied on June 27, 2022, with post-treatment data collected a year later. The study utilized a randomized block design, with the site divided into two sections to avoid previously seeded alfalfa strips. A total of 24 plots, each 7.5x7.5 meters, were used to compare six treatments: control (C), high-concentration (o.5 L/ha) Milestone™ herbicide during bolting (SH), low-concentration (0.29 L/ha) Milestone™ during bolting (SL), high-concentration (0.5 L/ha) Milestone™ in the fall (SF), hand pulling (HP), and mowing using a weed whacker (WW). Milestone™ has the active ingredient aminopyralid and is selective for broadleaf plants. Each plot was marked with fluorescent stakes and had a central 2x2-meter monitoring plot. Data collection included estimating percent canopy cover in categories such as grasses, forbs, shrubs, bare soil, and species richness was determined by counting different plant species within the plots.

Statistical analysis was conducted using a nonparametric Kruskal-Wallis test to assess whether the treatments had significant effects on the variables measured, including knapweed cover, bare ground, and native and non-native vegetation. Post hoc pairwise comparisons were used to analyze differences between treatments. The results were considered statistically significant if the p-value was less than 0.05, with SPSS used for all data analysis. Three replicates were used for most treatments, while hand-pulling and weed-whacking had six replicates each to assess treatment effectiveness.

Results

The results of the study indicated significant differences in knapweed cover across the various treatments ($p = 0.001$). Specifically, the spray treatments (high fall concentration, high bolting concentration, and low bolting concentration) successfully eliminated spotted knapweed, resulting in zero cover in those plots, as shown by the absence of error bars in the data (Figure 1a). In contrast, the hand pulling (HP) and weed whacking (WW) treatments did not produce a significant decrease in knapweed cover. The study also found differences in native grass cover among the treatments ($p = 0.026$), with the spray treatments demonstrating significantly higher native grass cover compared to the control, while HP and WW treatments did not yield significant changes in native grass cover (Figure 1b).

Additionally, the treatments impacted non-native and native forbs differently, with non-native forb cover showing significant reductions in the spray treatments (p = 0.008), including zero cover in the high bolting concentration. Although HP and WW treatments did not show a significant decrease in non-native forbs, they exhibited a higher mean cover of native forbs compared to the spray treatments (p = 0.004), albeit without significant differences from the control (Figure 1c). Species richness varied across treatments (p = 0.006), with spray treatments having lower species richness than the control, though not significantly different (Figure 1d). HP and WW treatments had higher species richness but also did not show significant differences from the control. Overall, the findings highlight the effectiveness of spray treatments in controlling knapweed and their implications for native plant recovery.

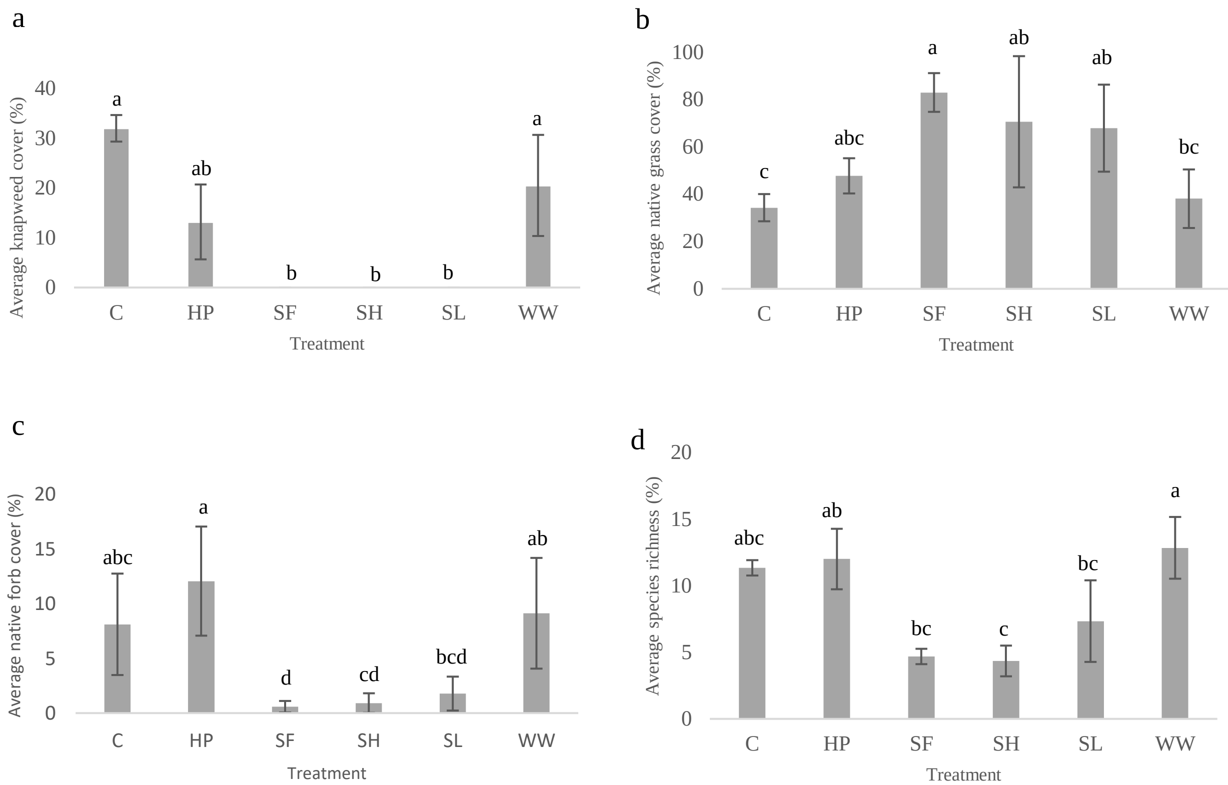

Figure 1. Mean percent cover in 2023 by treatment of a) spotted knapweed; b) native grass cover; c) native forb cover; and d) species richness. Treatments: control C, hand pull HP, spray Milestone™ high concentration fall SF, spray Milestone™ high concentration at bolt SH, spray Milestone™ low concentration at bolt SL and weed whack WW. Variables with different letters are significantly different ($p<0.05$) and error bars represent 1 standard deviation.

Discussion [Conclusions/Implications]

This study investigated the impact of various treatments on the management of invasive spotted knapweed and the subsequent recovery of native plant communities, focusing on bare soil cover, vegetation cover, species richness, and future management considerations. Findings revealed that the treatments resulted in low levels of exposed bare soil, all under 3%, aligning with reference conditions for grassland communities (Delesalle et al. 2009). While hand-pulling was expected to disturb the soil more than other methods, it did not significantly affect bare soil cover, allowing natural vegetation to recover over time. Overall, there was no excessive bare ground post-treatment, suggesting that the techniques employed did not lead to significant disturbance to the site.

In terms of vegetation cover, the herbicide Milestone™ proved to be the most effective treatment for controlling knapweed, achieving complete elimination in spray plots after a single application supporting the findings of Malone (2015) and Jacobs (2017). This treatment notably increased native grass cover to over 67%, a positive outcome in contrast to previous studies where herbicides led to increased non-native grass dominance (Skurski et al. 2013, Whitehouse 2021). Although the hand-pulling and weed-whacking methods did not demonstrate significant effectiveness in reducing knapweed density, they maintained a high cover of native forbs. The lack of notable changes in species richness across treatments suggests that while herbicide use facilitated native grass recovery, the overall species diversity remained stable.

The study acknowledges the limitations inherent in its design, such as the small number of replicates and the timing of treatments. The results indicate that in this specific setting Milestone™ herbicide can facilitate a return of native species without the need for additional seeding or restoration efforts, a promising result given concerns about invasive species dominance in similar contexts. However, it is important to emphasize the necessity of continued monitoring and treatment, particularly for hand-pulling and weed-whacking methods, which require repeated applications to be effective. Recommendations for future management include planting a native seed mix to promote biodiversity, investigating the introduction of biological control agents to complement existing treatment strategies, the application of treatments for at least two more years, the use of lower concentrations of Milestone™, and the development of a long-term monitoring plan to track the recovery of plant communities and the potential emergence of invasive species from the seed bank. Overall, the findings provide a solid foundation for enhancing grassland restoration efforts and addressing the challenges posed by invasive species like spotted knapweed.

Acknowledgements
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Native Pasture Restoration in the Kimberley Rangelands, Western Australia – Seed Production Areas

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Key words: seed; grass; revegetation

Abstract

The pastoral industry in the Kimberley region is an important economic contributor to Western Australia. However, as a result of past land management practices, there has been a decline of the more desirable native pasture grasses resulting in a loss of feed-base productivity. To reverse this decline, research is being conducted to help restore important native pasture grasses in this region.

In the Kimberley region, access to native grass seed for restoration is limited as wild-harvest is opportunistic, typically un-mechanised and ripe seed collection sites can be difficult to access during the wet season. Establishing a Seed Production Area (SPA) close to existing all weather roads will allow access to seed at the optimum harvesting time, and planting of single species on flat terrain will allow rapid and efficient collection of seed especially if using mechanical harvesters. Also, the use of fertiliser and irrigation could improve seed quality and increase seed production. This should improve the availability and reduce the cost of native grass seed for use in restoration of native grasses to degraded rangelands and mine-sites.

Six native grass species have been planted out on a small scale to trial a SPA located in Perth, Western Australia. Plants were fertilised and irrigated during summer. Plant growth and phenology were monitored and seed quality compared to wild-harvested seed. Irrigation extended the flowering period and hence seed production. Seed fill (a measure of seed viability) from the SPA was equal to or significantly greater than for wild-harvested seed. There was a trend towards increased seed yield and seed fill in the SPA when grasses were cut before summer re-growth, and with increased irrigation.

Introduction

The pastoral beef industry in the Kimberley region is an important economic contributor to Western Australia. The climate is tropical savanna, with hot wet summers (wet season) and dry winters (BOM 2024). Native grasses are the main forage resource for cattle (Chilcott *et al.* 2020), but the extremes of rainfall create seasonal patterns in forage quality. Extended periods of average and above average rainfall can encourage managers to increase livestock numbers. When seasons return to average or below average, these higher livestock numbers are often retained, which can result in overgrazing of preferred pasture plants, resulting in a loss of soil cover and therefore increased potential for degradation and a decline in productivity.

Seeding is one of the most used methods of restoring vegetation to degraded sites. Sourcing of seed for restoration largely relies on harvesting from wild plant populations (Neville *et al.* 2016). However, sourcing of seeds can be problematic, especially in remote areas like the Kimberley region of Western Australia. Access to seed is limited by a lack of suppliers and difficulty to access ripe seed after wet season rains due to road closures. The authors have noted after three years of seed collecting in the Kimberley, that seed ripening can be spatially and temporally heterogenous, requiring extensive resources and time to search large areas to find plants where seed has not dispersed or is ripe for collection. In addition, much of the rangelands are grazed or have experienced late wet season/early dry season burns reducing the available area for seed collection and requiring further travel. Also, seed collecting by foot can be hazardous especially on cracking-clay plains, where deep “crab holes” are concealed by long grass.

Establishing a Seed Production Area (SPA) close to existing all weather roads will allow access to seed at the optimum time, and planting of a single species on flat terrain will allow rapid and efficient collection of seed especially if using mechanical harvesters. Also, implementing horticultural practices like irrigation, the use of fertilizer and annual cutting of grasses could increase seed production and seed quality.

Methods

Wild seed was collected from a range of grass species growing on Napier Downs and Mt House Stations located in the Shire of Derby-West Kimberley in Western Australia during May, after the end of the wet season when road access was available. All six species chosen for this study (Table 1.) can be found growing in clay and/or loam soils with three species also found growing in sandy soils (Ryan et al. 2013).

Due to logistical and accessibility issues in setting up a SPA in the Kimberley, it was decided to trial a site at the University of Western Australia (UWA) research facility in Shenton Park, Perth. The soils are yellow-brown sands of the Spearwood dune system of the Swan Coastal Plain (McArthur and Bettenay 1960). The climate is subtropical, with a warm dry summer and cold wet winter (BOM 2024).

Tubestock was propagated from wild collected seed germinated in petri dishes and transplanted into tubes about 2-3 weeks after germination. Grasses were grown in a proprietary potting mix (supplied by Richgro, Jandakot, Western Australia) and in nursery conditions for 10 months before planting.

The SPA trial site at Shenton Park was established in late November 2022. The original planting comprised 206 plants consisting of five perennial and one annual grass (*Iseilema vaginiflorum*) species. In 2023, the trial was reduced to five perennial species of 176 plants (40 *Dichanthium fecundum*, 52 *Dichanthium sericeum*, 40 *Heteropogon contortus*, 18 *Panicum decompositum*, and 26 *Sehima nervosum*).

Each species was planted in separate plots. Within each plot, tubestock was planted in 3 rows 35 cm apart, with plants planted 40 cm apart in each row and offset with the adjacent row by 20 cm (6 plants/m^2). Fertiliser (Seamungus® by Neutrog) was added (1 handful) to the planting hole and mixed with soil before planting tubestock. All plants were hand watered for the first two weeks. Once established all plants were fertilised with NPK Blue (Cresco), one handful/m^2 on the 5 November 2023 and 26 February 2024. Overhead irrigation (approximately 30 minutes, 2-3 times/week) commenced 27th November 2023 with the volume applied doubling on the 20th of March 2024. To measure the effect of defoliation on future growth and seed production, approximately half of each perennial grass plot was cut (to a height of 10-15 cm) on the 11 September 2023. Seed was collected separately from cut and uncut sections of the plot every 1-2 weeks depending on the quantity of seed produced.

All seed harvesting, from the wild and SPA, was done by hand by lightly pulling at inflorescences to remove ripe florets and dropping into a bucket. Weights harvested are inclusive of florets for all grasses except for *P. decompositum* as seed readily fell out of florets during harvesting. Grass florets/seed were x-rayed to determine seed fill using a Faxitron Specimen Radiography System (MX-20 Cabinet X-ray Unit) (Faxitron, Wheeling, Illinois, USA).

Results

Wild seed was collected in May 2021, 2022, and 2023. While seed was found at Napier Downs every year, no or very little seed was found at Mount House in two of the three years. Seed collecting in the SPA commenced in February 2023 and seed was still being collected in June for *D. sericeum* and *S. nervosum*. While there was an extended period of seed production there was a peak of seed production in May for all species. Seed fill of grasses harvested in SPA was equal to or greater than wild-harvested seed (Table 1). In the SPA, seed yield and seed fill was greater when grasses were cut before summer growth. Also, following an increase in irrigation volume, seed yield increased by 3 to 50-fold and seed fill more than doubled for most species (Figures 1 and 2). There was an interaction between grass cutting and irrigation with the effect of cutting grass on seed yield and fill greater with low irrigation than high irrigation. For *H. contortus* there was no seed produced from uncut grass until after the irrigation volume was increased.

Table 1. Seed fill (%) of seed harvested from the wild (Wild) and the Seed Production Area (SPA) in Perth, (n = number of collections).

			Seed fill (%)			
Species	Common name	Soil type	SPA	n	Wild	n
Dichanthium fecundum	Bundle-Bundle	sand, loam, clay	12-51	5	12-39	3
Dichanthium sericeum	Blue grass	clay	48-87	5	43-63	3
Heteropogon contortus	Black Speargrass	sand, loam, clay	36-74	4	17-32	2
Iseilema vaginiflorum	Red Flinders grass	clay	32	1	21	1
Panicum decompositum	Native Millet	loam, clay	88-99	5	56-94	2
Sehima nervosum	White grass	sand, loam, clay	29-60	5	23-37	2

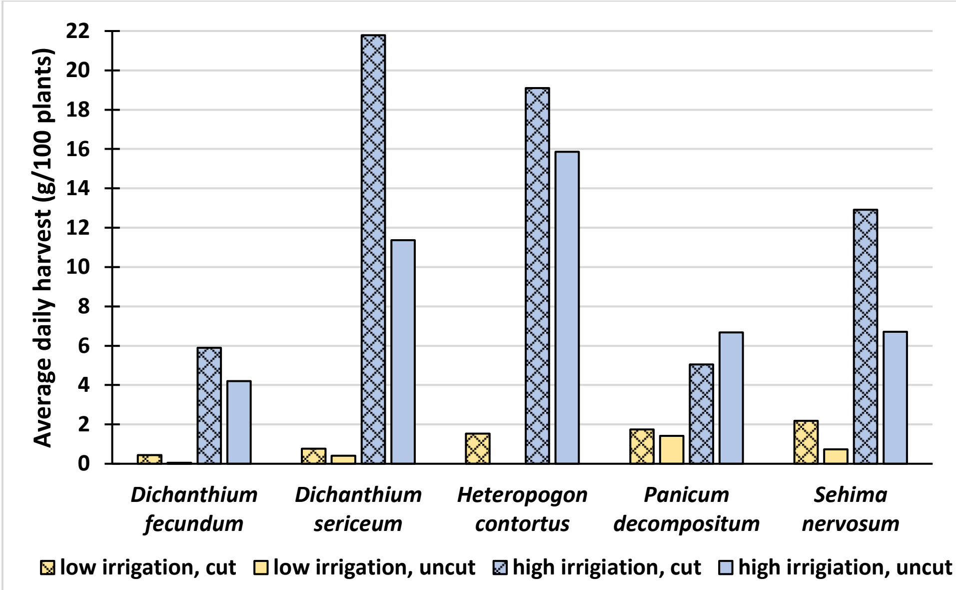

Figure 1. Average daily quantity of seed (g) collected from cut and uncut grasses grown in the SPA at Shenton Park, Perth before and after the increase in irrigation.

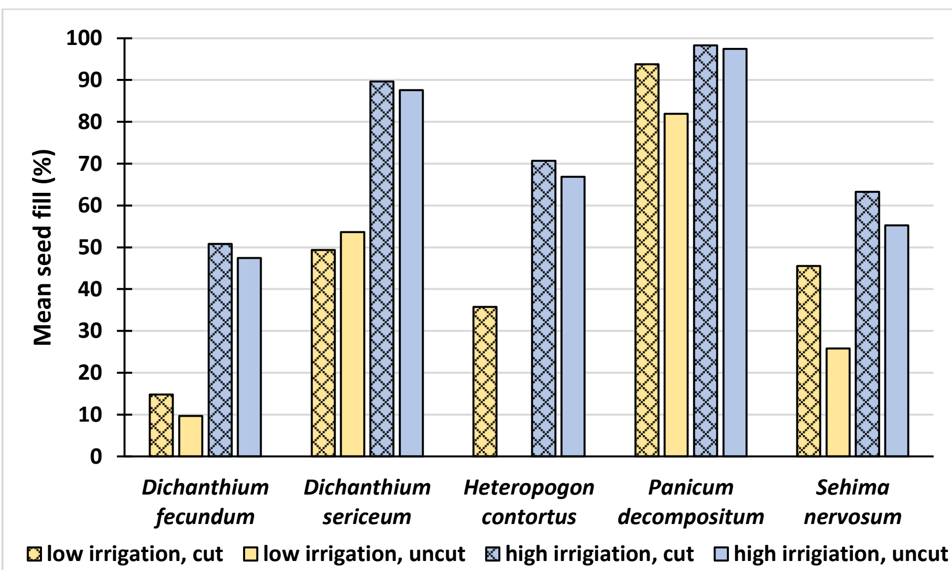

Figure 2. Mean seed fill (%) of seed collected from cut and uncut grasses grown in the SPA at Shenton Park, Perth before and after the increase in irrigation volume.

Discussion

This small-scale seed production area (SPA) in Perth demonstrated that the grass species trialled in this experiment can be successfully grown in climatic and soil conditions that differ to that of wild populations. Also, with irrigation and fertiliser, the SPA can produce larger quantities of viable seed by extending the period of flowering and hence seed production, and of higher quality (% seed fill) than seed collected from wild populations. Although the grasses were planted in soil and climate conditions quite different to wild populations, seed quality and productivity were not negatively impacted. The broad adaptability of these grasses to a range of site conditions, will enable the establishment of SPA close to population centres and infrastructure that will allow access to all weather roads, improve monitoring of plant growth and seed development, and allow the use of mechanized seed harvesting technology which will all lead to faster and more efficient harvesting of seed. We suggest the establishment of SPA is a feasible approach to improve the reliability of supply, quality of seed and potentially reduce the cost of supplying seed for use in restoring native pasture grasses in rangeland landscapes.

Acknowledgements
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Y Ranch squarrose knapweed control and pasture restoration

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Key words: Crested wheatgrass; AUM; Grazing; Forage; Livestock

Abstract
Almost half the total land area of the United States is used for pasture and grazing, and nearly all of it is infested with weeds (Monaco et al., 2002) Rangeland pastures worldwide are often invaded by various weed species (Vasques et al., 2010). These invasions cause significant biological (Christensen et al., 2011) and economic loss (Whitesides, 2004). In the Mountain West region of Utah, cheatgrass, knapweed, medusa head, and hoary cress are just a few of the numerous invaders. Even though weeds are a serious problem and are difficult to control, it is possible to manage weeds (Jones et al, 2010) and restore pasture health and productivity.

We undertook a pasture renovation project in 2012 at the Y Ranch in Tooele County and Juab County, Utah in the Great Basin Region of the western United States. Invasive weeds, primarily knapweed, had degraded Y Ranch pastures. We aerially sprayed herbicide to kill weeds in a 728-hectare pasture then later fertilized the pasture; we did no seeding. Two years later AUMs had increased by 200. We wanted to measure forage production after ten years of livestock grazing to see how many AUMs were currently available twelve years after the renovation.

A forage production sample taken in May 2024 showed 91 kg/ha. The primary forage species was Crested Wheatgrass, *Agropyron cristatum.* Although crested wheatgrass is an introduced species in the Great Basin, it has shown an ability to establish when and where other species struggle. This pasture currently provides 225 AUMs of grazing where before the treatment it provided virtually no AUMs.

Introduction
Many rangeland pastures are infested with weeds that reduce their usefulness and productivity. Livestock grazing and wildlife diversity and numbers are diminished when non-useable plant species dominate. Squarrose knapweed (Centaurea virgata ssp. squarrosa) is particularly troublesome as it is a long-lived, tap

rooted perennial (Whitson et al. 2006). It can often form dense stands that crowd out useful plant species. Mature plants are from 30 to 46 centimetres tall and are very rough and abrasive. Wildlife will avoid moving through impenetrable patches. Knapweed and other invasive weed species can be eliminated by using the right herbicide and with proper application timing. Pastures can be restored and maintained in a productive state for several years if managed properly (Bidwell and Woods, 2017). The objective of this project was to eliminate Squarrose knapweed with herbicide so that useful forage species would have a chance to re-establish and grow. Our objective for the present study was to see how much forage production was available twelve years after our initial herbicide and fertilization treatment of Y Ranch pastures.

Methods

An area of 728 ha of rangeland pastures on Y Ranch, Tooele/Juab Counties, Utah was treated with Milestone® herbicide (Active ingredient: Aminopyralid, an auxin type growth hormone) and LINK® 30L foliar fertilizer (30-0-0, 30% polymer-based Nitrogen). Milestone® was applied aerially at the rate of 0.198 kg/ha in May 2012. LINK® 30L was applied with a ground rig boom sprayer in November 2012 at the rate of 14 L/ha.

Results

Dense stands of Squarrose knapweed were eliminated and by November 2012 we were able to apply fertilizer to encourage forage growth for the following season. Forage grass species, primarily Crested Wheatgrass, *Agropyron cristatum,* grew in abundance. Grazing of livestock on the treated area was deferred for two growing seasons. In the summer of 2014 AUMs of available forage had increased from 25 to 200 (Figure 1). After ten years of grazing, forage species were still abundant (Figure 2). Samples taken in May 2024 showed forage levels of 91 kg/ha and 225 AUMs. There was no sign of Squarrose knapweed on the treated area.

Figure 1. Before and after treatment of Squarrose Knapweed

Discussion and Conclusions

Much emphasis has been placed on reseeding with native plant species to restore rangeland, however many native species are unable to establish successfully because of aggressive invasive annual species. Downy brome, *Bromus tectorum* L., is especially troublesome on rangelands of the western United States. It is a prolific seed producer with a high rate of germination as both an annual and winter annual (meaning it can germinate in either late fall or early spring) and is an early maturer prone to ignition from sparks, lightning, and other sources of fire. It has been responsible for many failed seedings.

Crested Wheatgrass is known for resilience to weed invasion (Looman and Heinrichs 1973). It has shown potential (Hulet et al. 2010) to be a transition species by out competing invasives such as Downy brome and allowing other species, especially natives, to establish.

Because forage production on treated Y Ranch land has remained high for ten years and because knapweed is non-existent, Crested Wheatgrass may also be effective in preventing re-establishment of invasive perennials.

In this project it has also demonstrated its longevity. It is known to have a 15–20-year lifespan (Looman and Heinrichs 1973).

Steps can be taken to reverse the effects of weeds and pasture productivity can be restored. Use of an effective herbicide combined with proper timing of application can bring about positive results. In our project a combination of herbicide and fertilizer proved to be very effective. No reseeding was necessary.

Figure 2. Y Ranch Pasture May 2024

Acknowledgements
The authors would like to thank Guy Cooper for his willingness to let us carry out this project on his property, the Utah Department of Agriculture and Food for funding the project, the Squarrose Knapweed Cooperative Weed Management Area for coordinating our efforts, and Jerry Caldwell for the photographs.

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A century of livestock exclusion reveals soil microbiome impacts in arid Australia.

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Key words: soil ; microbiome; grazing

Abstract

Soil microbiome responses to disturbance in arid ecosystems remains a critical knowledge gap. This study examines the soil microbiome in the north-east pastoral zone of South Australia, comparing the TGB Osborn Vegetation Reserve, established in 1925 with livestock and rabbit-proof fencing, to the adjacent grazed Koonamore Station, a merino sheep-grazing lease. Soil bacterial and fungal community compositions were analysed through amplicon sequencing, revealing that livestock grazing is associated with specific microbial abundances and community structure, with distinct spatial patterns between bare soil areas and soil under perennial vegetation. Soils from open spaces in livestock grazing areas showed more disparity through reduced microbial abundances compared to soils ungrazed for 98 years. However, soils underneath shrub canopies in grazed areas showed increased abundances and taxonomic differences in comparison to ungrazed. Further research is needed to understand the functional consequences of these soil microbiome shifts on ecosystem function and services.

Introduction

Our understanding of soil microbiome responses to disturbance in arid ecosystems remains limited, as well as the timescales required for functional rehabilitation following disturbance (Toledo et al. 2021; Zhang et al. 2023). Soil microbes form complex, highly diverse communities with significant roles in ecosystem function, yet are largely undescribed and understudied, especially in arid systems (Liu et al. 2023). Within a landscape, different microsites are conducive of different microbial communities, and as such contribute to important processes such as nutrient cycling and soil surface stabilisation. Arid lands are water and nutrient limited, so perennial vegetation which can alter the distribution of resources play vital roles in the functioning of the system (Ludwig and Tongway 1995; Morton et al. 2011). Individual perennial plants create small-scale areas of high fertility beneath the canopy surrounded by lower fertility soil, called "fertile islands" (Garcia-Moya and McKell 1970). Microbial abundance, diversity, and activity have been found to be higher in fertile islands (Goberna et al. 2007). The ameliorated conditions combined with higher substrate levels in fertile islands directly contribute to enhanced nutrient cycling by microbes when compared to open spaces (Macdonald et al. 2015). Soil microbial communities that form biological soil crusts also play major roles in ecosystem services provisioned in the open spaces as well by stabilising the soil surface and fixing atmospheric nitrogen (Belnap and Lange 2003; Castillo-Monroy et al. 2011). Identifying the differences in soil microbiomes where livestock are present and excluded in both open and within fertile islands is crucial for assessing the system wide consequences of livestock grazing. Alongside limitations in identifying microbial species and function, another significant barrier in our understanding of soil restoration and impacts of livestock grazing on soil microbial communities is that there is only a small number of long-term grazing exclusion study sites for comparison (Allington and Valone 2014). This study conducts a cross-fence comparison between a unique 98 year ungrazed reserve and adjacent livestock grazed arid rangelands to address these critical knowledge gaps. The main hypotheses to be tested are: 1) perennial vegetation fertile islands will foster unique microbial communities in comparison to open spaces, and 2) 98 years of grazing exclusion will result in substantive differences in microbial communities compared to livestock grazed areas, and the impacts will be more substantive in open spaces compared to those under plant canopies.

Methods

Sampling was conducted in chenopod shrublands of the arid north-east pastoral zone of South Australia within the TGB Osborn Vegetation Reserve (32°07′S, 139°20′E), established in 1925 with a livestock and rabbit-proof fence, and the surrounding merino sheep-grazing lease on Koonamore Station.

Soil sampling and microbiome extraction and sequencing

Three soil cores (10cm diameter to 5cm depth) were taken beneath the 'Canopy' of selected *Eremophila sturtii* shrubs (that are unpalatable to livestock) within 10m of the TGB Osborn Vegetation Reserve (hereafter "reserve") exclusion fence and combined to make a single sample. The same approach was used to provide a composite soil sample from a randomly chosen paired site on 'Open' ground approximately 5 metres away. Composite samples were homogenised, sub-sampled into 5g tubes and stored in a -18°C freezer. Sampling was replicated for both ungrazed sites inside the 'Ungrazed' reserve and at 'Grazed' sites outside the reserve in May 2023 (Autumn; n=24) an in September 2023 (Spring; n=41).

PCR amplification and sequencing of soil samples was conducted by the Australian Genomic Research Facility (AGRF, Adelaide, Australia) on the Illumina NextSeq2000 platform (San Diego, CA, USA). DNA was extracted using the PowerSoil Soil DNA Isolation Kit (MoBio Laboratories, Solana Beach, CA, USA). Two regions of ribosomal DNA, 16S and ITS, were amplified to assay the bacterial and fungal communities using the forward and reverse primers, 341F - 806R for bacteria, and ITS1F - ITS2R for fungi. Fungi and bacterial communities were sequenced from Autumn samples (n=24) and only fungi was sequenced from Spring samples (n=41) for logistical reasons.

Bioinformatic pipeline and statistical analysis

The bioinformatics analysis involved demultiplexing, quality control, Amplicon Sequence Variant (ASV) calling, and taxonomic classification. The demultiplexed raw reads are primer trimmed and quality filtered using the cutadapt plugin followed by denoising with DADA2 (Callahan *et al.* 2016) (via q2-dada2). Taxonomy was assigned to ASVs using the q2-feature-classifier classify-sklearn naïve Bayes taxonomy classifier (Bokulich *et al.* 2018). Diversity profiling analysis was performed using QIIME 2 2019.7 (Bolyen *et al.* 2019). To assess the multivariate response of microbes to grazing and canopy cover, multivariate permutational analysis of variance was used to model the ASV inter-sample Bray-Curtis dissimilarities as a function of Canopy/Open and Grazed/Ungrazed treatments while accounting for spatial clusters (i.e., blocks) and random spatial site-pairs (shrub Canopy-Open ground pairs). To determine microbial community compositon patterns between grazing and canopy treatments and sampling date, the assigned taxonomy of fungal (at Class level) and bacterial (at Phylum level) ASVs were aggregated to visualise the broad patterns of the read counts, representing the relative abundances, of these taxa at easily distinguishable taxonomic levels. To determine if ASV's are indicative of any multivariate treatment differences, Indicator Species Analysis (De Cáceres and Legendre 2009) was conducted on the read counts, representing the relative abundances, of the fungal and on the bacterial data and the Phylum and Class compositions as a proportion of the indicator species were plotted for visualisation.

Results

Fungal community

There were 4002 fungal amplicon sequence variants (ASVs) identified across 24 Autumn-sampled sites; the most abundant Phyla were Ascomycota and Basidiomycota, by majority, and Chytridiomycota, Mortierellomycota and Rozellomycota. Fungal abundance was higher under Canopy in the Grazed compared to Ungrazed Canopy, whereas in Open sites there was considerably higher fungal abundance in the Ungrazed compared to Grazed Open soils. This result was consistent across the two seasons (**Figure 1**). The multivariate response differed between Canopy and Open sites (*p-value* = 0.001) as well as between the Ungrazed and Grazed sites (*p-value* = 0.03). The same Phyla were rank-ordered most abundant in 3911 fungal ASVs identified across 41 sites sampled in Spring, with the exception that Glomeromycota replaced Rozellomycota as the fifth-ranked taxon. The multivariate ASV abundances differed between Canopy and Open (*p-value* < 0.0001) in Spring, though these fungal community differences were not the same across all surveyed blocks (microsite*block *p-value* = 0.01). Similarly, average differences among the blocks varied between the Ungrazed and Grazed sites (block*grazing (*p-value* < 0.05)).

There were 72 fungi ASVs identified as indicators for differences between Canopy and Open sites and an additional 38 indicator ASVs for Grazing-Ungrazed differences in Autumn. The number of indicator ASVs differed only slightly for the Spring data; 62 Canopy-Open indicators and 35 Grazing-Ungrazed indicators.

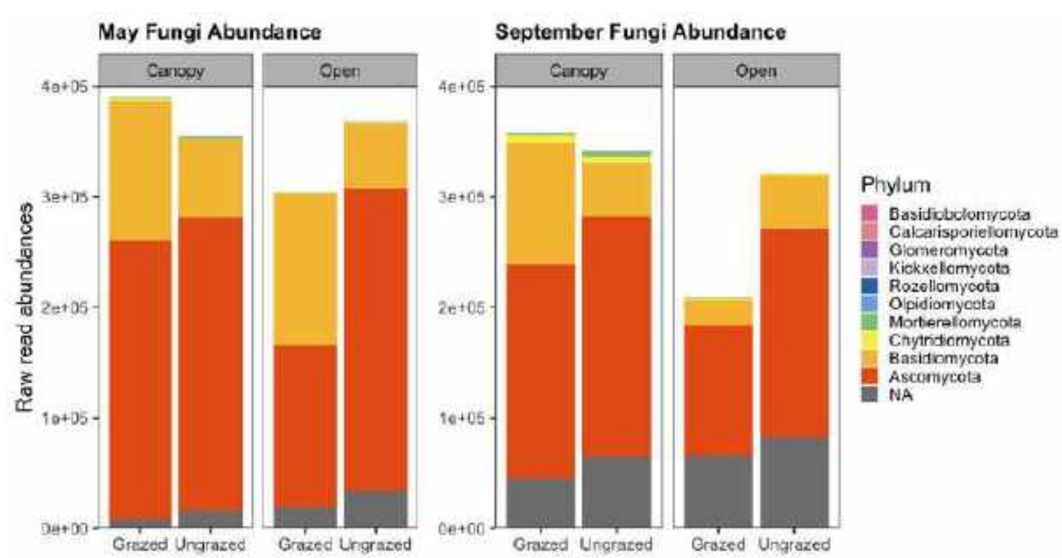

Figure 1. The raw read abundances of fungal Amplicon Sequence Variants (ASV) identified to Phylum across microsites and grazing treatment between sampling periods in May and September in 2023 at Koonamore, South Australia.

Bacteria and archaea community

There were 8412 ASVs (of which 8367 were bacterial and 45 archaeal) identified across 24 Autumn-sampled sites; the most abundant Phyla were Actinobacteria by majority, followed by Chloroflexi, Proteobacteria, Acidobacteria, Gemmatimonadetes, Cyanobacteria, and Firmicutes. The only recorded archaeal Phyla were Thaumarchaeota and Euryarchaeota. Bacterial abundance was higher under Canopy and higher in the Grazed areas compared to Ungrazed (**Figure 3**). The multivariate response differed between Canopy and Open sites (p-value = 0.02) as well as between the Ungrazed and Grazed sites (p-value = 0.006).

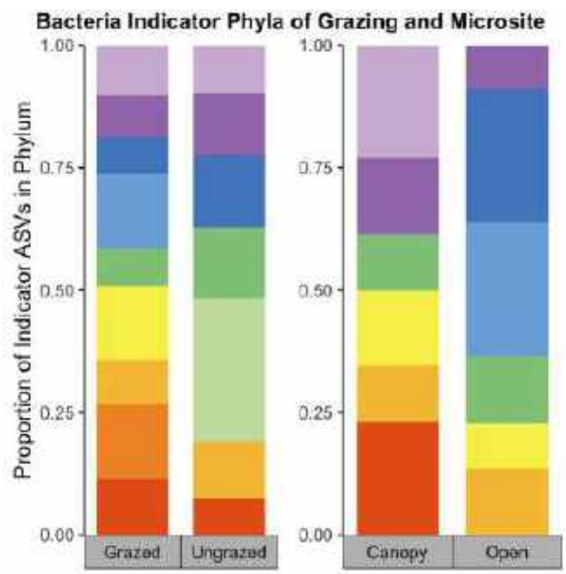

Figure 2. The proportion of bacterial Indicator species classified into Phylum plotted as a proportion of the total assigned indicator species in both grazing and microsites.

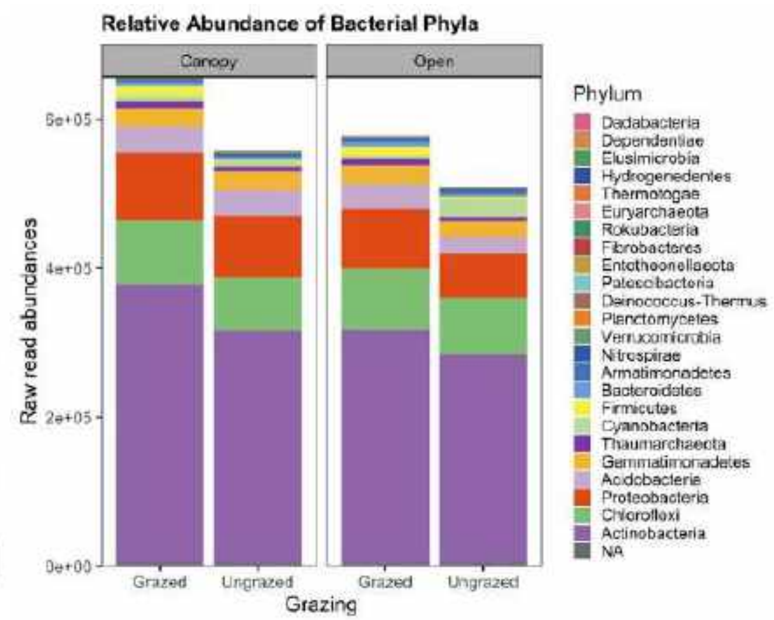

Figure 3. The raw read abundances of bacterial Amplicon Sequence Variants (ASV) identified to Phylum across microsites and grazing treatment in May 2023 at Koonamore, South Australia.

There were 61 fungi ASVs identified as indicators for differences between Canopy and Open sites and an additional 88 indicator ASVs for Grazing-Ungrazed differences in Autumn (**Figure 2**).

Discussion

This study's cross-fence comparison revealed significant differences between livestock Grazed and long-term Ungrazed soil microbiomes, with distinct variation in responses between fertile island soils and soils in open spaces. The fertile island effect was evident for bacterial taxa, with abundances higher in Canopy soils in both Grazed and Ungrazed soils compared to Open soils. Higher abundances of soil bacteria and fungi in fertile islands is well documented throughout both Australian and worldwide drylands, associated with increased substrates and ameliorated conditions under perennial vegetation (Ding and Eldridge 2021; Noy-Meir 1973). However, the distinct fertile island effect was not consistently found in both Grazed and Ungrazed soils for fungal taxa in this study. Specifically, fungal abundances in Ungrazed conditions did not consistently show a fertile island pattern, with Open soil fungal abundance higher than Canopy in May; however in September, a slight fertile island effect could be seen. Compared to the pronounced Canopy-to-Open differences in Grazed soils, it is hypothesised that this response may be due to physical disturbance of biological soil crusts by livestock. Previous studies indicate that fungi are more sensitive to physical disturbance than bacteria and that ungulates can adversely impact Australian dryland soils (Eldridge and Delgado-Baquerizo 2018; Eldridge et al. 2016; Zhang et al. 2016).

In addition to abundance differences, there are significant community composition differences between Grazed and Ungrazed soils that are hypothesised to result in differences in soil function. Bacteria were more abundant in Grazed areas, with that higher abundance mostly found in Canopy soils. Fungi were more abundant in grazed Canopy soils but considerably less abundant in open Grazed areas compared to the Ungrazed overall. For bacterial communities, the most abundant taxa remain similar across grazing treatments and between Canopy and Open, however differences emerge in taxa that form smaller proportions of the overall community. Taxa from the bacterial phylum Firmicutes were more abundant and indicative of Grazed soils, while taxa from phylum Cyanobacteria were more abundant and uniquely indicative of Ungrazed soils. These abundance and community composition shifts may impact the known spatial partitioning of ecosystem services such as nutrient cycling in arid ecosystems (Macdonald et al. 2015). While this study has identified multiple significant compositional and abundance differences, limited knowledge of the functional classifications of these taxa prevents interpretation of the processes leading to these differences without further soil functional analyses.

This study highlights the significant spatial heterogeneity of soil microbiomes, influenced not only by perennial vegetation but also by disturbance. These findings underscore the importance of considering small-scale variation to comprehend the broader impacts of disturbance and recovery in arid ecosystems.

Acknowledgements

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Inhibitory effects of *Phytolacca americana* extracts of different solvents on *Pestalotiopsis microspora*: The causal agent of blueberry leaf spot

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Key words: P*hytolacca americana*, *Pestalotiopsis microspora*, inhibitory rate, EC_{50}

Abstract

Inhibitory effects of different *Phytolacca americana* L. extracts on *Pestalotiopsis microspora*, a fungal pathogen isolated from blueberry leaf spot, were determined by a growth rate method. Effects of *P. americana* extracts from different tissues (leaves, roots, stems) obtained with five different solvents on inhibitory rates of *P. microspora* were determined by measuring fungal growth. Ethanol and acetone *P. americana* extracts clearly inhibited growth of the fungal pathogen, and inhibition rate was positively correlated with treatment concentration. Inhibitory effects of ethanol extracts were significantly greater than those of the acetone extracts, and the optimal inhibitory effect (Using EC_{50} to express the median lethal concentration) was at 0.004 g mL^{-1}. Water, petroleum ether, and benzene extracts did not significantly affect *P. microspora* growth. Leaf extracts of *P. americana* had the strongest inhibitory activity, followed by that of root and stem extracts. In this study, the ethanol extract from *P. americana* leaves had the greatest inhibitory effect on *P. microspora*, the causal agent of blueberry leaf spot, and thus, ethanol might be the best choice of solvents to extract bacteriostatic substances from *P. americana*. The study provides basic data for continued research and development of biopesticides.

Introduction

Phytolacca americana is in the family Phytolaccaceae, and it has a wide range of growth, strong adaptability, easy harvest and low price(Zhang *et al.* 2020).In addition to medicinal value(Zou *et al.* 2019), P. americana has attracted much attention for its insecticidal(Wang *et al.* 2019), acaricidal, bacteriostatic, and antiviral activities.

Zhao et al. measured the inhibitory effects of Phytolacca acinosa extract on four types of bacteria by a filter paper method(Zhao *et al.* 2010). In that study, some of the Phytolacca extracts had antibacterial activity, and most of the substances with the strongest antibacterial activity were in the root system. Overall, antibacterial activities of different extracts were different against different bacteria. Ge et al. showed that extracts from fruits and branches of Phytolacca significantly inhibited proliferation of tobacco mosaic virus(Ge *et al.* 2015). Although bacteriostatic effects of Phytolacca have been reported, bioassays of Phytolacca bacteriostatic activity on pathogenic fungi are lacking.

In this study, extracts were obtained from roots, stems, and leaves of P. americana by using five different solvents: water, petroleum ether, acetone, ethanol, and benzene. Inhibitory effects of the different extracts on the pathogenic fungi P. microspora isolated from blueberry leaf spot were determined. The goal was to clarify differences in the inhibition of P. microspora activity by the different extracts to provide ideas for the development of biopesticides.

Methods

The damaged blueberry leaves were collected from Maling Township Blueberry demonstration Garden, Huaxi District, Guiyang City, Guizhou Province, China (latitude 106.594775, longitude 26.275049). For identification based on ITS(NCBI nucleotide sequences PP346193 and PP346194). The fungal pathogen was identified as *Pestalotiopsis microspora*.

Whole *P. americana* were collected from Guding Village, Xiaba Town, Wudang District, Guiyang City, Guizhou Province, China(latitude 106.898299, longitude 26.692004). Roots, stems, and leaves were dried at 38° C, crushed, and sifted through a 20-mesh screen.

Water, petroleum ether, acetone, ethanol and benzene with different polarity were selected to form a series of solvents. Five concentration gradients were set, and two different extraction methods (Yang *et al.* 2005).

Fragments of the symptomatic leaves were used for indirect isolation of the causal agent in potato dextrose agar (PDA) medium (Jéssica *et al.* 2022). Mycelial disks of Pestalotiopsis microspora was prepared by a growth rate method. And colony diameter was measured by crossing method.

Results

Inhibition rate of acetone extracts from Phytolacca americana against Pestalotiopsis microspora

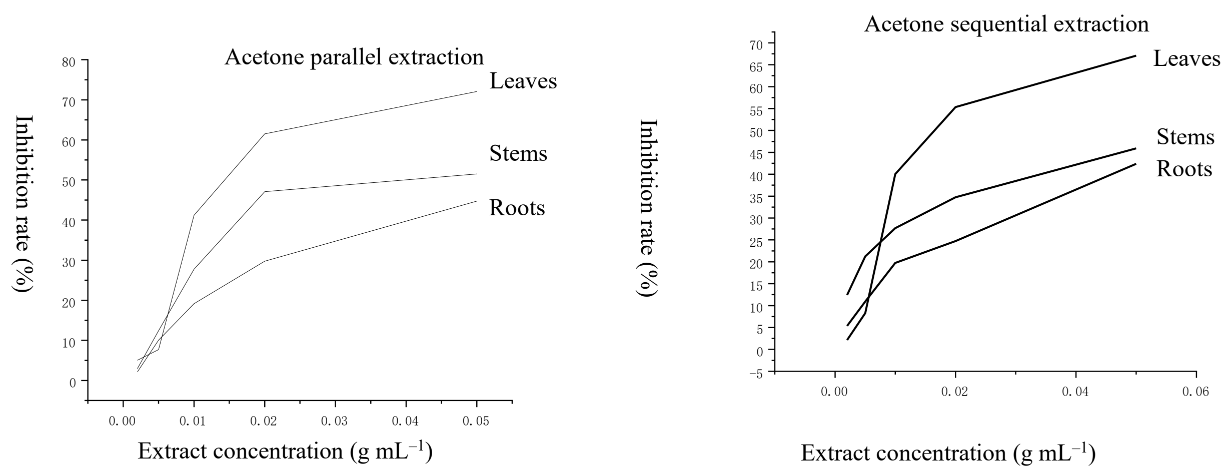

Figure 1 Comparison of inhibitory rate of *Phytolacca americana* acetone extracts from two different extraction methods

Inhibitory rate of acetone extracts from roots, stems, and leaves of *P. americana* on *P. microspora* are given in Figure 1 . When the concentration was 0.05 g mL^{-1} from parallel extraction, the leaf extract had the strongest inhibitory effect, with an inhibition rate of 72.1%. When the concentration was 0.002 g mL^{-1}, the inhibition effect of the root extract was weak, with an inhibition rate of only 2.1%. In sequential extraction, the inhibition rate of the leaf extract at 0.05 g mL^{-1} was 67.1%, which was the maximum inhibition rate of sequential extracts. Acetone extracts of both parallel and sequential extraction methods had inhibitory effects on *P.microspora* across the range of concentrations, with bacteriostatic rate increasing with increasing extract concentration. In parallel and sequential extractions, leaf extracts had the highest inhibitory rate. Overall, treatment concentration and inhibition rate were positively correlated for acetone extracts from different parts of *P. americana*.

Inhibitory rate of ethanol extracts from Phytolacca americana against Pestalotiopsis microspora

Inhibitory rate of ethanol extracts from roots, stems, and leaves of *Phytolacca americana* on *P. microspora* are shown in Figure 2 . In parallel extraction, the strongest inhibition effect was with the leaf extract at 0.05 g mL^{-1} , with the inhibition rate of 77.59%. In sequential extraction, the inhibition rate of the leaf extract at 0.05 g mL^{-1} was 71.99%, which was the maximum inhibition rate of sequential extracts. The inhibition rate of root, stem, and leaf ethanol extracts from parallel extraction increased with the concentration. Overall, treatment concentration and inhibition rate were correlated for ethanol extracts from different parts of *P. americana.*

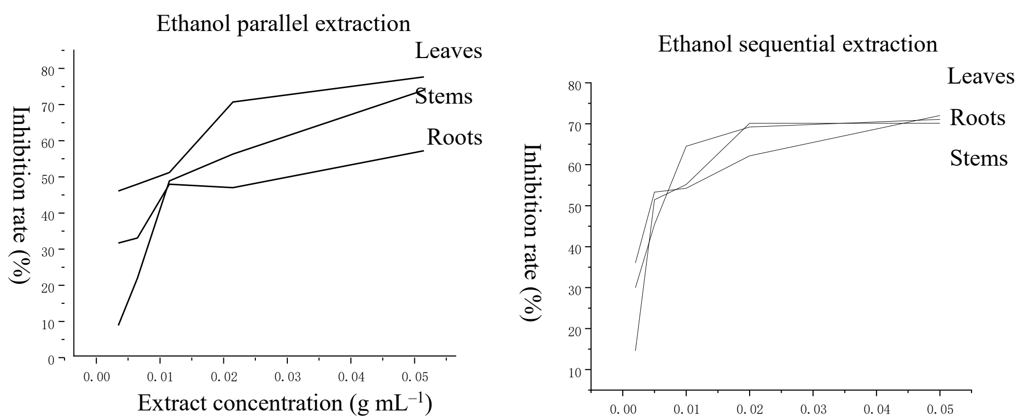

Figure 2 Comparison of inhibitory rates of *Phytolacca americana* ethanol extracts from two different extraction methods

Comparison of virulence and significance analysis of ethanol and acetone extracts of Phytolacca americana against Pestalotiopsis microspora

According to inhibition rates, virulence regression equations were established, and inhibitory medium concentrations (EC_{50}) were calculated. Virulence regression equations and correlation coefficients (r) were used to compare the toxicity of *P. americana* ethanol and acetone extracts to *P. microspora* (Figure 3). according to EC_{50} values of extracts from roots, stems, and leaves, the inhibitory effects of ethanol extracts were generally greater than those of acetone extracts, and the inhibitory effects of leaf extracts were better than those of root and stem extracts.

When acetone was used as the extractant at 0.05 g mL^{-1}, whether parallel or sequential extraction, the inhibitory rate of leaf extracts was significantly higher than that of stem and root extracts. When ethanol was used as the extractant, the inhibitory rate of the leaf extract was significantly higher than that of the stem extract with parallel extraction, but there was no significant difference among root, stem, and leaf extracts when extracted sequentially. Thus, extraction method and order affected the bacteriostatic rate.

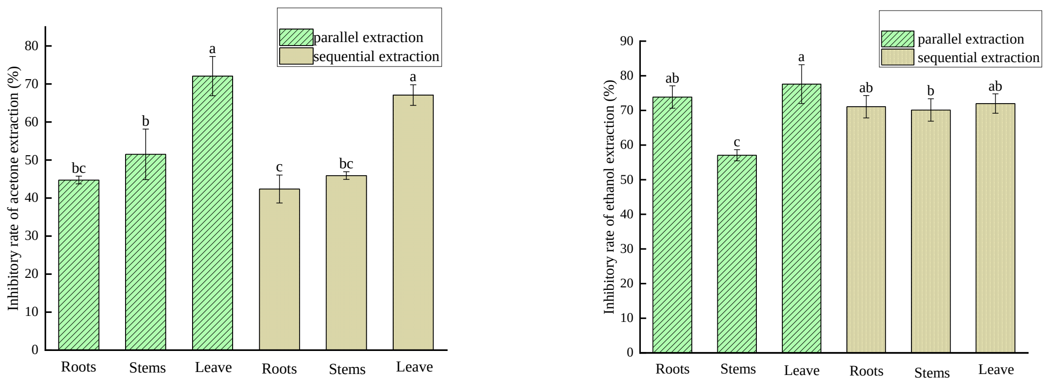

Figure 3 Comparison of inhibition rates of acetone and ethanol extracts of *Phytolacca americana* at 0.05 g mL^{-1} using two extraction methods. Acetone extract on the left and ethanol extract on the right.

Discussion

Secondary metabolites in many plants can inhibit, kill, or promote the growth of pathogenic fungi (Luo *et al.* 2022), and those of *P. americana* also have this characteristic (Li *et al.* 2021). In this study, Both ethanol and acetone extracts inhibited the growth of *P. microspora*, and the concentration of extracts was positively correlated with the inhibition rate. When the concentration of extracts increased, the effective content of the plant extract and the inhibition rate also increased. In addition, analysis of the relation between solvent polarity and bacteriostatic rate indicated that the content of active inhibition components extracted from *P. americana* was positively correlated with solvent polarity. The water extract showed no inhibitory effect, and we thought that the inhibitory components against *P.microspora* were insoluble or slightly soluble in water.

The effective inhibition components of *P. americana* were concentrated in the leaves, which is consistent with the conclusion that most secondary metabolites are primarily concentrated in leaves(Salvat *et al.* 2004). The results are in contrast to those of Zhao *et al.* who found that most substances with the strongest antibacterial activity are in roots, which may be due to Zhao et al.testing effects on bacteria. The inhibition mechanisms of extracts from different parts of *P.americana* against fungi and bacteria might be different and should be investigated in future studies.

Antibacterial substances in different parts of *P.americana* were most easily extracted by strong polar organic solvents.Ethanol extracts of leaves had the highest levels of bacteriostatic active components, which were significantly higher than those of root and stem extracts. To develop plant-derived blueberry leaf spot inhibitors from extracts of *P.americana*, strong polar organic solvents such as ethanol should be used with extraction of leaves.

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Examining the impact of ruminal and abomasal fermentation on the viability of coated rangeland seed species

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Key words: faecal seeding; seed coating; endozoochory, ruminants; grazing, rangelands

Abstract

Cheatgrass *(Bromus tectorum)* has established itself as a prolific invader across the rangelands of the western United States, resulting in an abundance of fine fuel and an increased wildfire frequency. The increased frequency of fires has led to a significant reduction in native vegetation, causing degradation of wildlife habitat, forage availability, and other ecosystem services. To address this destructive wildfire cycle, cattle can be utilized to reduce cheatgrass fuel loads and mitigate cheatgrass dominance through targeted grazing. Concurrently, livestock may be used as vectors for the dispersal of desired rangeland plant species seeds through faecal seeding. Many seeds of interest are susceptible to microbial degradation in the rumen, which is why our study aimed to utilize *in situ* methods to evaluate the effects that seed coat enhancements have on the viability of seed germination post ruminal fermentation. Four target species, Indian ricegrass (*Achnatherum hymenoides*), crested wheatgrass *(Agropyron cristatum),* bottlebrush squirreltail *(Elymus elymoides),* and bluebunch wheatgrass *(Pseudoroegneria spicata)*, were coated with either Polyvinylpyrrolidone (PVP) or PVP + ethyl cellulose (Ethocel). The seeds were subjected to ruminal fermentation for 0, 6, 12, 24, 36, 48, 96 hours, after which, the seeds were placed into petri dishes and germination was monitored for five weeks. PVP and PVP + Ethocel coating treatments resulted in decreased germination rates for the 0-hour treatment across all species except Indian ricegrass. However, coated seeds exhibited greater resistance to microbial degradation through time. The exception to this was Indian ricegrass, which exhibited an increase in germination through time for PVP and control groups. Additionally, coated crested wheatgrass seeds were incubated *in vitro* for 48 hours and incorporated into faecal pats of varying depths to examine emergence. Emergence in faecal material was notable for the PVP + Ethocel group, indicating its potential to protect seeds under harsh environmental conditions.

Introduction

Rangeland ecosystems are essential for maintaining biodiversity, supporting livestock grazing, and providing ecosystem services such as carbon sequestration and water filtration. Despite their importance, these ecosystems are under increasing pressure from a variety of anthropogenic and natural factors, including habitat fragmentation, altered fire regimes, and the proliferation of invasive plant species (Baughman et al., 2022; Whisenant, 1989). Among these threats, the introduction and dominance of invasive grasses such as cheatgrass (*Bromus tectorum*) pose significant challenges, transforming native rangelands and exacerbating wildfire frequencies. As vegetative diversity declines, ecosystem resilience weakens, leading to cascading effects on trophic dynamics and ecosystem functions (Pace et al., 1999; Quijas et al., 2010).

The loss of plant community diversity in western rangelands, particularly within sagebrush steppe environments, has prompted land managers and researchers to investigate innovative methods to restore these ecosystems. Healthy rangelands depend on diverse plant communities with functional traits that enable them to adapt to challenging and fluctuating environmental conditions (McCann, 2000; Baughman et al., 2022). Restoration practices often aim to bolster this functional diversity, which enhances ecosystem resistance and adaptability to disturbances.

Restoration efforts in the western United States date back over a century, but harsh environmental conditions and logistical constraints make these efforts costly and often ineffective. Traditional reseeding methods face low success rates due to factors like poor seed-soil contact, water scarcity, and competition with invasive species (Monsen & MacArthur, 1995; Svejcar & Kildisheva, 2017). In recent years, seed coating technology has emerged as a promising solution to improve restoration outcomes. By applying physical, chemical, or biological enhancements to seeds, seed coating technologies can improve seedling establishment, viability, and resistance to environmental stressors (Davies et al., 2018; Pedrini et al., 2020). For example, surfactants added to seeds reduce soil-water repellency, enhancing water availability at the seed microsite, while coatings with abscisic acid (ABA) delay germination to align with favourable conditions (Madsen et al., 2014; Richardson et al., 2019).

The application of seed coating technologies in rangelands presents a dual opportunity: to improve the establishment of desirable native species and to suppress the dominance of invasive grasses. For example, effective reseeding with perennial grasses can reduce cheatgrass density, thereby altering fire regimes and restoring wildlife habitat (Francis & Pyke, 1996; Whisenant, 1989). Targeted grazing strategies further support this effort by reducing cheatgrass seed banks and fine fuels while avoiding harm to beneficial vegetation (Clark et al., 2023; Perryman et al., 2020). Grazing also presents a unique opportunity to leverage natural seed dispersal mechanisms through endozoochory—the spread of seeds via livestock or wildlife excrement (Teichman et al., 2013).

Faecal seeding, where seeds are dispersed in livestock faeces, is a low-impact restoration method that capitalizes on natural trophic interactions. While this approach minimizes mechanical disturbance to the soil, the digestive processes of ruminants can reduce seed viability, particularly for invasive species like cheatgrass (Holton et al., 2024). This challenge necessitates innovative solutions, such as hydrophobic seed coatings, to protect seeds during digestion and improve their establishment post-dispersal (Qoism et al., 2024; Sashi et al., 2019).

This study investigates the potential of hydrophobic seed coatings, specifically Polyvinylpyrrolidone (PVP) and PVP combined with ethyl cellulose (PVP + Ethocel), to protect seeds during ruminal digestion. Our objectives were to evaluate germination and emergence rates of coated seeds post-digestion and assess their viability under simulated rangeland conditions. We hypothesize that hydrophobic coatings will enhance seed protection during digestion and improve seedling establishment in faecal seeding applications.

Methods

In Situ Ruminal Incubation

Six rumen-cannulated Angus × Hereford steers (610 ± 54.5 kg) were fed a grain-hay diet and used to evaluate the effects of seed coatings on the viability of crested wheatgrass (*Agropyron cristatum*), bluebunch wheatgrass (*Pseudoroegneria spicata*), bottlebrush squirreltail (*Elymus elymoides*), and Indian ricegrass (*Achnatherum hymenoides*). Seeds were coated with PVP, PVP + Ethocel, or left uncoated as controls. Seed samples were placed in heat-sealed nylon bags and incubated in the rumen for varying durations (0, 6, 12, 24, 48, and 96 hours). Bags were removed at designated time points and prepared for enzymatic digestion simulations.

In Vitro Abomasum Incubation

After ruminal incubation, seeds were subjected to in vitro digestion to simulate passage through the abomasum. This process involved incubating seeds in a solution of rumen fluid, pepsin, and hydrochloric acid at 39°C for three hours. The treated seeds were then rinsed and prepared for germination trials in sterile petri dishes.

Germination Trial

Fifty seeds from each treatment group (species, coating, and incubation time) were placed in sterile petri dishes with blotting paper for moisture retention. Dishes were incubated at 20°C with a 12-hour photoperiod and monitored for germination every five days over five weeks. Germination was defined by the emergence of a 2-mm radicle.

Faecal Emergence Trial

Seeds incubated for 48 hours in the rumen were mixed into homogenized faecal material at depths of 1.3, 2.5, and 3.8 cm in greenhouse conditions. Emergence was monitored over ten weeks, beginning with five weeks of water restriction followed by watering every three days. Seedling counts were recorded every ten days.

Statistical Analysis

Generalized linear mixed models were used to analyse the effects of seed coatings, ruminal incubation time, and faecal depth on germination and emergence. Statistical significance was set at $P \leq 0.05$, with trends noted between $P < 0.1$ and $P > 0.05$.

Results

Germination Post-Incubation

Germination rates decreased as ruminal incubation time increased for all species (Figure 1). PVP + Ethocel coatings significantly improved germination for crested wheatgrass and bottlebrush squirreltail after extended incubation times, while Indian ricegrass performed poorly with this coating. Notably, Indian ricegrass treated with PVP maintained germination rates similar to the control group, with a slight increase at 24 hours of incubation (Figure 2).

Faecal Emergence

Seedling emergence varied significantly by faecal depth and coating type. Control seeds exhibited the highest emergence at shallow depths (1.3 cm), while PVP + Ethocel coatings outperformed at deeper levels (2.5 and 3.8 cm). Deeper faecal deposits provided better moisture retention, supporting greater emergence rates across treatments (Figure 3).

Discussion [Conclusions/Implications]

Our findings reveal that seed coatings, particularly PVP + Ethocel, can enhance the viability of certain rangeland species during ruminal fermentation. Species-specific responses indicate the importance of tailoring coatings to match seed morphology and dormancy characteristics. For example, Indian ricegrass, which relies on dormancy to regulate germination, exhibited poor performance with PVP + Ethocel coatings, likely due to the coating's interference with dormancy-breaking mechanisms.

The faecal emergence trial highlights the importance of environmental conditions, such as faecal depth, in seedling establishment. Deeper faecal deposits mitigated moisture loss and crusting, creating favourable conditions for emergence. However, the reduced performance of PVP-coated seeds at shallow depths underscores the need for further refinement of coating formulations to maximize their applicability across diverse rangeland environments.

This study demonstrates the potential of seed coatings to enhance restoration efforts through faecal seeding. PVP + Ethocel coatings showed promise for improving seed viability and emergence under harsh conditions, making them a viable tool for restoring degraded rangelands. However, further research is needed to optimize coatings for a broader range of species and field conditions. Tailoring coating technologies to the specific ecological and operational contexts of restoration projects will be essential for maximizing their impact.

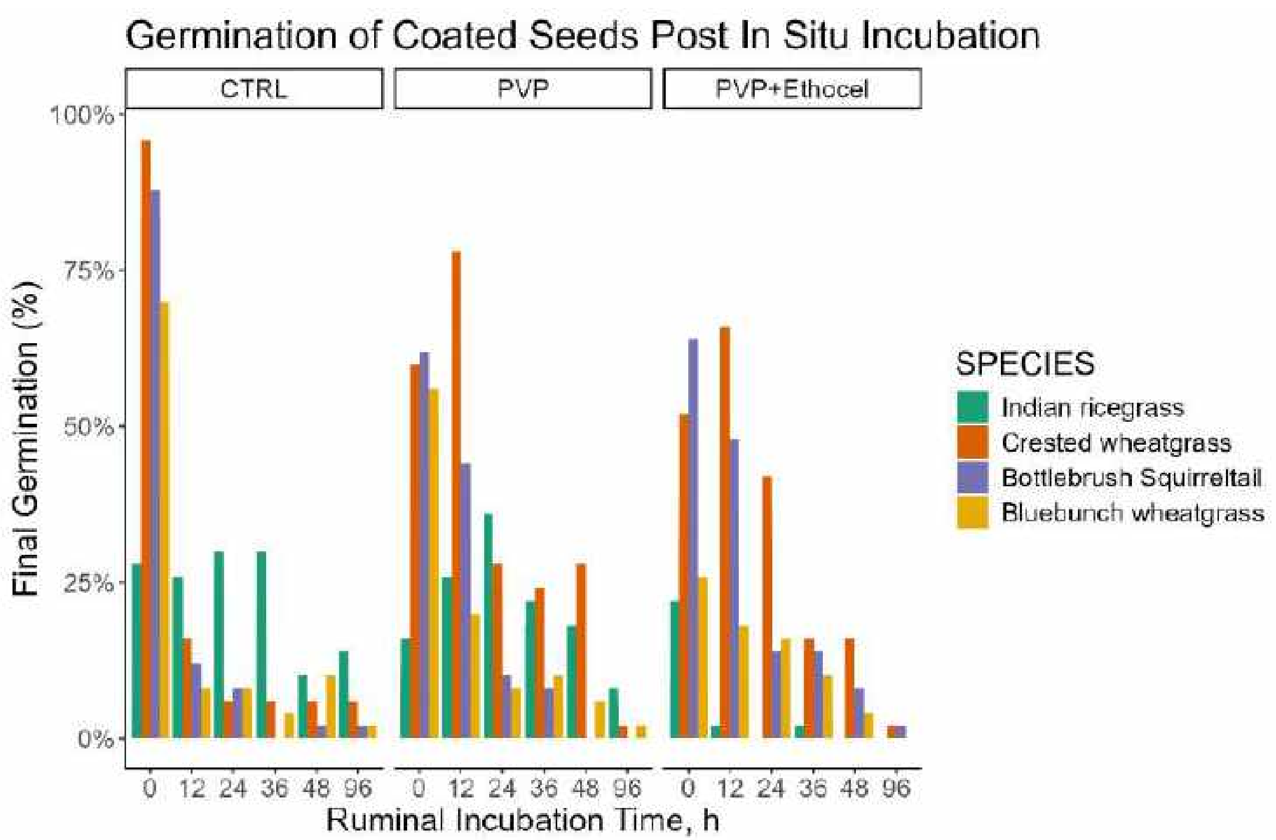

Figure 1. The evaluation of the germination potential of rangeland seed species coated with either polyvinylpyrrolidone (PVP), PVP + Ethocel, or control, after exposure to *in situ* ruminal fermentation through time (in hours) followed by 3 hours of *in vitro* abomasal enzymatic digestion. The final germination is expressed as a percentage of total seeds examined.

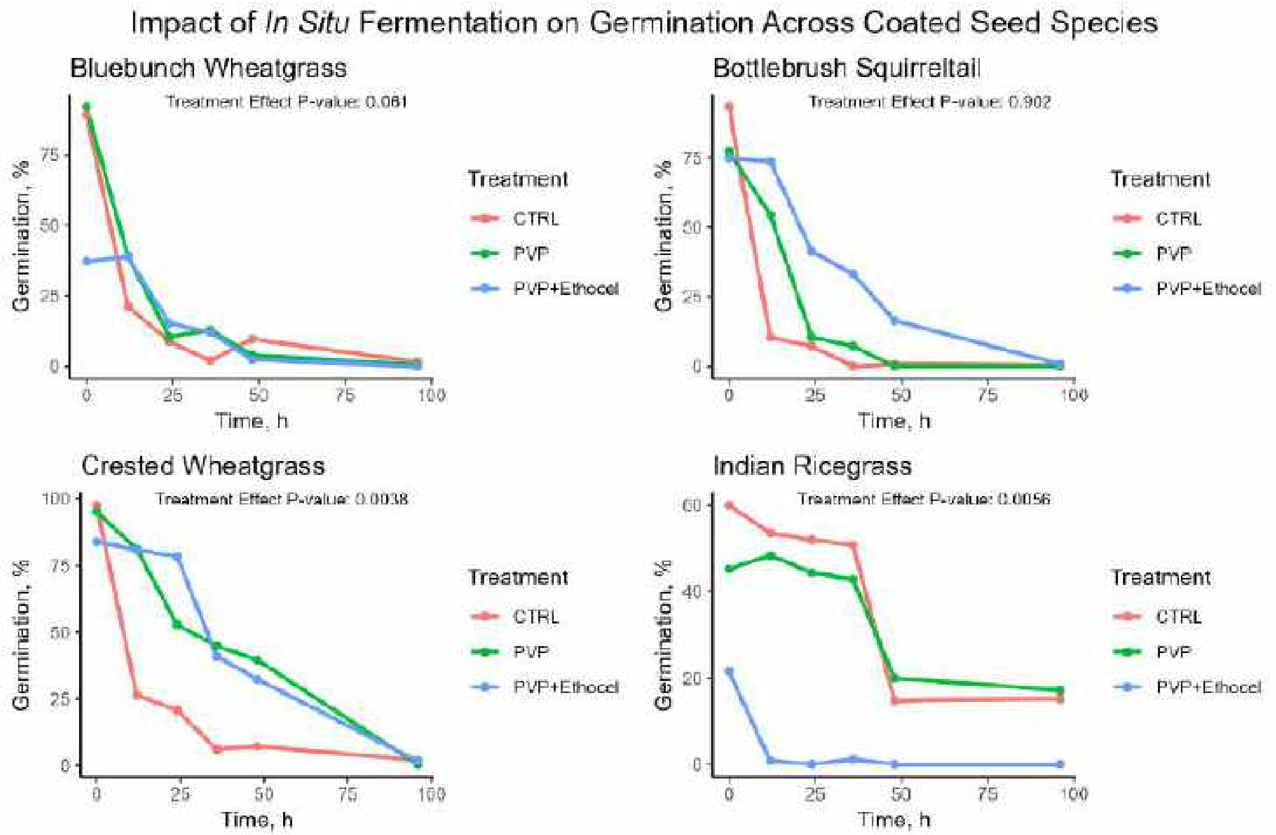

Figure 2. An examination of germination rates through time (in hours) for rangeland seed species coated with polyvinylpyrrolidone (PVP), PVP + Ethocel, and a control group. Seeds were incubated in the rumen, followed by 3 hours of *in vitro* abomasal enzymatic digestion.

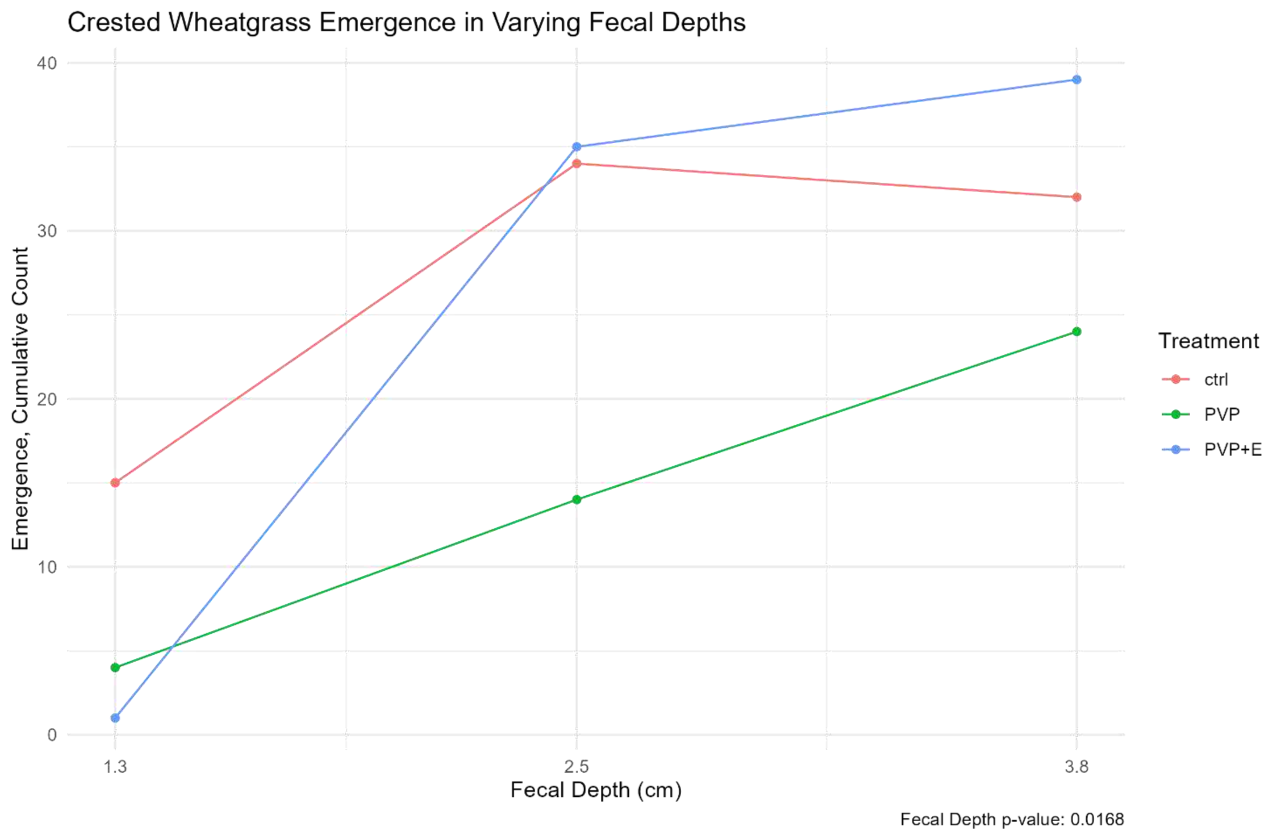

Figure 3. The evaluation of crested wheatgrass (*Agropyron cristatum*) emergence in faecal material substrate at varying depths (1.3 cm, 2.5 cm, and 3.8 cm) after seeds were coated with Polyvinylpyrrolidone (PVP), PVP + Ethocel (PVP + E), or control, and subjected to 48 hours of *in vitro* ruminal fermentation paired with 3 hours of *in vitro* abomasal enzymatic digestion. Emergence was determined by above surface expression of vegetative material.

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Vegetation changes ten years after contour furrowing in a Short Grass Prairie at northern Sonora, Mexico

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Key words: Sonoran Desert, native grasses, biomass, runoff, water harvesting.

Abstract

Large areas of short grasslands have undergone vegetational changes in northern Mexico. Overgrazing, droughts, fire reduction, and climate are among the main factors responsible for these changes. This study was conducted in Cananea, Sonora, Mexico, to compare vegetation changes in *Bouteloua-Aristida* grassland under regular conditions, with and without contour furrowing. Contour furrows, 3 m wide at the base and 1 m tall, were constructed at 30 cm elevation intervals using a disk furrower pulled by a D-6 bulldozer. The topography at the site is characterized by flat ranges with less than a 5% slope. Soils have a deep loamy sand texture. The climate is semi-warm and dry, with a mean annual precipitation of 425 mm and an average temperature of 15 °C. Changes were measured in three permanent plots of 400 m^2 each. Plant density, height, basal coverage, and forage production were monitored during the summer from 2013 to 2022 in ten permanent quadrants of 1 m^2 each per plot. A randomized block design was used, and the data were analyzed by ANOVA ($P \leq 0.05$). Precipitation was near average for 4 years, below average for 3 years, and above average for 3 years. All variables were higher ($P \leq 0.05$) in the contour furrowed areas than in the control plots. Plant density averaged 10.7 plants/m^2 in the control plots and increased by 116.8% ten summers after treatment in the contour furrowed areas. Plant cover increased by 67.5% in the same plots, and plant height increased by 47% ten summers after treatment in the contour furrowed plots. Total annual forage production averaged 635.8 kg D.M. ha^{-1} in the control and 1,546.5 kg D.M. ha^{-1} in the contour furrowed areas, resulting in an increase of 143.2%. We conclude that water harvesting through contour furrowing is an effective method to promote the establishment, development, and productivity of native grass species in short grass prairies.

Introduction

Overgrazing, climate change and severe droughts have caused strong changes in rangelands where a reduction in vegetation cover and an increase in the loss of soil and water through runoff can be seen. Grasslands are plant communities where short and medium-sized grasses predominate with few trees and shrubs (Holechek et al., 2010). They are of ecological and economic importance and constitute strategic areas for the North American livestock industry. Most grasslands are used for raising cattle, horses and large and small wildlife and are considered sources of food, fiber and fuel, contributing to climate regulation, pollination, purification and recharging of aquifers, control of invasive species and carbon sequestration (Milchunas and Lauenroth, 1993; CONABIO, 2023).

Water is a fundamental element to produce forage and for livestock farming, since it is a vital input for the nutrition of animals and for the pasture and irrigation of crops, so the availability of water and the production of food is the main concern for the future of the human population. We believe Short Grass Prairies in regular condition require only the application of water conservation practices to restore productivity. This study was conducted in Cananea, Sonora, Mexico, to compare vegetation changes in a *Bouteloua-Aristida* grassland under regular condition, with and without contour furrowing during a 10-year period.

Methods

The study was carried out during the summers of 2013 to 2022 at the Experimental Ranch of the University of Sonora, located 15 km east of the city of Cananea, Sonora, (30º 58'00" Lat. N and 110º 08'30" Long.W). In a short grass prairie in fair condition, at an elevation of 1,417 meters above sea level, with relatively uniform topography with flats and low hills, slopes that vary from 3 to 7%. The soil type corresponds to haplic chestnut with a sandy loam texture and an average depth greater than 50 cm. The climate is temperate semi-dry BS1 kw (x') (e'). The average annual precipitation and temperature is 425 mm and 15 ºC, respectively (García, 1973). The vegetation is composed of native grasses of the *Bouteloua-Aristida* genera (COTECOCA, 1988). An area of 1 ha surface was selected, where 6 experimental plots (20 x 20 m) each were randomly chosen, 3 in areas with level furrows and 3 in untreated flat areas (control), excluding grazing. The furrows 3 m at the base and 1 m high were built on contour lines at intervals of 30 cm in height, with an 8-36" diameter disk furrower pulled by a D6 bulldozer. Main grass species in the study area were: Blue grama *Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths., Sideoats grama *Bouteloua curtipendula* (Michx.) Torr., Sprucetop grama *Bouteloua chondrosioides* (Kunth) Benth. ex S. Wats., Green sprangletop *Leptochloa dubia* (Kunth) Nees, Common wolfstail *Lycurus phleoides* Kunth, and Sixweeks Threeawn *Aristida adscensionis* L. (Rendowski, 2006).

Variables evaluated were plant density, basal cover, height and biomass production. Plant density, basal cover and height were monitored during the summers of 2013 to 2022, in ten permanent quadrats 1 m^2 per plot. Plant density and basal cover were estimated for each species by counting the total number of plants and the sum of their crowns, respectively. Height was determined by measuring the length of the plants from the soil surface to the apex. Forage production was estimated by clipping in 10 quadrats of 1 m^2 distributed randomly by plot, species and total production. For the determination of dry matter, the forage samples were dried in a forced air oven at 60 ºC for 72 hours. A completely randomized block design was used with two treatments and three repetitions (Steel and Torrie 1980). All variables were analyzed by ANOVA ($P \leq 0.05$), using Duncan's Multiple Range test for the comparison of means. Statistical analyzes were conducted using the SAS package (SAS, 1988).

Results

Precipitation was near average for 4 years, below average for 3 years, and above average for 3 years. All variables were higher ($P \leq 0.05$) in the contour furrowed areas than in the control plots. Plant density averaged 10.7 plants/m² in the control plots and increased by 116.8% ten summers after treatment in the contour furrowed areas. Plant cover increased by 67.5% in the same plots, and plant height increased by 47% ten summers after treatment in the contour furrowed plots. Total annual forage production averaged 635.8 kg D.M. ha^{-1} in the control and 1,546.5 kg D.M. ha^{-1} in the contour furrowed areas, resulting in an increase of 143.2% (Table 1). Forage production of main grass species was consistently greater ($P\leq0.05$) on plots where water was harvested and varied from 25.4 to 204.3 kg of dry matter (DM)/ha on untreated plots and varied from 134.4 to 318.3 kg of dry matter/ha on contour furrowing plots. Biomass of individual grass species was consistently increased from 18.9 to 64.18% on the contour furrowing plots (Table 2).

Table 1. Plant density, basal cover, plant height and biomass production of range grasses in a short grass prairie ten years after contour furrowing at Northern Sonora, Mexico.

Variables	Contour Furrowing	Untreated Check	Percent of change
Plant density (p/m^2)	23.2 a	10.7 b	116.8
Basal cover (%)	16.08 a	9.6 b	67.5
Plant height (cm)	96.46 a	65.62 b	47.0
Biomass Production (kg DM/ha^{-1})	1,546.50 a	635.8 b	143.2

** Means between treatments with different lowercase letter are different ($P\leq0.05$).

Table 2. Total Forage production (kg DM/ha^{-1}) of several grass species at a short grassland with and without contour furrowing after ten years of treatment at Northern Sonora, Mexico.

Species	Contour Furrowing	Utreated Check	Percent of change
Blue grama	264.5 a	148.6 b	56.18
Sideoats grama	318.3 a	204.3 b	64.18
Sprucetop grama	234.7 a	77.5 b	33.02
Green sprangletop	249.1 a	92.5 b	37.13
Common Wolfstail	147.0 a	30.7 b	20.88
Sixweeks Threeawn	198.5 a	56.8 b	28.61
Others	134.4 a	25.4 b	18.89
Total	1,546.5	635.8	

* Means between treatments with different lowercase letter are different ($P\leq0.05$).

Discussion

The purpose of creating contour furrow is to control the surface runoff and increase vegetation establishment and forage productivity. The runoff water is stored in soil profile for plant growth during prolonged periods of moisture stress (Kugedera et al., 2018). Studies conducted with sorghum in Kenya show that the increase in soil moisture content accelerated the crop growth, leaf size, panicle length, number of tillers and above-ground biomass yield (Mwami et al., 2024). Appropriate application of *in situ* and micro-catchment techniques could improve the soil water content of the rooting zone by up to 30% (Biazin et al., 2012). It has been shown that soil and water conservation practices reduce runoff and increase the water content in the soil by 13 to 22% up to one meter deep (Mondaca et al., 2024).

In this study all grass species on disk furrowed plots showed greater plant density, height, basal cover as well as greater forage production as compared to the control. Similar results are reported by Ali et al. (2010), suggesting that water harvesting in micro-structures in the soil captures excessive runoff for subsequent use by plants, helping the development of roots and foliage and reducing the mortality rate of new seedlings. Other studies carried out in Jordan show that forage production increased from 380 to 1,151 kg ha^{-1} with the use of water retention practices (Abu-Zanat et al., 2004). Traditional in situ water harvesting improves soil moisture retention by 59% and effectively reduces runoff by 53% and soil loss by 58.66%, demonstrating their robust water and soil conservation benefits (Tefera et al., 2024). In Sudan, increases of 2.25 to 3.65 tons ha^{-1} of forage are reported in rangelands with rainwater retention, compared to the control with 0.65 tons ha^{-1} (Ezzat et al., 2013).

Conclusion

Contour furrowing in soils of Short Grass Prairies favored the density, basal growth and height of grasses, which together, increased the individual and total forage production of the pastures. The practice allowed the capture and conservation of additional water. Rainwater harvesting resulted in an increase in the biomass production of plants in soils with high runoff potential, thereby increasing soil cover and the production potential for feeding livestock and wildlife. Water harvesting through contour furrowing is an effective method to promote the establishment, development, and productivity of native grass species in Short Grass Prairies.

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Challenges and opportunities for broad-scale state-and-transition model development

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Key words: ecological site; ecosystem services; soil survey; ecosystem dynamics; site potential

Abstract

State-and-transition models (STMs) provide an intuitive framework for interpreting ecological observations in support of assessment, monitoring, research, and management of rangeland ecosystems. Australian scientists proposed STMs as a non-linear alternative to the equilibrium range succession model after the latter was scrutinized during the 1984 International Rangeland Congress in Adelaide. As the Congress returns to Adelaide 40 years later, the paradigm shift away from linear succession toward a non-linear mental model is self-evident. Yet despite consensus that rangelands often exhibit multiple stable states and irreversible transitions, the broad-scale development of STM products cataloguing alternative states, transitions between states, and differences among states is lacking, thus hindering the ability of natural resource managers and researchers to fully implement the STM paradigm. Renewed efforts by the United States Department of Agriculture are incorporating new ideas to elevate future STM products. We discuss challenges of STM development and present a vision for systematic, broad-scale production of STMs based on the following principles and assertions: spatial context – ecosystem properties or classes to which an STM applies must be well defined to reasonably interpret field observations and predict the behaviour of similar areas; inclusive collaboration – STMs must represent the collective ecological knowledge of field scientists, resource managers, local and indigenous experts, and other observers; reliability – STM developers must curate knowledge and data from reputable sources and implement quality control measures; accessibility – interactive online applications must be designed to easily identify an STM of interest and address specific questions about states, transitions, risks, and opportunities; diverse interpretations – STMs must describe interpretive differences among ecological states (e.g., habitat, fire behaviour, forage, water balance) to reflect diverse management and societal priorities. In addition to these principles and assertions, we discuss a variety of mechanisms to achieve our vision of easy access to reliable ecosystem knowledge in support of rangeland management and research.

Introduction

The broad-scale development and application of state-and-transition models (STMs) has proven to be inherently challenging. The STM paradigm remains alluring to many because it systematically organizes existing knowledge about ecosystem dynamics into simple box-and-arrow diagrams (Fig. 1), and it has the potential to put reliable scientific information directly into the hands of rangeland managers and other decision-makers. The basic process of STM development is to 1) define an ecosystem of interest, 2) observe and define the ecological states that occur in that ecosystem, 3) describe the circumstances under which one ecological state transitions to another, and 4) describe the variability in ecosystem attributes and services within each ecological state. STM development is relatively simple when applied to a small area with a few distinct ecosystems, however, the complexity significantly increases when producing STMs for hundreds or thousands of ecosystems across an entire region or continent. Scientists from several countries have made commendable efforts at nationwide STM development in the 35 years since Westoby et al. (1989) proposed the framework as an alternative to the range succession model; yet each attempt has encountered some combination of conceptual, administrative, and technical impediments that stifled broad-scale development and application of STMs (Bestelmeyer et al. 2017). The STM paradigm and its products are seemingly much easier to comprehend and envision than they are to implement and produce.

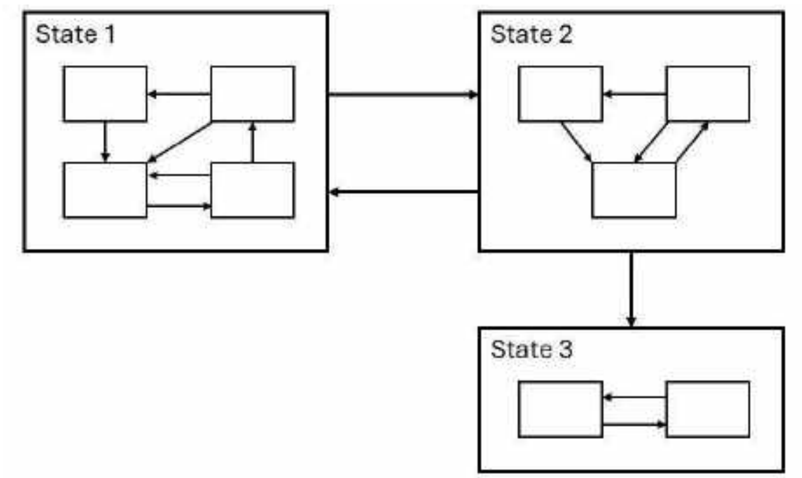

Fig. 1. A generalized STM showing three ecological states, a reversible transition between states one and two, an irreversible transition from states two to three, a lack of transition between states one and three, and community dynamics within each state. The number and nature of states and transitions in STMs varies depending on the ecosystem. To become a complete STM product, these box-and-arrow diagrams should include a legend, photos, tables, figures, and narrative descriptions that describe the variability in attributes and ecosystem services of each state, as well as the primary drivers, triggers, feedbacks, and indicators of each transition.

Despite the many challenges presented by broad-scale STM development and application, the United States (US) Department of Agriculture (USDA) is learning from past efforts and implementing the organizational structure, processes, and systems needed to tackle this complex task for the entire nation. This paper first outlines the challenges associated with broad-scale STM development and application, then outlines specific opportunities that the USDA and partners are pursuing to address each challenge.

Challenges

Impediments to nationwide STM development can be categorized as conceptual, administrative, technical, and utilitarian.

Conceptual challenges

The most significant conceptual challenge to broad-scale development efforts in many parts of the world is defining the reference domain to which each STM applies. STM development across broad regions requires a systematic ecosystem classification based on the environmental features that determine ecosystem potential and dynamics (Bestelmeyer et al. 2009). Climate, soils, physiography, hydrology, and other attributes vary across the landscape and determine the ability of each site to provide ecosystem services (i.e., site potential) and respond to natural and anthropogenic disturbances (i.e., ecosystem dynamics). For example, a peat bog may be adjacent to a well-drained sandy hillslope. Despite sharing a similar climate, these two sites have very different soils, hydrology, geomorphology, disturbance regimes, and ecosystem services associated with their distinct landscape context. These ecosystems are inherently different; thus, the STMs must reflect differences in states, transitions, and the interpretations thereof. Early efforts to produce broad-scale STMs in Australia and Argentina stalled, in part, due to a general lack of soil and other site attribute data at management-relevant scales (Bestelmeyer et al. 2017). Another conceptual challenge suggested by the STM literature is the need to systematically incorporate useful information about ecological processes and resilience into STMs, since the site-specific data needed to do so is generally lacking (Stringham et al. 2003; Briske et al. 2008).

Administrative challenges

In countries where detailed soil and site information is sufficient for systematic classification of ecosystems, administrative challenges represent the next barrier to nationwide STM development (Bestelmeyer et al. 2017). Organizational structure is necessary to develop 1) a coordinated network of experts with experience across all regions of the country, 2) coordinators responsible for bringing the experts and data together to produce useable products, and 3) clear STM product standards that include robust quality control and assurance processes. Of course, this level of organization requires sustained support and funding from institutions and individuals that value comprehensive, reliable ecosystem knowledge in support of ecosystem-based resource management. A one-time investment to develop a national STM reference library is at odds with the incremental nature of scientific knowledge generation. Instead, a sustained commitment must be procured to establish and maintain an organizational structure capable of developing and updating STMs over time as new knowledge is generated (Karl and Talbot 2016).

Technical challenges

Given administrative support and an ecological classification system, technical challenges abound when implementing a broad-scale STM development program. Most of the technical challenges stem from data management needs and training technical staff. Data systems must facilitate the efficient capture, organization, and summarization of soils, vegetation, climate, disturbance, and many other observational data types from reputable sources across all regions and ecosystem classes. While field data collection methods can be standardized for future STM refinements, first draft STMs often rely on the use of existing datasets, which can vary greatly in quality, methods, scale, and other variables. Capturing, organizing, and preprocessing new and existing data can be a monumental undertaking. Efficient workflows and processes must be designed for streamlined analysis and synthesis. Significant training is required for technical experts to learn the STM paradigm, apply standards consistently across all regions, and analyse and summarize data into useful STM products. Perhaps the greatest training challenge is for field ecologists and data analysts to become effective STM development coordinators, capable of utilizing a network of contributors with diverse experiences and perspectives in a truly collaborative process (Bruegger et al. 2016). Moderating meetings, active listening, social skills, and concise writing are critical communication skills necessary to successfully integrate our collective knowledge of ecosystem potential and dynamics into authoritative STM products.

Utilitarian challenges

The ultimate utilitarian challenge is to create STM products that are so informative and intuitive that a person would be foolish not to use them. Unfortunately, STM developers can become so enthusiastic about the science of STM development that they lose focus on the customers' fundamental need to interpret STMs for the purpose of making land management decisions in the real world. Decision-makers use STMs to assess trade-offs in ecosystem services among different ecological states as they consider the costs and benefits of managing in favour of one ecological state over another (Miller et al. 2011). Because many end users have their own work to do, it can be difficult to engage them directly to understand what information is most relevant to them, at what scales, and in what delivery format. Once customer needs are identified, new challenges arise. Software applications must be developed to deliver the STMs in an intuitive, accessible, reliable format that offers quick access to specific answers to the most common questions. A successful software application would also encourage the collection of user feedback as a method to further validate the concepts within the STM. Finally, the arithmetic of developing tables, graphs, photos, and narratives for many ecosystem services occurring on multiple ecological states and across hundreds or thousands of different ecosystems adds up to an enormous workload that requires competent teams with diverse expertise.

Opportunities

The USDA Natural Resources Conservation Service (NRCS) is poised to address each of the conceptual, administrative, technical, and utilitarian challenges facing STM development in the US today.

Conceptual opportunities

The US benefits from more than 125 years of soil survey. The US soil survey produced the spatial and edaphic data needed to develop the "range site" classification system in the mid-twentieth century. Once NRCS began adding STMs to range site descriptions in the late 1990s, the name of the classification was changed to ecological sites (ES), and the scope of ES development expanded to include all native landscapes, with the inclusion of all intensively managed lands in 2010. The ES classification system provides an ideal reference domain for STMs because ESs define the soil and site attributes that determine site potential and dynamics of ecosystems at human operative scales (Moseley et al. 2010). Shortly after the STM paradigm was adopted by NRCS, a complementary concept of dynamic soil properties (DSPs) emerged within the agency (Tugel et al. 2008). The premise of DSPs is that some soil properties change in measurable ways when an ecosystem changes to a different state. The number of DSP projects in the US has steadily increased in the past 15 years, creating new insights about soil-plant feedback process and resilience that can be incorporated into STMs as the literature suggests (Stringham et al. 2003; Briske et al. 2008).

Administrative opportunities

Even as the ES paradigm was evolving to include STMs in the US, nationwide STM development failed to accelerate due to a lack of organizational structure. Several western US states made marked progress in STM development in the first decade of the twenty-first century, yet from a national standpoint, the products were not consistent nor the coverage complete. In 2009, NRCS made administrative changes by establishing a national ES leadership team within the Soil and Plant Science Division (SPSD) to oversee nationwide STM development. Dozens of new ES specialists were hired by the SPSD to coordinate STM development work in all regions of the country. As part of the SPSD, ES specialists have sustainable funding and administrative support and have built upon the many strengths of soil survey, including access to soils experts, established networks of local technical expertise, a long history of nationwide standards, and established product quality review processes. With proper ES staffing in the SPSD, the first nationwide standard for STM development was implemented in the US in 2015 (USDA-NRCS 2014) by an initiative to develop provisional STMs for every ES in the country. Today, over 90 percent of the major soils in the US have a provisional STM product published online, and NRCS is on pace for complete nationwide coverage of provisional STM products in 2025. Many lessons were learned during this first nationwide STM effort, improvements are being made to the STM quality review processes, and new field projects have been designed to collect data for STM revisions.

Technical opportunities

Provisional STMs for the US can be accessed online via the Ecosystem Dynamics Interpretive Tool (EDIT; Bestelmeyer et al. 2016). EDIT is an STM database that houses tabular, photographic, and narrative data describing ranges in characteristics of ESs, states, transitions, and the variability in ecosystem attributes and services within each state. These ranges are summarized from observational data that is stored and analysed outside of EDIT. Since STMs must be derived from the best available information, and since vegetation plot data and experiential knowledge can take many forms, it is virtually impossible to design a single database or workflow to capture, organize, and summarize the best available information across all regions of the country. Therefore, NRCS has developed standards for determining when and how ecological plot data must be entered into the corporate soils database (the National Soils Information System: NASIS), and how to cite other data, publications, or expertise used to develop the STM. Entering vegetation plot data into NASIS should create countless analysis opportunities within the proper soil, ecological, and spatial context. One recent example is the use of NASIS vegetation plot data to forecast changes in the spatial distribution of several berry species important to indigenous Alaskan communities under different climate change scenarios (Hamilton et al. 2024). Standardized data analysis workflows are being developed to streamline STM development, which requires specialized training. NRCS and partners have developed several online training modules and instructor-led courses to expose new staff and partners to the fundamentals of STM development. Developing STM expertise, data management systems, and efficient workflows are just a few of the many opportunities to address technical challenges of nationwide STM development.

Utilitarian opportunities

Understanding how people use STMs is the key to creating a meaningful product. In 2024, NRCS established a national ES team to identify, prioritize, and address STM customer needs within the agency, as well as an interagency ES focus team with the US Forest Service, Bureau of Land Management, US Geological Survey, and Agricultural Research Service. These two new teams foster open and regular communication about how to best meet STM user needs. For example, the Bureau of Land Management would like to use STMs for landscape-scale assessment, planning, and wildfire response, but the ES scale is too detailed for these purposes. Therefore, NRCS has begun developing STMs for ES groups (ESGs) as a complementary product to the STMs already produced at the ES scale (Bestelmeyer et al. 2016). ESGs reduce the number of STMs by approximately one order of magnitude, which addresses the workload problem of developing interpretive information for many ecosystem services across multiple ecological states. With fewer total STMs, it should be easier to draft interpretations for states at the ESG scale and then apply the interpretation to similar STMs at the ES scale, for use in the short-term at least. The EDIT database includes a catalogue of STMs at the ESG scale, but unfortunately, EDIT is not designed to deliver interpretations for ecological states in a simple, intuitive format at the ESG or ES scale. As NRCS invests more resources in IT development, there may be an opportunity to redesign the EDIT data model to include tables, photos, graphs, and other functionality that better communicates interpretations of ecosystem services by ecological state (e.g., wildlife habitat, fire behaviour, water balance). The Grazing land Resource Analysis System is a software application that imports annual forage production values from EDIT directly into the conservation planning software used by NRCS planners. Similar upgrades to EDIT functionality promise to greatly improve the use of STMs.

Conclusions

Ecosystems are infinitely complex, and organizational development is complicated. It has taken several decades to work through the conceptual, administrative, technical, and utilitarian challenges facing broad-scale STM development, and now all the pieces are all in place to produce high quality STM products for the entire US. Perhaps other countries that value accessible, reliable ecosystem knowledge will benefit from these lessons learned in the 35 years of systematic STM development in the US.

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Establishing perennial pastures at Yalda Downs, western NSW

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Key words: Rangeland Restoration; Perennial Pastures; Regeneration; Biodiversity; Grazing

Abstract

The rangelands of NSW depend on rainfall driven native pastures to support privately managed grazing operations. The Perennial Pastures, Resilient Rangelands project aims to improve drought resilience by managing for biodiverse pastures with a focus on establishing and managing perennial species. Utilising a community of practice approach, landholders near White Cliffs collaborated with scientists and advisors to identify priority areas for restoration and implement innovative strategies to increase key perennial species. The group selected a stony plain on Yalda Downs north of White Cliffs and the landowner agreed to implement a demonstration site to trial regeneration strategies chosen by the group. Water ponding has been successfully demonstrated to improve scalded soils with low water infiltration, providing opportunities for seedling establishment leading to increased vegetation cover and plant diversity. However, establishment of key perennial grass and shrub species in these ponds is often limited. At Yalda Downs ripping, seeding of perennial grass and shrub species, and grazing exclosure treatments within water ponds were established in August 2023. Multiple rainfall events in early 2024 assisted with the early germination of perennial species (inc. *Astrebla spp*., *Panicum decompositum*, *Chloris truncata)* in the seeded treatments. The effectiveness of this trial is being monitored and species counts have shown establishment of sown seed and additional perennial species.

Introduction

Perennial species are important in the rangelands for both sustainability and productivity, protecting the soil surface during dry periods and being able to persist through dry seasonal conditions. A combination of prolonged droughts and high levels of total grazing pressure has resulted in considerable land degradation, including soil erosion and a loss of productive palatable, perennial species over extensive areas in western NSW rangelands (Green, 1989).

Regeneration strategies are often required to improve water infiltration and encourage seed germination and survival in degraded landscapes (Gintzburger, 1987; Kinloch and Friedel, 2005). Water ponding, water spreading and diversion banks have been used throughout Australia as an effective restoration method. Productivity has been reported to double within areas that have been water ponded compared to uneroded areas on the same soil (Cunningham, 1974a). Ripping and furrowing can encourage plant establishment by collecting moisture, litter, seed and reduce soil water evaporation (Gintzburger, 1987; Green, 1989; Rorive and Bainbridge, 1993). Attempts to rehabilitate semi-arid woodlands in Australia by reseeding bare areas with grasses have often been unsuccessful, and limited by seed supply (Broadhurst et al., 2015). Many studies concluded there is adequate seed naturally available to facilitate regeneration in the landscape. In addition, changes to grazing management can promote desirable plant species. In western NSW rangelands a tactical grazing approach is recommended (Hacker and McDonald, 2021) and resting after a major rainfall event allows establishment of key species (Hacker and Tunbridge, 1991; Sparrow *et al*., 2003). The aim of this study is to trial if ripping, seeding and grazing exclosure within ponding banks increase palatable perennial species density and diversity.

Methods

A demonstration site was established in 2023 located on an eroded and scalded area of Yalda Downs, ~60 km north of White Cliffs in far west NSW, Australia (30°18'28"S 143°01'28"E). The site is gently sloping, located in the Oakvale land system (Walker, 1991) with vegetation historically being primarily *Astrebla* (Mitchell Grass) grassland and chenopod shrubland, although very few perennial grasses were present. The climate is arid with an average annual rainfall of approximately 200mm.

One hundred and forty eight water ponds were established in July 2023 across ~80ha of predominately bare, stoney ground within a large (10,069ha) paddock on Yalda Downs. Ponds were constructed with a 12H Caterpillar (CAT) grader with a 14ft blade and rippers attached on the back, creating a bank ~0.5m high, ponding up to 10cm of water.

Five ponding banks of similar design were selected for monitoring in three replicate areas (15 ponds total), each receiving a different treatment:

1. Control (P), ponding only, without rip lines along the base of the pond
2. Ripping (PR), ponding with rip lines along base of pond
3. Ripping and Seeding (PRS), ponding with rip lines and seed added to ripped lines
4. Ripping and grazing exclosures (PRC), ponding with rip lines, and a 6 x 24m cage established at base of pond
5. Ripping, seeding and grazing exclosure (PRSC), ponding with rip lines and seed added to rip lines, and a 6 x 24m cage established at the base of the pond

Ripping treatments

Using a 12H Caterpillar (CAT) grader, 5 tines ripped the soil to ~30cm depth, with rows ~30cm apart, total 2m width, at the base on the topside of the ponding bank.

Seeding treatments

A list of desirable perennial species was generated for the site in collaboration with the Community of Practice and advisors. Not all desirable species were able to be sourced. Seed species sown included: *Cloris truncata, Astrebla lappacea, Astrebla pectinata, Pancium decompositum, Einadia nutans, Rhagodia spinescens, Enchylaena tomentosa, Atriplex semibaccata, Atriplex vesicaria* and *Atriplex nummularia*. For treatments with seed, seed was spread throughout the whole pond. Seeds were sown by hand, walking the length of the pond distributing seed evenly.

Cage treatments

A 6 x 24m cage was erected at the base of the pond, running parallel to the pond bank, constructed out of 5mm wire, 150mm x 100mm mesh, 1100mm high. Cages were erected in March 2024, to exclude the treatment area of being grazed by livestock and unmanaged herbivores. Although the paddock had been destocked of livestock between the time of ponding, sowing seed and the erection of the grazing exclosures.

Vegetation monitoring

At each ponded treatment (P, PR, PRS, PRC, PRSC), a permanent 20m transect was established at ~3m from the centre (top) of the bank, running parallel to the bank, with a star picket post at each end and a cattle tag denoting the treatment name and transect start. For treatments with exclusion cages, the transect was located inside the cage. The start and end points of each transect were marked on GPS and photo points (portrait and landscape) established at each transect.

Baseline monitoring of treatments was undertaken in August 2023, approximately 1-3 weeks after construction of the ponds and prior to any rainfall following the ponding. Measurements were repeated in September 2024.

Percent cover of each species present, herbage mass and percent cover of ground cover components (plant, litter, cryptogram, rock, course woody, dung, bare) was estimated in ten 0.5 x 0.5m quadrats along each 20m transect. The number of key perennial plant species within each quadrat was also recorded. All species one meter either side of the transect ($40m^2$ total) were identified, and the number of individual plants of key perennial species within this area counted.

In April 2024, ~7 months after seed was sown, establishment counts of the sown species were undertaken by recording the number of individual plants rooted within 0.5m either side of the 20m transect (total area $20m^2$).

Mixed effect models using the lme4 package in R (Bates et al. 2015; R Core Team 2021) were used to test the impact of treatment on plant and litter cover and herbage mass (log+1 transformation applied), with replicate and pond included as random effects. Anova was performed to test for significant differences between treatments ($P<0.05$).

Results

Rainfall

Summer rainfall recorded near the site resulted in totals of 54mm in December 2023, 98.5mm in January 2024 and 101mm in February 2024.

Groundcover and biomass

Overall, in September 2024, approximately 12 months after establishment of the trial, there were no significant differences in vegetative (plant+litter) ground cover ($P = 0.132$), with considerable variability depending on the pond and replicate (Fig. 1a). Herbage mass was significantly higher in the PRS treatment than the PR treatment ($P = 0.043$), but there were no other significant differences between treatments ($P>0.05$, Fig. 1b)

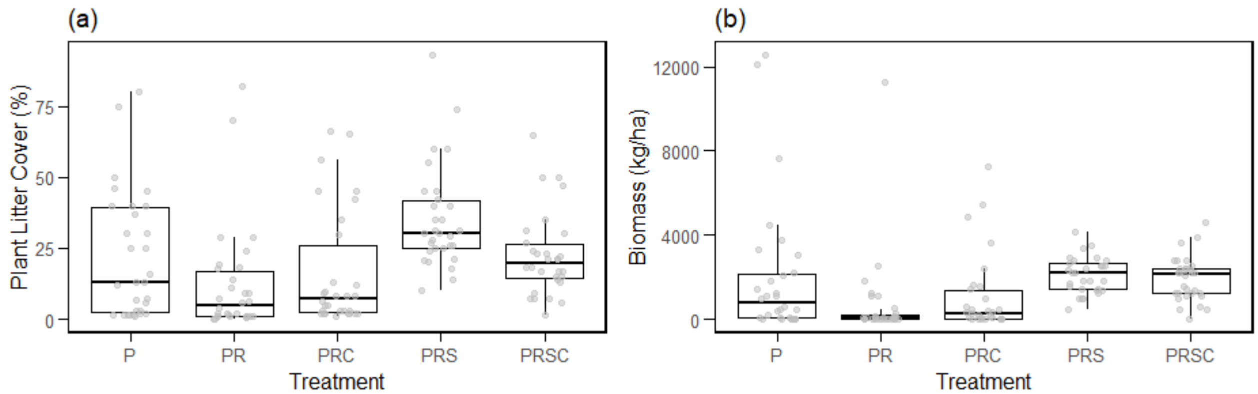

Fig 1. Boxplots of a) vegetative (plant + litter) cover and b) herbage mass across treatments in September 2024. P = ponding only, PR = Ponding and ripping, PRS = ponding, ripping and seeding, PRC = ponding, ripping and grazing exclosure, PRCS = ponding, ripping, seeding and grazing exclosure.

Species establishment

The seeded treatments (PRSC and PRS) saw *Chloris truncata* being a dominant species of sown seed with a ~9 plants per m^2 established, followed by a large count of *Panicum decompositum* and *Astrebla spp.* (Fig. 2). Other sown species, including *Einadia nutans, Rhagodia spinescens, Enchylaena tomentosa, Atriplex semibaccata, A. vesicaria* and *A. nummularia* were not present in transects in April 2024, and still had no to very low counts on assessment in September 2024.

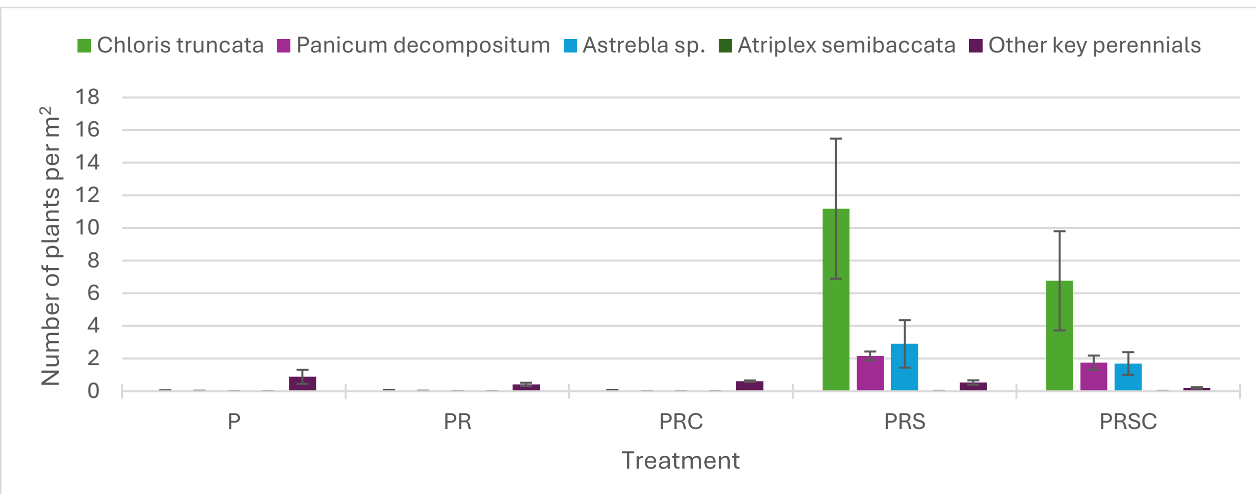

Fig 2. Average number of individual plants per m^2 of sown perennial and other perennial species recorded in different treatments in April 2024 (± 1 standard error) P = ponding only, PR = Ponding and ripping, PRS = ponding, ripping and seeding, PRC = ponding, ripping and grazing exclosure, PRCS = ponding, ripping, seeding and grazing exclosure.

Discussion

Summer rainfall in January and February of 2024 provided a germination opportunity for the seed that was sown the previous spring and continued favourable conditions throughout 2024 alongside the water ponding resulted in an increase of ground cover (>10%) in all treatments.

It has been well documented that supply and access to native species seed for large restoration projects can be limited and not efficient economically, however in this trial the treatments without seed showed a low response in perennial germination and ground cover compared to the treatments that had been seeded. Six different suppliers were required to source the quantity of seed necessary for this trial, and due to limited availability, we were unable to ensure local provenance, as would be preferable (Broadhurst *et al.* 2017). Access to limited species can also have an impact on the project outcomes and overall restoration (Broadhurst *et al.*, 2015; Broadhurst *et al.* 2017). This demonstration site used 13.51kg of seed and included differing rates of 10 different species of perennial grasses and shrubs. Although there has been success in germination and establishment of some species in the seeded treatments, the efficiencies in accessing the seed along with the economic investment should be considered alongside the risk of relying on the rainfall. By targeting seeding within water ponds this risk was reduced by increasing water availability for seed germination and establishment. Targeted seeding such as this may be a more practical and efficient approach to restoring perennial species in degraded landscapes more broadly in NSW rangelands. Early results (12 months from seeding) did not find an increase in ground cover, biomass or species germination with the removal of grazing (cage treatments). However, as the paddock was initially destocked, and later grazed by only 8 cattle, and with a favourable season reducing pressure from unmanaged herbivores within the ponded trial area, this was to be expected.

The ponding and ripping combination treatment (PR) had the lowest levels of ground cover, biomass and species establishment particularly in comparison to the ponding treatment alone (P). This was also evident when a cage was added to the treatment (PRC). Studies have shown that the effectiveness of ripping is highly dependent on the soil type and annual rainfall. Friedel at al. (1996b) found that soil disturbance techniques such as discing and pitting in the Northern Territory were successful when there was no more clay than a sandy loam.

When considering the efficiency of regeneration methods, it is important to consider the economic trade-offs and treatments across a large scale (Friedel at al.,1996b). The success of water ponding and seeding is evident in this trial however the cost relative to benefit of seeding is still in question on a broad scale application. The success of ripping should be considered alongside other treatments and soil types while a longer timeframe is required to assess the impact of the exclosures to control grazing.

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Complex nature of South Australian Pastoral Lands

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Key words: desert; landscape; pastoral; conservation

An overview

South Australia (SA) is the driest state in the world's driest inhabited continent. The "SA Outback" constitutes more than 80% of the State's land area or approximately 741 000 km^2. About half of this is allocated to conservation areas and Aboriginal land use – the remainder consists of pastoral stations. There are 219 stations that make up the pastoral estate in South Australia.

Socioeconomic features

The South Australian pastoral lands have long held significance as both economic resources and cultural landscapes, shaping the history, environment, and economy of the region. Covering vast semi-arid and arid regions, these lands have been utilised primarily for grazing livestock, particularly sheep and cattle, since the early 19th century. Today the many land uses occurring in the region include pastoralism, mining and petroleum extraction, conservation, renewable energy and tourism.

The pastoral estate is made up of a number of community-based districts which were originally based on Soil Conservation Boards. These districts now form the Landscape SA groups of today which link local communities to the South Australian Arid Lands Landscape Board (SAAL). There are six groups in the in the SAAL region and a seventh group in the Murrylands and Riverland Landscape Region the southernmost pastoral zone (Figure 1).

The pastoral estate is comprised of pastoral leases. Each lease is a rolling 42 year term which is reviewed every 14 years (lease assessment) and then extended to the full term of 42 years. There are 219 individual pastoral stations which may comprise of one or many pastoral leases, and cover an area of approximately 422,000 km^2. The properties or stations are operated by 160 individuals or companies and the pastoral estate (leases) is administered by the Pastoral Board of South Australia.

South Australian Dog Fence

The dingo or wild dog is Australia's only native canid, and freely roams much of inland Australia. The South Australian Dog Fence, approximately 2250 km long, runs through the pastoral lands from the New South Wales border to the east, around the North Flinders, across the middle of the state between Lake

Torrens and Kati Thanda – Lake Eyre South and then south to the cliffs of the Nullarbor Plain above the Great Australian Bight. The fence was built in sections as the pastoral estate was expanded in South Australia from the late 1800's, initially as a rabbit proof fence and then later heightened to exclude the dingo and wild dogs. In 1947 the Dog Fence Act came into operation and established a formal dog-proof fence "for the purpose of preventing the entry of wild dogs into the pastoral and agricultural areas of the State'. Today the fence creates a wild-dog free area to the south enabling grazing by both sheep and cattle, and the area north of the fence predominantly cattle and where wild dogs are still present.

Biophysical features

The geology and topography of the state consists of sandy deserts to the north and west, large inland salt lakes separated by ancient mountain ranges, saltbush and majestic tree woodlands, grassy tablelands, broad gibber plains and large free-flowing arid waterways which drain through vast lagoons and swamps into arid inland salt lakes.

The climate of the pastoral zone varies from the north to the south and east to west as South Australia is affected by weather patterns in the Pacific, Indian and Southern oceans. Both temperature and rainfall vary across the pastoral zone as a result of the latitudinal gradient affecting the weather patterns through-out the year with the north experiencing very hot summers and the east having freezing conditions in the winter.

Average annual temperatures have been gradually increasing in South Australia since the early 1970's with the highest rates of increase occurring in the north of the pastoral zone with mean annual temperatures having increased by 1.5 degrees Celsius (ºC) over the past 50 years. The hot summers in the north and north-east can see temperatures exceeding 40 ºC for a number of successive days. Climate scenarios are predicting potential average daily temperature increases of up to 2.2 ºC by 2050.

Rainfall trends vary across the pastoral zone, with averages ranging from 150 mm in the east and south, up to 300 mm on the highest reaches of the Flinders ranges in the North Flinders region. Thunderstorms and tropical inflows in the north can result in short but intense rain events that may produce a year's rainfall in one event. The northern rangelands are dominated by summer rainfall, with cyclonic weather systems of northern Australia entering SA from the north-west or occasionally from south-west Queensland. The southern portion of the rangelands is dominated by winter rainfall with cold fronts coming up from the south-west. Regional variation show that the far north of the pastoral zone is experiencing an increase in summer rainfall and the winter rainfall of the southern areas decreasing over the last 30 years. In general, the extremes in summer temperatures that occur across the pastoral zone often result in evaporation rates far exceeding rainfall.

These climatic variations across the pastoral region are reflected in the many diverse landscapes and associated vegetation communities that form the seven landscape regions.

Regional Features

Marree – Innamincka region

The Marree Innamincka region is in the far north-east of the state extending over 200 000 km2 or 20% of SA. This region contains free flowing arid rivers of the Diamantina and Cooper systems comprising the Goyder lagoon and the Coongie lakes near Innamincka. Both systems flow because of monsoonal rains in central and south-western Queensland and which, on extreme and rare rain events, will eventually empty into Kati Thanda - Lake Eyre. Sandy desert landscapes also dominate the region with the Simpson Desert, Strzelecki, and Tirari Deserts. Less extensive, the Sturt Stony Desert lies between the river channel country and is comprised of extensive flat clay dominated gibber (small, polished stones) plains with very sparse vegetation, scattered dunes and productive sand mounds. Land use is primarily pastoral with oil and gas production in the eastern parts with private and state conservation parks forming part of the increasing tourism industry.

Marla – Oodnadatta region
The Marla Oodnadatta region is in the far north of the state covering an area of 132 400 km2. The region comprises numerous landscapes, ranging from sweeping gibber plains with fertile sand lenses and dunes, tablelands with numerous drainage lines running east to Kati Thanda – Lake Eyre. There are weathered hills and plateaus forming "Breakaways" and extensive gibber plains with scattered gilgais containing perennial grasses and chenopod shrubland vegetation. Mulga woodlands scattered across the region on the sandier soils. A number of Conservation areas occur in the region and ancient mound springs of the Great Artesian Basin still occur in a number of areas. Land use is pastoralism with key resource mining, private conservation, and mining of precious stones of the Coober Pedy and Andamooka opal fields.

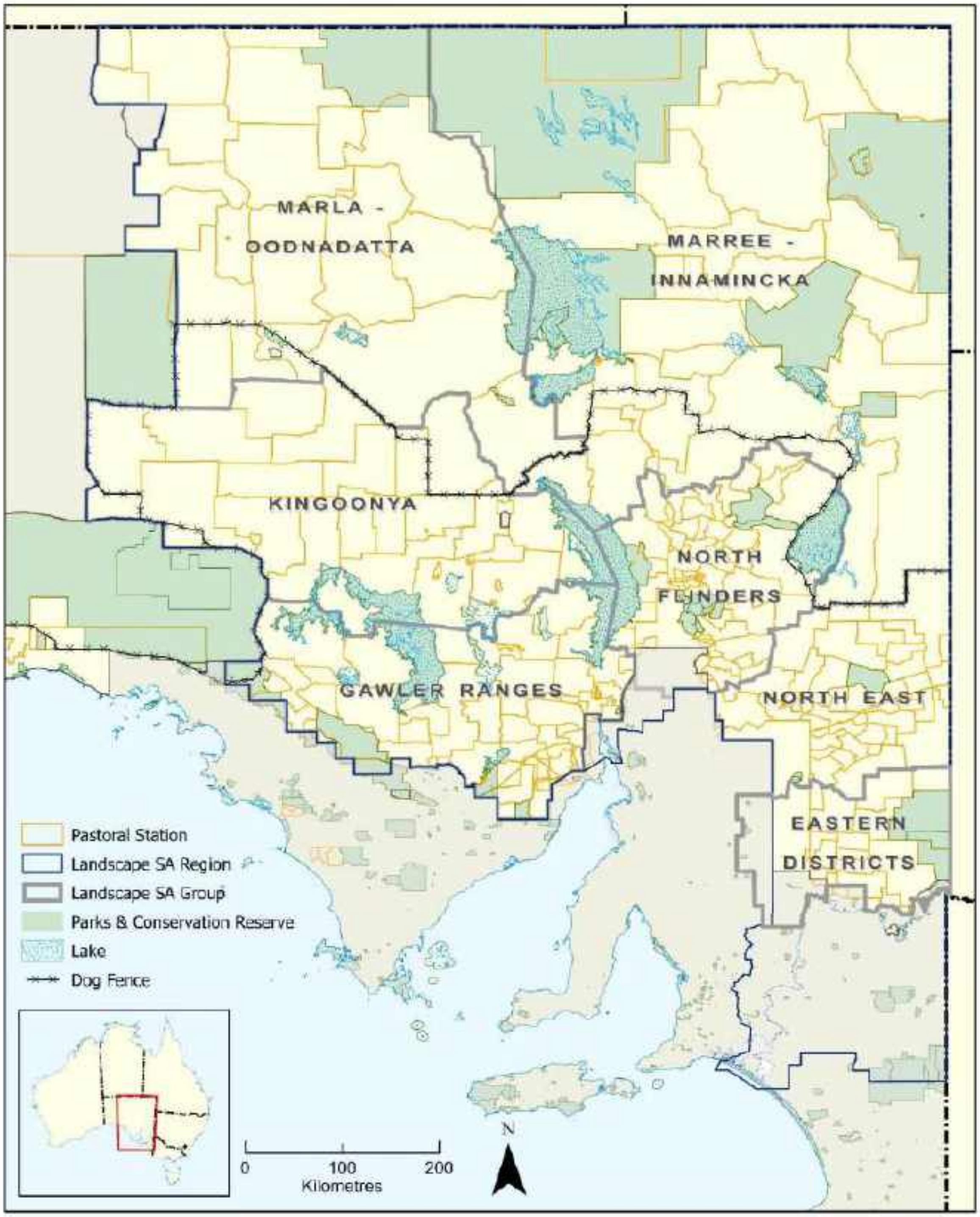
Kingoonya region
The Kingoonya region is in the centre of South Australia and covers 65 815 km2. This region is bounded by the Dog fence to the north and west and large salt lakes to the south and east. The national railway network crosses the region both the north-south and east-west. Vegetation is comprised of mulga and myall woodlands with chenopod shrublands, mallee dune systems and treeless undulating tablelands of low chenopod shrublands. The primary land use is sheep pastoralism with several properties running cattle enterprises. Mining and conservation are also represented with several large mines, the largest of which is Olympic dam, and one of the earliest pastoral leases purchased for private conservation, Bon Bon Station, also occurring in the region.

Gawler Ranges region
The Gawler Ranges region is 51 900 km2 in size and is comprised of several large salt lakes, including Lake Everard and Lake Gairdner and the rounded rocky hills and broad valleys of the Gawler Ranges. These ranges form the principal component of the region and are dominated by chenopod shrublands and mixed woodlands of mulga, black oak, myall and wattle. The region also has a system of parallel dunes with plains and salt lakes. Mallee, myall, sugar wood and mulga woodlands with chenopod shrublands occur across the region. The primary land use of the region is pastoralism with the first pastoral leases established in the 1850's.

North Flinders region
The North Flinders region lies between Lake Torrens, Lake Frome and south of Kati Thanda - Lake Eyre being 33 500 km2 in size and encompassing the Flinders and Gammon Ranges. The dog fence bounds the north and east of the region. This diverse landscape is comprised of plains, rugged ranges and outcrops. The complex nature of the ranges gives rise to the many landscapes of the region ranging from alluvial plains with mixed grasses and chenopods, undulating grassy gibber tablelands and plains to gentle rises and hills of annual grasses and chenopods. The ranges vary from shaley hills of mallee and pine, sandstone hills of mallee and mulga to high rugged ranges with cypress pine, spinifex and grasses and deep red gum gorges. Pastoralism began in the region in the early 1850's and continues today as the primary land use. Tourism and conservation have increased with many properties having accommodation facilities for visitors. Formal conservation in the region is supported through three national parks occurring in the region: Ikara – Flinders Ranges, Vulkathunha – Gammon Ranges, and Nilpena Ediacara National Park.

North East region

The North East pastoral region is 34 500 km2 and is bounded by the Dog fence to the north and the New South Wales / South Australian border to the east. The main feature of the region is the Olary Spur, a series of ancient hills, geologically an extension of the Flinders Ranges. The region also comprises flat to undulating plains with chenopod shrublands and areas of low woodlands and shrublands. The Olary Spur consist of chenopod plains and open woodlands with numerous water courses and river red gum lined creeks. Mallee box open woodlands can be found on hills and ridges with mallee, sugar woods, and black oaks woodlands with chenopod shrublands with mallee on the sand plains and low dunes. To the north of the region chenopod shrublands and grasslands on open plains and rises and low hills are a major feature of the landscape. The major land use of the region is pastoral grazing of sheep for wool production and some cattle enterprises. Other land uses include mining and conservation with several conservation areas previously being operational pastoral enterprises.


MARLA -
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NORTH
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GAWLER RANGES
NORTH EAST
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Landscape SA Region
Landscape SA Group
Parks & Conservation Reserve
Lake
Dog Fence
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100
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Eastern District region

The Eastern District region is the smallest in SA at 22,240 km2 and contains the most southern pastoral leases administered by the Board forming the northern half of the Murrylands and Riverland Landscape Region. The pastoral properties of the region encompass both sheep and cattle production along with individual conservation leases and adjoining large conservation parks on the eastern boundary. The landscape is diverse ranging from alluvial and gentle plains with black oak and chenopod shrublands, sand plains and dune fields of extensive mallee occupying half of the district, through to chenopod shrublands and grasslands.

Further Information – Government of South Australia

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Impact of high-density grazing compared to conventional grazing on the woody vegetation of the Kalahari Savannah of South Africa

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Key words: bush encroachment, stocking rate

Abstract

Kalahari Savanah rangeland of Southern Africa is known for well-balanced herbaceous and woody layers. Historic use of conventional grazing, with long grazing periods and insufficient rest periods, caused bush encroachment. High density grazing might prevent bush encroachment. Two grazing approaches were compared to quantify their impact on tree density. The conventional grazing (CG) approach consisted of four camps. Cattle grazed each camp for 14 days, at a grazing pressure of 0.5 large stock units (LSU) per hectare (ha), followed by 42 days of rest. This equates to a stocking rate of 8 ha per LSU. For the high-density (HD) approach, camps were grazed one to two days, at 27.5 LSU/ha, with rest periods of 120 days. Which equates to a stocking rate of 4 ha per LSU. Surveys were done along a 100m x 2.5m belt transect (four replicates, three distances from watering point), using the Biomass Estimates from Canopy Volume model (BECVOL). This method measures woody species richness, total tree density (plants ha^{-1}), total dry matter production estimates (kg DM ha^{-1}) and Total Evapotranspiration Tree Equivalents (ETTE ha^{-1}). Tree density was lower at HD (780 plants ha^{-1}) compared to CG (1 077 plants ha^{-1}), ($P > 0.05$). Evapotranspiration tree equivalents was significantly ($P < 0.05$) lower at HD (1 605 ETTE ha^{-1}) than at CG (2 295 ETTE ha^{-1}). Total woody biomass production was almost similar for CG (2 730 kg DM ha^{-1}) and HD (2 790 kg DM ha^{-1}). Seedling density was significantly ($P < 0.05$) higher at CG (1 303 plants ha^{-1}) than at HD (684 plants ha^{-1}). High-density grazing generally had a far less negative impact on tree density than conventional grazing. It can therefore be concluded that a HD grazing approach could contribute positively towards ecosystem health in the Kalahari Savannah of South Africa.

Introduction

Pristine Kalahari Savanah rangeland of Southern Africa is known for well-balanced herbaceous (grass) and woody (tree and shrub) layers (Mucina and Rutherford, 2006). Historic application of continuous grazing and later conventional rotational grazing systems, with long grazing periods and insufficient rest periods, has caused bush encroachment (Smit 2004, Ward 2005, Bond & Midgley 2012, Belayneh and Tessema 2017). High density grazing, which entails higher densities of grazing livestock for shorter periods, followed by longer resting periods, proofed to enhance general ecosystem health (Chaplot et al. 2016; Malan 2022; Malan and Paulse 2023). This method of grazing forms part of regenerative grazing which has the benefit, amongst others, of preventing bush encroachment (Teague and Barnes 2017; Franke and Kotze 2022, Gebremedhn et al 2023). The objective of this study was to compare the tree densities of two adjacent farms, one under conventional grazing and the other under high density grazing.

Methods

The study area is situated within the Kalahari bushveld bioregion (SVk 1, Mafikeng bushveld), (Mucina and Rutherford, 2006), with a long-term grazing capacity of 8 ha LSU^{-1} (hectare per Large Stock Unit) as indicated in the Long term Grazing Capacity Provincial Maps (2018). This region is characterized by a well-developed grass layer consisting of species such as *Stipagrotis uniplumis, Eragrostis lehmanniana, Schmidtia pappophoroides* and *Schmidtia kalihariensis* (Mucina and Rutherford, 2006; Sandhage-Hofmann et al. 2015). The dominating trees and shrubs are: *Dichrostachys cinerea, Grewia flava, Grewia retinervis, Tarchonanthus camphoratus, Vachellia erioloba, Vachellia hebeclada,* and *Ziziphus mucronata* (Mucina and Rutherford, 2006). The aim was to compare the vegetation dynamics of two adjacent, commercial cattle farms, who were grazed at different grazing approaches over a 20-year period. Two grazing approaches were compared to quantify their impact on the density of woody vegetation. The conventional grazing (CG) approach (normal stocking rate of 8 ha/LSU per year) consisted of four camps, 62 ha each. Cattle (Brahman cross breeds, mean cow weight 550kg, weaning rate 95% at 260kg) grazed each camp for 14 days, at a low stocking density of 0.5 large stock units (LSU) per hectare (ha), followed by 42 days rest. For the high-density (HD) approach (double the stocking rate at 4 ha/LSU per year) camps (10 ha each) were grazed (with Bovelder cross breed cattle, mean cow weight 470kg, weaning rate 98% at 230kg) one to two days at a high stocking density of 27.5 LSU/ha, with rest periods of 120 days.

Surveys were done along a 100m x 2.5m belt transect (four replicates at each of three distances from watering point), using the Biomass Estimates from Canopy Volume model (BECVOL) (Smit 1996; Smit 2014). This method measures woody species richness, total tree density (plants ha^{-1}), total dry matter production estimates (kg DM ha^{-1}) and Total Evapotranspiration Tree Equivalents (ETTE ha^{-1}). The ETTE is defined by Smit (2014) as the leaf volume equivalent of a 1.5m single-stemmed tree. The SPPS statistics for windows package was used for statistical analyses (IBM, 2017)

Results

Results are summarized in Table 1. Total woody biomass production was almost similar for CG (2 730 kg DM ha^{-1}) and HD (2 790 kg DM ha^{-1}), while the other characteristics had big differences. The reason for similar biomass is due to the presence of more big trees in relation to small trees on the HD farm. This phenomenon usually corelates with a healthier savanna ecosystem (Bond and Midgley 2012; Smit 2022). Tree density was lower at HD (780 plants ha^{-1}) compared to CG (1 077 plants ha^{-1}), ($P > 0.05$). Evapotranspiration tree equivalents was significantly ($P < 0.05$) lower at HD (1 605 ETTE ha^{-1}) than at CG (2 295 ETTE ha^{-1}). The higher number of ETTE's on the CG farm is an indication of more, but smaller trees, an indication of a bush encroached area (Belayneh and Tessema 2017; Smit 2022). Similar results were found with seedling density, which was significantly ($P < 0.05$) higher at CG (1 303 plants ha^{-1}) than at HD (684 plants ha^{-1}). The majority of the seedlings present on the CG farm was that of unwanted species like *Dichrostachys cinerea* and *Gymnosporia buxifolia*.

Table 1: Mean tree density, ETTE, total biomass production and seedling density of woody plants for two grazing approaches. (mean ± SE).

Woody layer	**CG**	**HD**
Tree density (Plants ha^{-1})	1 077 ± 42	780 ± 46
ETTE (ETTE ha^{-1})	2 295 ± 59	1 605 ± 55*
Total biomass (kg DM ha^{-1})	2 730 ± 74	2 790 ± 99
Seedling density (Plants ha^{-1})	1 303 ± 19	684 ± 15*

*P < 0.05. Total Evapotranspiration Tree Equivalents (**ETTE**), Grazing approaches [conventional grazing (**CG**), high-density grazing (**HDRa**).

Although this paper focusses on the woody layer, it is worth mentioning that CG had a lower veld condition score of 412 compared to 581 of HD, while the percentage of perennial grasses was also higher (64%) at HD than at CG (43%).

Discussion

Bush encroachment due to wrong grazing practices is a huge problem in the savanna areas of the world (Kgosikoma and Mogotsi 2023; Di Virgilio et al. 2019, Gebremedhn et al. 2023). Such grazing practices includes continuous grazing and approaches with long grazing periods and improper resting periods. High density grazing leads to a high grazing impact for a short period, followed by an extended rest (recovery) period (Chaplot et al. 2016, Franke and Kotzè 2022). This grazing approach is believed to hold many benefits by improving soil health, vegetation health and animal health (Hawkins et al. 2017; Malan 2022). In this study, high-density grazing generally had a far less negative impact on the density of woody vegetation than lower density (conventional) grazing. It can therefore be concluded that a HD grazing approach could contribute positively towards ecosystem health in the Kalahari Savannah of South Africa.

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Economic impact associated with Leaf blight damage in buffelgrass seed production in central Sonora, Mexico

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Key words: *Pennisetum ciliare*, Sonoran Desert, *Pyricularia*, seed quality.

Abstract

Buffelgrass (*Pennisetum ciliare*) leaf blight is a disease caused by the fungus (*Pyricularia grisea*), which may kill plants and reduce the quantity and quality of foliage and seeds. The study was conducted on three ranches during 2016-2017 in Sonora, Mexico, to determine the effect of leaf blight on seed production and the economic impact on ranchers. Pastures damaged by the pathogen were selected to evaluate the number of affected plants, plant density, raw and clean seed production, seed cost, net gain from seed sales, and economic loss. Data were analyzed using ANOVA ($P \leq 0.05$). Precipitation was 10 to 40% above the average at all sites and in all years of the study. From 46 to 59% of the buffel grass plants showed some damage. Null to very light plant damage was found in 31.5-36.6% of the plants, slight damage in 21.3-42.8%, and moderate damage in 25.7-42.1%. The production of raw seed was affected ($P \leq 0.05$) by the damage from the fungus and varied from 61.4-81.8 kg/ha for no damage, 46.2-53.8 kg/ha for light damage, and 28.6-36.9 kg/ha for moderate damage. The cost of clean seed for sale averaged $90.00 Mexican pesos during 2017 and 2018, and the clean buffelgrass seed produced differed ($P \leq 0.05$) among treatments. It averaged 41.27, 30.9, and 17.3 kg/ha for areas with no damage, light damage, and moderate damage, respectively, representing a net profit from seed sales of $3,714.3, $2,781.0, and $1,557.0 pesos/ha for areas with no damage, light damage, and moderate damage, respectively. Therefore, the loss caused by fungal damage was $933.0/ha in areas with light damage and $2,157.3/ha in areas with moderate damage. We concluded that leaf blight affects the seed production of buffelgrass, and necessary measures must be taken to reduce plant and seed damage.

Introduction
Buffelgrass leaf blight is a disease caused by the fungus (*Pyricularia grisea*), (*Magnaporthe oryzae*) or (*Magnaporthe grisea*) which reduces the quantity and quality of the foliage and the amount and quality of seed produced by the grass. The grass has been successfully established in more than 2 million hectares in Mexico and in more than 30 million hectares in different regions of the world (Ibarra et al., 1989; Cox et al., 1988). In Northeast Mexico and Southeast United States reductions between 10 and 50% in grass production are reported (Rodriguez et al., 1999; Diaz et al., 2007). More recently, under the climatic conditions of Northwestern Mexico, leaf blight damage has been also reported with severe foliage and seed damage (Ibarra et al., 2022). Perrott and Chakraborty (1999), report similar results in foliage and seed damage by the fungus in buffelgrass in rangelands at Queensland Australia.

The buffel blight fungus is very small and cannot be seen with the naked eye, it lives in the ground and in the base of the plants, can last several years there and it is moved by wind, water, livestock and man (Ibarra *et al*, 2022). Severe damage can reduce the amount of dry forage by 25 and 62% and between 20 and 55% the nutritional quality of the grass. During severe attacks total buffelgrass seed production may be reduced by 45 and 60% and in years even with less humidity, less severe attacks may appear, and they can kill from 20 and 35% of the grass seed. Several million ha of desert brushland has been planted with buffelgrass to restore productivity. Forage production and cattle numbers in these areas have five to ten-fold (Martin *et al*., 1995) and a decline in forage production by fungus damage will reduce meet production and ranchers' income. Information that shows how *Pyricularia* will affect buffelgrass forage production as well as seed quantity and quality does not exist. The objective of this study was to measure how much buffelgrass forage and seed will be affected by the fungus at different ranches in central Sonora Mexico.

Methods
The study was conducted on three ranches during 2016-2017 in Sonora, Mexico, to determine the effect of leaf blight on seed production and the economic impact on ranchers. Ranches selected were la Loma, located 15 km west of Santa Ana; El Águila ranch, located 20 km south of Santa Ana, Sonora; and Pozo Crisanto ranch, located 86 km north of Hermosillo. Pastures damaged by the pathogen were selected to evaluate the number of affected plants. Evaluated variables were number of young and adult plants affected, plant density, gross seed production, clean seed production, percentage of loss in harvested seed, seed cost, net profit from seed sales and economic loss due to fungus damage. The number of damaged and undamaged adult and young plants was determined by quantifying the total number of plants present in 10 quadrats of 10 x 20 m in each ranch. In each plot, the degree of damage was quantified in three categories. The scale used was created using the three categories: (1) No damage or very slight damage, when the plants showed green foliage and no chlorotic or spotted symptoms typical of the pathogen were present and less than 10% damage was shown in the total of foliage, (2) Light damage, when the plants showed between 11 and 30% of the leaf material damaged, and (3) Moderate damage, when the plants showed between 31 and 50% of foliage with damage. Data were analyzed using ANOVA ($P \leq 0.05$ (Steel and Torrie, 1980)). To estimate the cost of clean buffel grass seed, three of the main harvesters and seed producers in the state were interviewed in order to ask the cost of selling it during the production periods of 2017 and 2018, which resulted in $90.00 per kilogram for sale, with an average germination that varied from 27.9 to 37.8% and a viable seed percentage from 79.5 to 92.0%, the same information was compared with the Department of Machinery Division of the Cattlemen Union of Sonora, (UGRS, 2017). The net profit from the sale of seed in each farm was estimated by multiplying the kg of clean seed/hectare harvested in each farm, by the cost of the clean seed assigned previously. The economic loss in seed production associated with *Pyricularia*

damage was determined by difference, comparing its production in areas with light and moderate damage against the production achieved in areas without damage.

Results

Precipitation was 10 to 40% above the average at all sites and in all years of the study. From 46 to 59% of the buffel grass plants showed some damage. Leaf blight caused significant damage ($P \leq 0.05$) to buffelgrass plants at all evaluation sites (Table 1). Null to very light plant damage was found in 31.5-36.6% of the plants, slight damage in 21.3-42.8%, and moderate damage in 25.7-42.1%. More importantly, even new buffelgrass seedlings 5 to 10 cm tall show severe fungus damage.

Although on average 38.9% of the total plants in the grasslands showed no to very light damage, 61.1% showed light to moderate damage. Adult plants, which generally represent the largest volume of coverage of the occupied land, showed a varied intensity of damage. Lightly damaged plants represented between 31.5 and 48.7% of the plants in all farms, with moderate damage between 19.8 and 42.8% of the plants were detected and with intense damage between 25.7 and 42.1% of the plants.

The production of raw seed was affected ($P \leq 0.05$) by the damage from the fungus (Table 2) and varied from 61.4-81.8 kg/ha for no damage, 46.2-53.8 kg/ha for light damage, and 28.6-36.9 kg/ha for moderate damage. Clean seed was also affected by the pathogen. The cost of clean seed for sale averaged $90.00 Mexican pesos during 2017 and 2018, and the clean buffelgrass seed produced was different ($P \leq 0.05$) among treatments. Clean seed averaged 41.27, 30.9, and 17.3 kg/ha for areas with no damage, light damage, and moderate damage, respectively, representing a net profit from seed sales of $3,714.3, $2,781.0, and $1,557.0 pesos/ha for areas with no damage, light damage, and moderate damage, respectively. Therefore, the loss caused by fungal damage was $933.0/ha in areas with light damage and $2,157.3/ha in areas with moderate damage.

Table 1. Degree of leaf blight damage in adult buffelgrass plants in three locations during the summers of 2016 and 2017 in the central region of Sonora, Mexico.

Degree of Damage	Ranches			Average
	La Loma	El Águila	El Pozo	
None to very Light	31.5 b*	36.6 b	48.7 a	38.9
Light	42.8 a	21.3 c	19.8 c	28.0
Moderate	25.7 c	42.1 a	31.5 b	33.1
Total	100	100	100	100

* Means between treatments with different lowercase letters are different ($P \leq 0.05$).

Table 2. Production of raw seed of buffelgrass (kg/ha) affected in various intensities by leaf blight during the summers of 2016 and 2017 in three cattle ranches in the central region of Sonora, Mexico.

Degree of Damage	Ranches			Average
	La Loma	El Águila	Pozo Crisanto	
None to very Light	81.8 a*	71.9 a	61.4 a	71.7
Light	53.8 b	46.2 b	48.4 b	49.5
Moderate	36.9 c	28.6 c	34.6 c	33.4
Average	57.5	48.9	48.1	

* Means between treatments with different lowercase letters are different ($P \leq 0.05$). The average is the result of two years of harvest.

Discussion

The results of this study agree with those reported by FAOSTAT (2010); Baker et al. (1997), Yoon et al., (2011) and Shirasawa et al. (2012), on the susceptibility of the grass family such as corn and rice, reporting that the plants are not equally damaged by *Pyricularia,* varying from 10 to 15% of the annual yield losses. In the case of common American buffelgrass, the results in this study show a reduction in foliage of 61% in plants that present light to moderate damage. In Tamilnadu, India, in rice cultivation this is one of the most devastating diseases in susceptible cultivars, causing a yield loss of up to 90% (Mehrotra, 1998; Jaiganesh et al., 2007).

Blight affects the foliage of plants, directly interrupting the synthesis of chlorophyll production, which influences the seed production capacity and quality of the affected plants (Díaz et al., 2007), Consequently, the spikes do not develop completely, since the florets do not have complete caryopses or are empty. On the other hand, it has been shown that the quality of the seed is affected due to the physiological disorders suffered by the plant, reporting losses of up to 11% of chlorophyll, 20 to 26% in biomes, 13% in protein and 30% in the digestibility (González, 2002). This is very important, especially for producers who sow or use the seed for the rehabilitation of buffel pastures, since, in the grass seed, the pathogen is found that can be transmitted and transported to other areas where it does not exist and runs the risk of contaminating

Conclusions and implications

Common buffelgrass plants were damaged by leaf blight, but not all plants in the prairie were similarly affected, seedlings from 5 to 10 cm tall were also severely attacked by the pathogen. We concluded that leaf blight affects the seed production of buffelgrass, and necessary measures must be taken to reduce plant and seed damage. Ranchers with buffelgrass pastures under similar conditions can expect a 25.1 to 58.0% decrease in annual seed production, representing approximate losses of $933.00 to $2,157.00 pesos per hectare per year.

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Larger trees facilitate understory herbaceous biomass but not diversity in a South African savanna

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Keywords: Grass biomass; grass cover; invasive species; species richness; tree architecture; woody plant encroachment

Abstract
Large single-standing trees contribute to the structural diversity of savannas as they strongly influence their immediate surroundings such as soils and understory plant communities. The influence of woody vegetation at a stand level on the understory vegetation has been extensively studied; however, the understanding of the role of single large trees is limited. The objectives of the study were to 1) evaluate the impact of large trees on understory plant species diversity and composition, herbaceous cover and grass standing biomass, and 2) to establish if plant size and functional qualities such as N-fixing ability modulate understory vegetation responses to overstory trees over two growing seasons (January 2022 and 2023). *Vachellia tortilis* (a leguminous tree) and non-leguminous woody species (*Searsia l*ancea and *Ziziphus mucronata*) were studied. We systematically selected 30 trees for each woody species and divided them into two size classes (i.e. small and large trees). Understory plant vegetation was assessed using quadrats under and outside the tree canopies. Plant species diversity and abundance were highest under small tree canopies and outside tree canopies compared to under large trees. Panicum maximum was the dominant grass species under large trees regardless of N-fixing ability. Nonetheless, grass cover was enhanced under large *V. tortilis* and *Z. mucronata*. Standing grass biomass was higher under the canopies of large trees compared to small trees and outside canopies, with N-fixing ability having no significant effect ($p > 0.05$). The current findings imply that in agrosilvopastoral systems and game farming, where ecological conservation is a priority for farmers, it is essential to have an overstorey composed of both small and large trees to sustain understory diversity and biomass.

Introduction

Our understanding of the role of trees of varying sizes and functional qualities is limited (Pillay and Ward, 2012). There is a considerable variance on the impact of large trees on the understory vegetation. For instance, studies conducted in a semi-arid savanna of Ethiopia have found that large trees enhance herbaceous understory richness and biomass, with significant increases recorded under N-fixing leguminous trees (Tessema and Belay, 2017). Other studies conducted in South African savannas have found non-significant effects, particularly on standing herbaceous biomass, regardless of N-fixing ability (Treydte et al., 2007).

Nonetheless, certain nitrophilous grasses, particularly *Panicum maximum* (Jacq) have been documented to colonise and flourish under trees (Smit, 2005). *P. maximum* is a shade-tolerant and highly competitive grass species (Smith et al., 2013). Consequently, *P. maximum* may threaten species richness and diversity under tree canopies. Nevertheless, effects of woody plants to understory may vary by encroaching species, and understory herbaceous species (Kahi et al., 2009), thus, site-specific assessment of herbaceous plant responses to overstory trees is crucial.

Methods and Study Site

The study was conducted at Roodeplaat experimental farm (25°56′S, 28°35′E) of the Agricultural Research Council (ARC) in Gauteng Province of South Africa. Three dominant woody species representing one leguminous (*Vachellia tortilis*) and two non-leguminous tree species (*Searsia lancea* and *Ziziphus mucronata*), found in isolation, were selected for this study. These woody species are representative of the dominant trees in the study area. We systematically selected 30 trees for each woody species and divided them into two size classes (i.e. small and large trees). Small trees had a similar canopy area (≈ 10 m^2) and height (≈ 3 m). Large trees also had a similar canopy area (≈ 40 m^2) and tree height (≈ 6 m) (Ludwig et al., 2004). In total 90 trees (three species × 30 trees) were selected for this study in a permanently fenced area where grazing was excluded.

We recorded the species composition of understory vegetation including herbaceous species as well as seedlings of woody species under and outside individual tree canopies over two growing seasons (January 2022 and 2023). Four quadrats (0.5 m × 0.5 m) in four directions (north, south, east and west) were used for herbaceous assessments under the inside and outside canopy (i.e. the area surrounding the canopy within a 2 m range) of each individual tree. Outside canopy sampling points functioned as a control for possible changes in microclimate or plant cover in the understory. To ascertain the relative contributions of each functional group, the species were further divided into grasses, forbs and woody species. All individual plant species were counted and identified to species level in each 0.5 m × 0.5 m quadrat. Herbaceous cover (grass and forb) was visually assessed within the quadrat by two individuals, and their estimates were subsequently averaged to produce a single representative measurement. Standing grass biomass regardless of species was harvested in each 0.5 m × 0.5 m quadrat. The grass samples were oven dried at 70ºC for 72 h and weighed to determine dry-matter yield.

A two-way ANOVA was conducted using general linear models (GLMs) to determine the main effects of tree species and microsites on mean total species richness and diversity, herbaceous cover and standing grass biomass.

Results

A total of 26 plant species were recorded with perennial species being the most abundant, with grasses recording the highest contribution (n = 14). Poaceae was the most dominant family with predominantly native species, whilst forbs were mostly invasive species.

Plant species diversity was substantially affected by microsites ($F = 26.429$; $p < 0.001$), tree species ($F = 11.818$; $p < 0.001$) and their interactions ($F = 5.723$; $p < 0.001$). A Bonferroni post hoc test indicated that small *S. lancea*, *Z. mucronata* and *V. tortilis*, and outside of the canopies recorded a greater species diversity compared to large *S. lancea* and *Z. mucronata*. Plant species richness was significantly greater under small trees and outside canopies than under large trees ($p < 0.05$), particularly under large *S. lancea* and *Z. mucronata*.

Grass cover was substantially low under large *S. lancea* trees compared to outside canopies, and under large V. tortilis and Z. mucronate ($p < 0.05$). Large trees of *S. lancea*, *V. tortilis* and *Z. mucronata* significantly increased understory standing grass biomass ($p < 0.05$). In addition, large *S. lancea*, *V. tortilis* and *Z. mucronata* trees were associated with a higher abundance the highly nutritious *P. maximum* than other understory grass species.

Discussion

Effects of mediated microsites on plant species diversity and richness

Reduced species diversity under large trees could be attributed to the dominance of *P. maximum* under large trees, which significantly reduced understory diversity and richness. In support, Mlambo et al., (2005) demonstrated that *P. maximum* increases in abundance under large *Colophospermum* mopane trees. The findings from the current study suggest that an increase in abundance of *P. maximum* under tree canopies result in a significant reduction in understory species diversity. Nonetheless, the results from the current study indicated that the facilitative effects of smaller trees on the diversity and richness of understory vegetation out-weighed the competitive effects of trees on understory species. Thus, our result confirmed that the facilitative effects would lead to more number of species and plant abundance under canopies of smaller trees compared to large trees. However, this relationship shifts as tree size increases.

The effects of tree-meditated microsites on herbaceous cover and standing grass biomass

The substantial reduction in grass cover under large *S. lancea* trees was attributed to that herbaceous cover under woody plants with evergreen leaf phenology significantly decline (Belay and Moe, 2015). The study findings suggest that the traits of specific woody plants are more useful for predicting the effects of woody plant encroachment on grass herbaceous cover than increased tree densities. Although grass cover declined under large *S. lancea* trees, grass biomass was substantially enhanced under large trees of all the study species. we attributed the increased standing grass biomass under large trees to the enhanced soil fertility through N-fixing ability (i.e. *V. tortilis*) and greater litter biomass that returns to the soils (i.e. *S. lancea* and *Z. mucronata*). Nonetheless, our study shows that the impact of small trees on standing grass biomass may operate independently of diversity and richness because small trees had a similar number of species compared with outside canopies but distinct standing grass biomass, particularly *V. tortilis* and *Z. mucronata*.

Responses of plant species composition to mediated microsites

Large *S. lancea*, *V. tortilis* and *Z. mucronata* were associated with a high abundance of *P. maximum*, which was not surprising result because of the possible elevated micro-climate under the canopies of these species. The study findings demonstrate that the increased abundances of *P. maximum* plants under canopies of large trees is more important for grazers because of the high nutritional value of this species (Hare et al., 2021). Although *P. maximum* was the dominant plant species under large trees, the invasive Lantana camara was also associated with large trees, particularly *V. tortilis*. These results concur with McMahon and Ward (2021) who reported a higher abundance of *L. camara* under large trees, particularly of leguminous species.

Conclusions

Overall, the findings showed that understory plant vegetation, particularly of the herbaceous layer, responses regarding grass cover and biomass, diversity and composition depend on the tree sizes and microsites (i.e. under or outside the canopies). The increased standing grass biomass under large trees indicate that it may be beneficial to maintain large trees in savannas, particularly where pastoralism and game farming are the main objectives, although herbaceous diversity may decline. Additionally, the dominance by *P. maximum* under large trees have the greatest potential for providing forage for herbivores its high production and nutritive value (Hare et al., 2021).

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You Can Lead a Horse to Water: Mapping Seasonal Water Resources to Predict Wild Horse Movements on Utah Rangelands

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Key words: Wild Horses; Rangelands; Water Resources.

Abstract
Livestock producers in Utah can be adversely impacted by competition from wild horses whose seasonal distribution is strongly influenced by the availability of temporary surface water. We used a simple analysis of Landsat imagery acquired over an 18-year period to determine the distribution and duration of surface water in Utah rangelands. The resulting maps can be used to identify conflict hotspots and prioritize management activities. Improved prediction would result from future mapping of water sources not resolved at the 30-m scale of our analysis.

Introduction
Deserts are defined not only by the lack of water, but also by tremendous year-to-year variation in the timing and amount of precipitation. Water distribution strongly influences animal movements and habitat use in these systems. A major problem on western ranges in the United States is that areas managed for wild horses overlap those managed for livestock.

Seasonal movements of wild horses (*Equus caballus*) are determined by water availability (Schoenecker et al., 2022), which varies with elevation, latitude, and from year to year. In summer, herds with access to permanent springs or stock ponds may remain relatively sedentary, whereas those without these resources may become nomadic, searching for temporary water resulting from rainfall or snowmelt. Field studies in Utah and Arizona have shown that surface water availability is the strongest determinant of habitat use for horses and livestock (Miller, 1983; Schoenecker et al., 2022). Migrating horses traverse cattle grazing allotments (areas of public land managed by federal agencies like the Bureau of Land Management – BLM - and the U.S. Forest Service -USFS - where livestock grazing is permitted), croplands, and highways, resulting in conflict with other land uses.

Wild horses and burros in Utah are managed by the BLM within congressionally designated wild horse herd management areas (HMA), all of which overlap BLM grazing allotments. In dry periods or droughts, to which the region is prone, wildlife and livestock concentrate in mesic areas, which can become problematic for farmers and livestock producers.

We aimed to map the annual distribution of temporary surface water across Utah as an aid in predicting the likely impact of wild horses on livestock grazing operations.

Methods

To estimate the extent and duration of surface water (perennial and ephemeral, combined), we employed the methods described in Feng et al. (2016). This procedure involved compiling images from the Landsat archive from May through October, 2000-2018. These months were selected as they encompass the growing season when temperatures and therefore evapotranspiration are highest, and water is most limiting to animals. This is also the driest time of year as all snow cover has melted and the only ephemeral surface water available is the result of highly sporadic summer thunderstorms. Based on these criteria, we selected all available images for the study area across this interval. This amounted to approximately 2-4 images per month at 30-m pixel resolution. We then used the Normalized Difference Water Index (NDWI) to detect areas of water cover. This index uses near-infared (NIR) to distinguish water from soil or vegetation, as water strongly absorbs NIR, whereas vegetated surfaces reflect this wavelength. The NDWI is defined as [NIR-Red]/ [NIR+Red]. Index values range from -1 to 1, with negative values indicating water cover (McFeeters 1996).

To estimate the duration of surface inundation, we overlaid all images compiled between 1 May and 31 October and calculated the proportion of time each pixel displayed evidence of surface water using NDWI < 0 as our threshold. Thus, a pixel with NDWI values < 0 for the entire 6-month duration would be indicative of perennial water, and proportions less than 100% would be indicative of corresponding degrees of ephemeral water cover. Some localized water sources could not be detected at 30-m resolution, so our estimates are biased low.

To estimate the number and areal extent of public-lands grazing allotments potentially affected by wild horses, we used spatial data from the Utah Automated Geographic Reference Center (AGRC: https://gis.utah.gov/). This dataset delineates all allotments designated for grazing on USFS or BLM land. Attributes include the area (in acres) and the species of livestock that are permitted. We then overlaid HMA polygons, to determine the identity and size of all grazing allotments that fell within any HMA. Lastly, we overlaid this new data layer on the water rasters described above to calculate the amount and duration of water on each allotment.

Results

Within the state of Utah, there are approximately 9,709 grazing allotments, covering 57,566 square miles of federal and state rangelands (BLM, USFS and State Institutional Trust Lands Administration). Of these, 1,651 (17%) fall within 6 miles (9.7 km) of a HMA, representing 27% of all grazing lands by area. The number of allotments and total grazing area are inversely related to the seasonal duration of surface water (Table 1). Allotments on which water is only available for approximately 10% of the growing season account for 24% of rangelands within the 6-mile buffer while those with perennial surface water (available for > 90% of the growing season) account for only ~ 5%. Figure 1 illustrates this relationship.

Table. 1. The proportion of the growing season during which the ground is covered by water (1 May to 31 October). This does not include manmade sources, such as guzzlers, stock ponds, or leaking pipes. The number of allotments is determined by a six-mile buffer around each HMA.

Water present (days)	Proportion growing season	No. allotments	Total area of grazing allotments (mi^2)
18	10%	940	13,472
37	20%	495	9,163
55	30%	326	7,811
73	40%	240	6,479
92	50%	199	5,162
110	60%	170	4,507
128	70%	141	3,501
146	80%	122	3,115
165	90%	88	2,671

The distribution of water, grazing allotments, and vulnerability to competition with wild horses were not distributed evenly across the study area (Table 2).

Discussion

Horses in the American West typically travel > 6 miles per day in search of forage and water. Approximately 17% of public lands grazing allotments fall within this distance of a HMA, representing 27% of all grazing lands, by area. Since this figure does include some allotments potentially affected, or account for horses moving on and off tribal, military, or national park lands, it probably underestimates the number of allotments affected. Competition between wild horses and free-ranging livestock thus has the potential to affect many Utah producers, especially when consumption of forage by horses prevents ranchers from returning their livestock to grazing allotments in the spring after the traditional winter rest.

Areas in which water is reliably available are likely to experience a disproportionate amount of crop depredation and competition for water from wild horses. We found that only about 5% of the area grazed within the HMA buffers had water available for 90 % of growing season (although water can also be permanently available from other natural and anthropogenic sources). Conversely, the 24% of the grazing area that has water available for only 10% of the growing season is likely to experience a much lower level of conflict.

Our approach provided a quick assessment of the locations and times when ranchers may be impacted by wild horses. Managers can use these maps to identify conflict hotspots, provide proactive deterrents during droughts, prioritize fence constructions and maintenance, and establish range monitoring stations to evaluate grazing impacts. Future mapping of water sources that were not resolved at the 30-m scale would further refine our predictions.

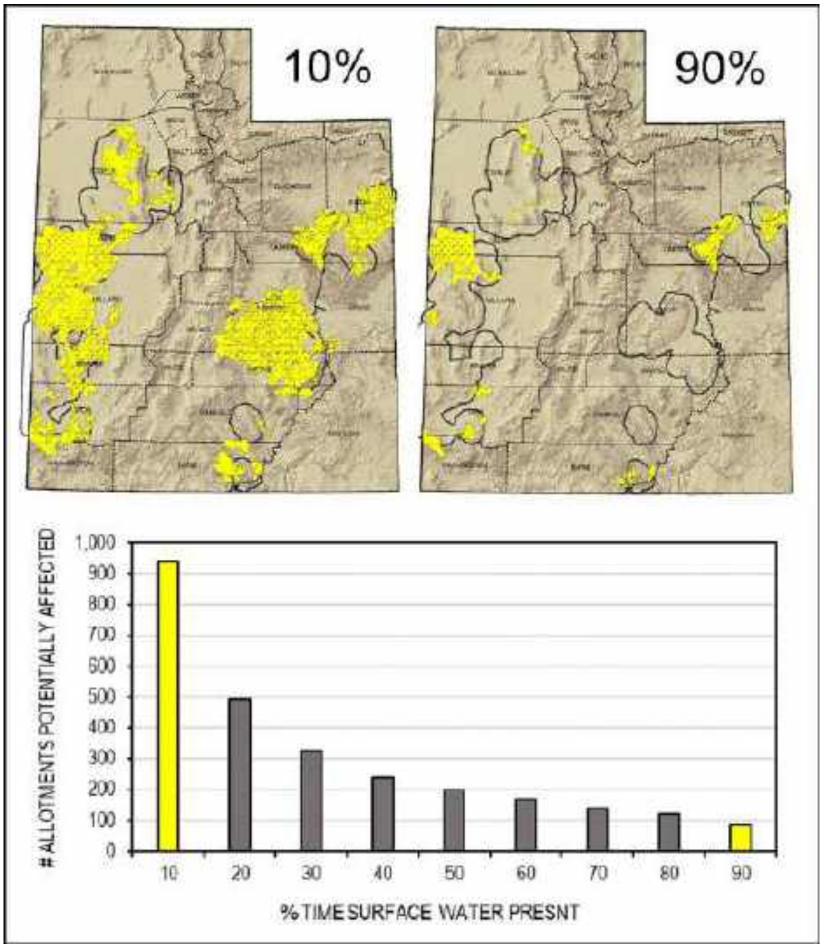

Figure 1. Relationship between the number of grazing allotments within a 6-mile buffer of HMAs and duration of surface water. Yellow bars represent the driest (10%) and wettest (90%) conditions (i.e. only ~ 100 allotments have surface water present for 90% of the growing season). Maps illustrate the distribution of grazing allotments that could be affected by wild horses for corresponding periods.

Table. 2. The number, proportion of total, and area of grazing allotments potentially affected by wild horses. All figures are for allotments within 6 miles of a HMA.

	GRAZING ALLOTMENTS		
COUNTY	NO.	PROPORTION OF TOTAL	AREA (km^2)
Beaver	221	21%	678
Carbon	10	1%	351
Emery	162	15%	2,200
Garfield	10	1%	237
Iron	126	12%	1,039
Juab	66	6%	1,708
Kane	2	0%	77
Millard	141	13%	3,177
Tooele	148	14%	2,205
Uintah	127	12%	1,363
Wayne	44	4%	1,038
TOTALS:	1057		678

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What can herbaceous forbs tell us about sustainably managing mesic grasslands in South Africa?

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Key words: Forbs; diversity; grazing; mesic grassland

Abstract

High plant diversity maintains ecosystem functioning and delivery of services in response to disturbance through the insurance of functional redundancy. Forbs (herbaceous dicots and non-graminoid monocots), rather than grasses, comprise most of the species in South African mesic grasslands, which receive more than 600 mm of annual rainfall. Research in South Africa's mesic grasslands has shed light on the critical role of forbs in maintaining ecosystem health. Grazing significantly impacts forbs, with overgrazing drastically reducing diversity and replacing native species with hardy, often exotic ones, underscoring the importance of light stocking and judicious grazing management. Certain forb species serve as indicators of grazing intensity, with their relative abundance informing a forb condition score for monitoring and adjusting grazing practices accordingly. High-density, short-duration grazing (HDG) may not immediately affect forb diversity but can damage individual plants, promote unpalatable grasses, and alter forb composition, potentially harming soil health. Forbs exhibit individualistic responses to grazing and competition, highlighting the need for nuanced management strategies. Although forbs regrow after defoliation, their underground storage organs are depleted, affecting future growth and potentially reducing diversity in the long run, emphasizing the importance of lenient grazing pressure. While HDG can increase litter accumulation, it might not effectively replace fire's role in stimulating growth and reducing competition, underlining the significance of fire in maintaining forb diversity. Beyond grazing, certain forbs provide valuable food for herbivores, support pollinator communities, and offer essential resources for human livelihoods, necessitating a deeper understanding of their role in the ecosystem. Managing for forb diversity involves maintaining forb-rich habitats through responsible fire and grazing management practices to sustain biodiversity and the various services these grasslands provide. In conclusion, forbs are an indispensable component of healthy mesic grasslands in South Africa, and understanding their responses to disturbances informs effective land management practices for ensuring long-term ecosystem health.

Introduction

Mesic grasslands, which receive more than 600 mm of annual rainfall, are fire-dependent and consist of a diverse herbaceous plant community (Uys 2006). Forbs, including herbaceous dicots and non-graminoid monocots, contribute more to species richness than grasses in these grasslands (Siebert et al. 2024). High plant diversity ensures functional redundancy and maintains ecosystem functioning and stability when faced with intense disturbance (Hallett et al. 2017), such as by high-density, short-duration grazing. This grazing system, known as high-density grazing (HDG) or regenerative grazing, concentrates livestock in small areas for short periods to create a 'herd effect' that breaks soil crusts, accelerates the recycling of litter and dung, stimulates microbial communities, and boosts rangeland productivity—all while discouraging fire use (Savory and Parsons 1980). The contended benefits of HDG include increased livestock production by increasing the production of key foraging species and improved biodiversity (Savory and Butterfield 2016). Historical research focused on grasses and less was known about the response of forbs to different grazing management systems. This paper reviews the relevant literature to summarize the effects of HDG and heavy continuous grazing on the forb component of mesic grasslands.

Short and long-term effects of HDG and continuous heavy grazing

Long-term studies (over 10 years) in South African mesic grasslands have shown that high grazing pressure and the prolonged exclusion of fire results in the loss of most mesic grassland forbs with a community shift (Chamane et al. 2017a; Morris and Scott-Shaw 2019). Increased grazing pressure leads to changes in forb dynamics, shifts in species composition, life history strategies and growth forms (Nkuna and Morris 2024). Forbs play a critical role in rangeland ecosystems and can serve as indicators of habitat health as studies have shown that heavy grazing shifts perennial forb composition from erect decreaser species to prostrate increaser species (Table 1) (Chamane et al. 2017a; Morris and Scott-Shaw 2019; Morris 2021a). Additionally, annual ruderal and alien invasive forbs are favoured over perennials under intense grazing (Table 1, Table 2). Morris and Scott-Shaw (2019) identified a subset of indigenous mesic grassland forbs that showed a clear negative response to increased grazing pressure (Decreaser species) and other Increaser species that appear to be favoured by heavy grazing (Figure 1).

Contrary to HDG claims, intense trampling under high stocking density led to more compacted soils, with no significant difference in nitrogen and carbon levels compared to low-density grazing (Table 1). Litter mass was higher under HDG compared to an adjacent ranch that employed a lower stocking density (Table 1). A similar pattern was observed over a shorter time period where HDG resulted in a four-fold increase in (and deeper) litter accumulation (Chamane et al. 2017b). Dense litter can reduce evaporation and increase water availability but soil moisture is not limiting in these mesic grasslands and excessive litter can reduce irradiance received by plants, thereby limiting their growth (Chamane et al. 2017a).

More than 90% of forb species were defoliated by grazing or mechanically damaged by the ripping, shredding and tearing of hooves under HDG over the short-term (<10 years) period (Chamane et al. 2017b). Even low-abundance species do not always escape damage. These impacts may be reversible provided it is over a short period or less frequent with adequate recovery time because several mesic forbs have underground storage organs (USOs) that they can resprout from.

Table 1: Schematic presentation of the long-term effects of high-density grazing (HDG) compared to low-density grazing (LDG) on vegetation and soils (data from Chamane et al. 2017a).

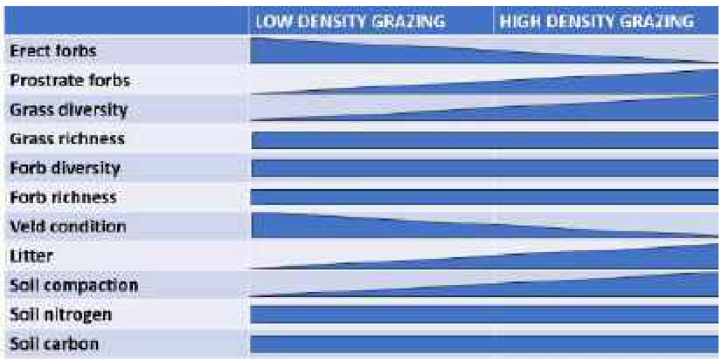

Table 2: The life-history strategy and growth form of mesic forbs under different types of grazing pressure. Data are from Chamane et al. (2017a; Morris and Scott-Shaw 2019).

LIGHT GRAZING	HEAVY GRAZING
Perennials	Ruderal annuals & perennials
Native	Mostly non-native
Erect	Prostrate
Leaves on stems	Leaves at base

Response of forbs to repeated defoliation

Recurrent leaf damage due to heavy grazing in the growing season reduced the vigour (Morris and Nkuna 2024) and regrowth in the following spring (Morris 2021b) of *Hypoxis hemerocallidea* and *Thungergia atriplicifolia*. Regrowth and USOs declined progressively under recurrent leaf damage. For both species, the USOs were more vulnerable to herbivory than the aerial organs; in *H. hemerocallidea*, corms were nearly halved in mass, accompanied by reduced inflorescence production (Morris 2021b; Morris and Nkuna 2024). This indicates that persistent defoliation reduces the USOs under chronic disturbance by overgrazing or frequent mowing which may weaken and eventually kill the plant. That would reduce the overall forb species richness and in turn reduce the resilience of forbs, diminishing their competitiveness against grasses and threatening their long-term survival (Siebert et al. 2024). Interestingly in another study of *Merwilla plumbea,* spring defoliation did not result in lasting impacts on carbohydrate reserves or macronutrients, suggesting that *M. plumbea* may be resilient to infrequent, intense defoliation, including in spring (Morris and Nkuna, unpublished data). Further research is needed on defoliation effects across different seasons.

Ecosystem services provided by forbs

Forbs provide essential services such as forage for livestock, food for humans and habitat for wildlife (Morris 2024; Siebert et al. 2024). The common cultural uses of forbs include spiritual uses and medicine for humans and animals (Siebert et al. 2021). Forbs also play a role to regulatory and support services by contributing more to diversity which ensures ecosystem resilience and stability (Morris and Nkuna 2024).

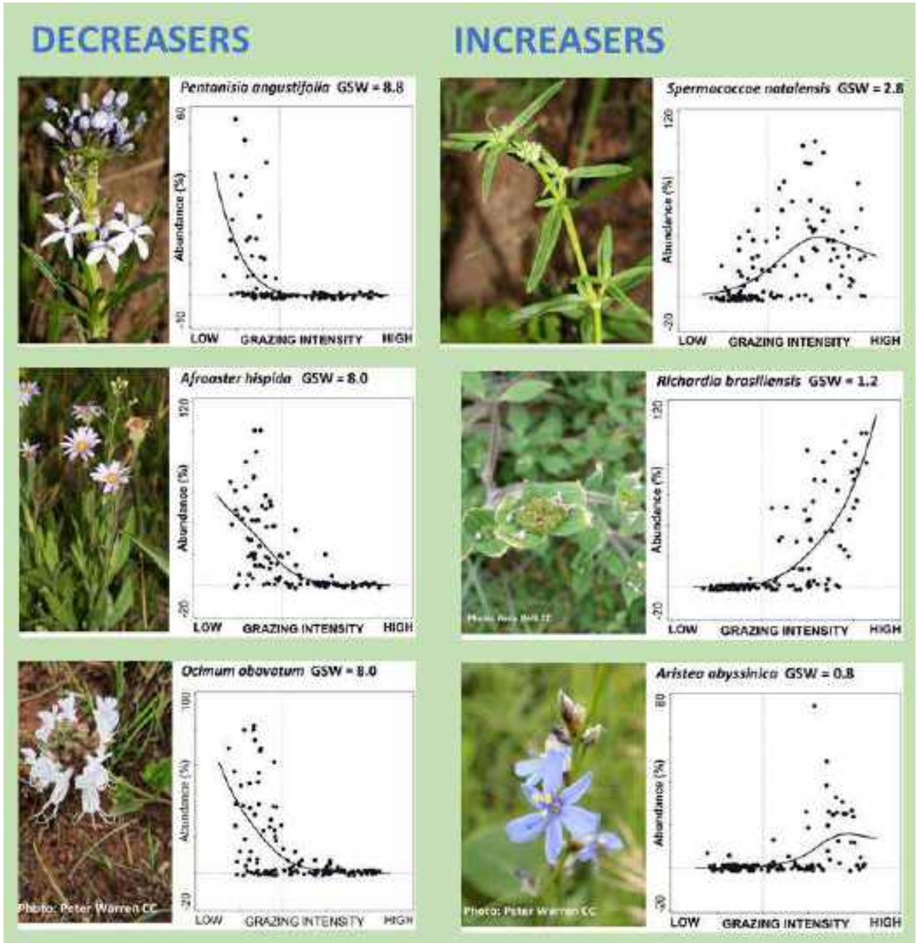

Figure 1: Examples of Decreaser and Increaser mesic grassland forbs that respond negatively or positively, respectively, to increased grazing pressure (Morris and Scott-Shaw 2019). GSW is a grazing score weight indicating a higher sensitivity to grazing. Reproduced from Morris (2019).

Managing for forb diversity in mesic grasslands

Grazing management tools for livestock production can be adapted to maintain forbs in mesic grasslands (Morris and Nkuna 2024). Strategies include adjusting stocking rates, selecting livestock types and managing movements (Kirkman et al. 2023). The combinations of management actions which include the frequency, intensity, duration and timing of grazing and trampling will affect the defoliation regime experienced by forbs and thereby, should influence their vigour and long-term survival (Morris and Nkuna 2024). The response of forbs can be explained by the intermediate disturbance hypothesis, which suggests that moderate disturbance is important while too little or excessive disturbance can reduce their abundance (Fynn et al. 2004). Complete protection from defoliation may favour shade-tolerant forbs and alter community structure (Fynn et al. 2005). Although it is known that forbs require some disturbance, the optimal frequency and intensity for maintaining forbs as well as the effects of disturbance timing are not well known (Morris and Nkuna 2024). Given the insufficient empirical data for managing perennial forbs, a precautionary approach is recommended. To help forbs recover from intense grazing and trampling or cumulative defoliation, it is important to provide periodic, year-long rest from grazing. Such extended rests will allow forbs to regain their vigour, develop bud banks, replenish underground storage reserves, and reproduce vegetatively or by flowering. Controlled burning is also important for removing excess litter and for stimulating the growth of some mesic forbs. Regularly assessing the abundance of key indicator forb species and monitoring reduced flowering or stem growth can help managers to adjust grazing practices to prevent long-term degradation and maintain species-rich grasslands (Morris and Nkuna 2024).

Conclusions

Studies in mesic grasslands have shown that forbs are sensitive to chronic disturbances from HDG or heavy continuous grazing. While the importance of grassland forbs is increasingly recognized (Siebert et al. 2024), the optimal timing and intensity of management practices for forbs are still not well understood. Therefore, to support diverse forb populations, a precautionary approach is recommended: avoid intense and frequent grazing, provide year-long rest periods for grazed areas, use controlled burning, and implement adaptive management through regular monitoring of forb vigour and abundance.

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Alluvial gully erosion: evolution, processes and management

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Key words: Great Barrier Reef, Land degradation; Remediation; Water Quality

Abstract
Gully erosion is a globally significant form of land degradation, adversely affecting agricultural and rangeland productivity as well as downstream ecosystems. In northeast Queensland, Australia, substantial investments in alluvial gully remediation are being made to improve water quality within catchments draining to the Great Barrier Reef World Heritage Area. However, understanding of alluvial gully evolution, processes, and management strategies remains limited. This PhD project aims to investigate the long-term evolution of alluvial gullies, contemporary erosion processes, and the effectiveness of remediation strategies, focusing on the Upper Burdekin catchment. The research findings will inform alluvial gully management and contribute to reducing sediment runoff into the Great Barrier Reef's lagoon.

Introduction
Gully erosion is a significant land degradation process that leads to loss in land productivity, damages infrastructure, and degrades downstream ecosystems (Poesen et al. 2003). In northeast Queensland Australia, gully erosion accounts for approximately 40% of the total suspended sediment (<63µm) load delivered to the Great Barrier Reef (GBR) lagoon, posing a significant threat to the reef's health (Waterhouse et al. 2024). Growing concern about the deteriorating health of the GBR has prompted millions of dollars of investment over the past decade to improve catchment-scale water quality through gully remediation and other land management practices (State of Queensland 2018).

In this region, gullies are typically classified as either hillslope gullies or alluvial gullies. Hillslope gullies are typically linear and more isolated incisional features eroding into colluvium and are primarily driven by concentrated overland flow processes (Poesen et al. 2002). In contrast, alluvial gullies are erosional features entrenched into vast alluvial landscapes not previously incised since initial deposition (Brooks et al. 2009). In the GBR catchment, early sediment budget models assumed hillslope gullies were the dominant sediment source to downstream waterways (McKergow et al. 2005), and as a result, remained the primary focus of gully erosion studies and management practices (Wilkinson et al. 2018). More recent studies, however, recognise alluvial gullies as a dominant source of fine sediment delivered to the GBR lagoon (Brooks et al. 2021).

Despite this recognition, there remains a limited understanding of long-term alluvial gully evolution, contemporary erosion processes and rates, as well as the effectiveness of common remediation strategies. A comprehension of long-term dynamics is key to address issues concerning whether the contemporary rates of gully erosion are within the normal range or are accelerated due to land use, climate change or other anthropogenic factors. This PhD project will contribute to addressing each of these key knowledge gaps.

Methods

The research is focussed in the Upper Burdekin, a sub-catchment of the Burdekin Basin, identified as a major source of fine sediment delivered to the GBR lagoons (Bainbridge et al. 2024) (Figure 1). On-ground field studies will focus on a group of alluvial gully systems deeply incised into the Quaternary alluvium within 1km of the Burdekin River (Figure 2). The predominant soil types are Brown Chromosols and Brown Sodosols, characterised by highly dispersive subsoil horizons. The region experiences a dry tropical climate with annual average rainfall of 628mm, 80% of which falls during the wet season (October to March).

To achieve project aims, a range of methods will be applied (Figure 3). To obtain the minimum age of gully initiation, sediment stratigraphy and Optically Stimulated Dating (OSL) will be conducted following the method described by Lee et al. (2011). Historical gully expansion and lifetime volumetric loss will be quantified using the method described by Daley et al. (2021). Past land-use and climate proxies of the area will be analysed to investigate the factors driving gully development (Lewis et al., 2021). Temporal variation of gully development will be assessed to examine the growth model (Nachtergaele et al., 2002). An empirical approach will be adopted to assess the dominant factors and processes driving contemporary gully development, incorporating hydrological and water quality monitoring, terrain analysis, and erosion pin measurements. The effectiveness of alluvial gully remediation will be determined through a Before-After-Control-Impact (BACI) approach as described by Brooks et al. (2024).

Results

The project is in the preliminary stage and results are not yet available.

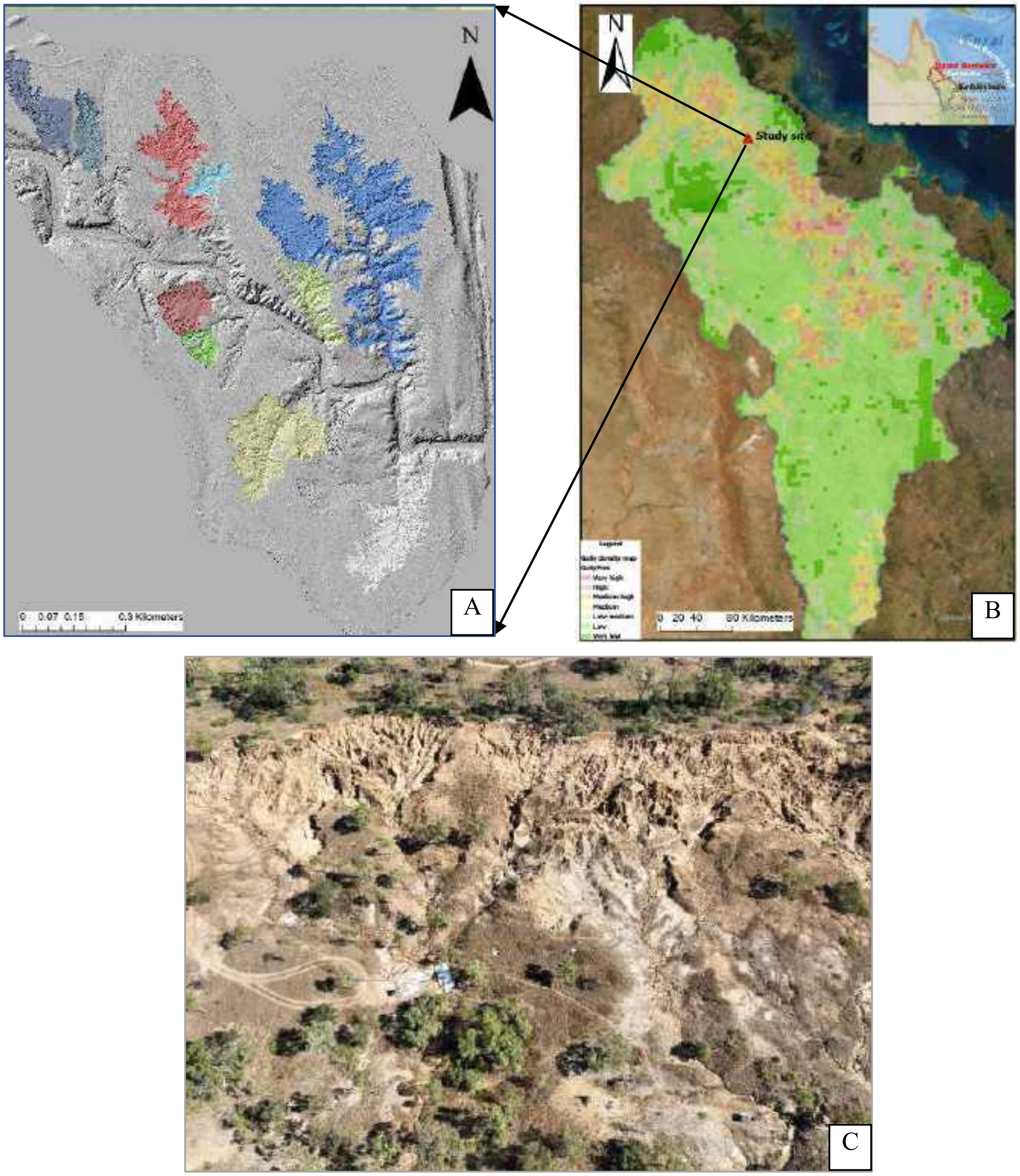

Figure 1 (A) Location map showing gullies in the study area. (B). Gully density map of the Burdekin catchment, modified from Tindall et al., (2014). (C) Picture showing an example of alluvial gully in the study area.

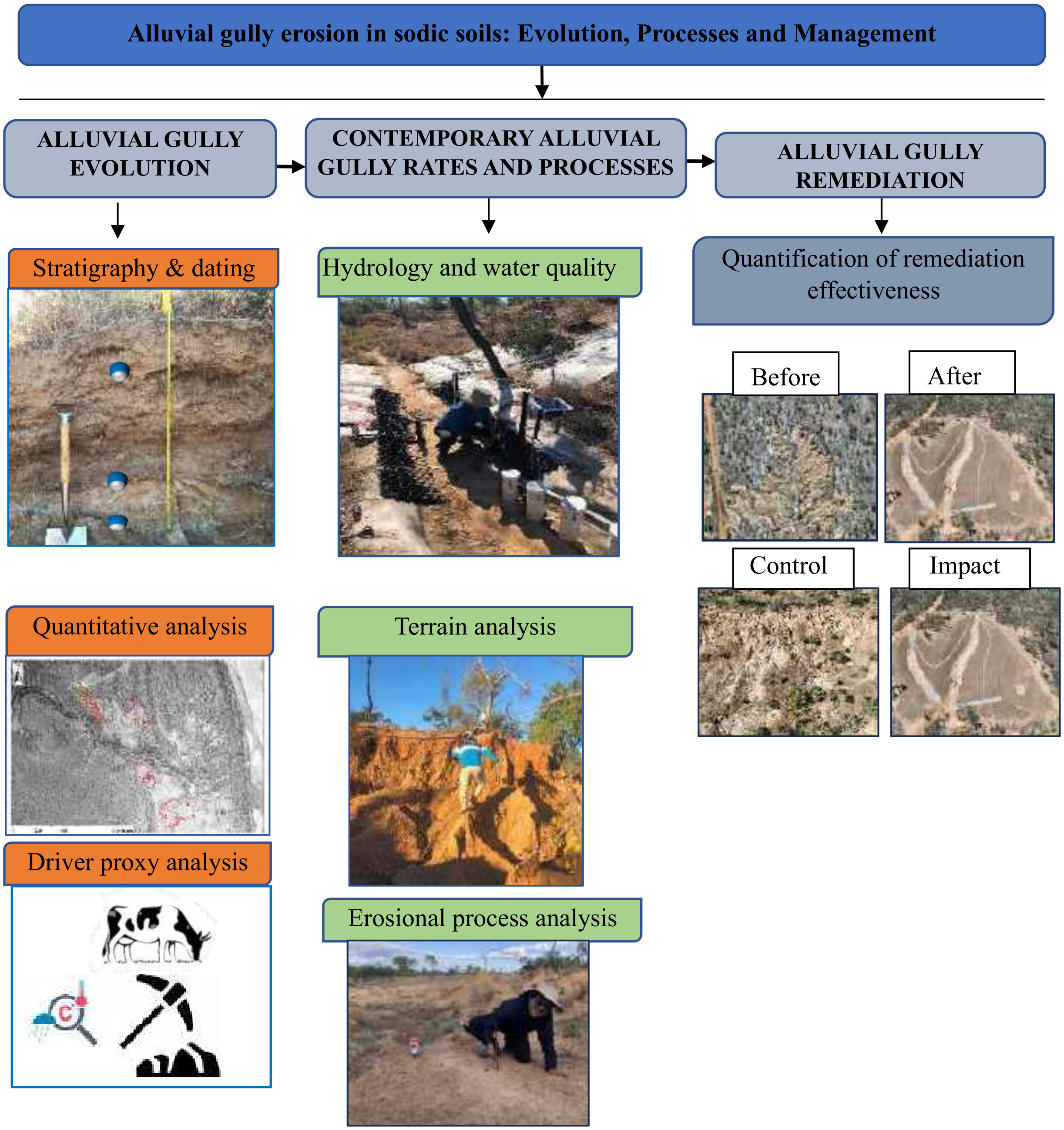

Figure 2. Schematic diagram showing different methods to be used for the study. Detail description in the text.

Discussion

The proposed research will enhance fundamental scientific understanding of alluvial evolution, contemporary processes, and remediation effectiveness. The study on long-term gully evolution will enhance understanding of key factors and processes influencing alluvial gully formation, long-term sediment yields, and potential future trajectories. The study on contemporary process and rates will enhance understanding into the current dynamics of alluvial gullies occurring in sodic soils, including an assessment of the quantitative relationship between different erosional processes and the sediment yield. The study on gully remediation will provide new insights into the effectiveness of various remediation approaches implemented within the alluvial gully system. The new data, knowledge and understanding generated through this research will be of great value to a range of stakeholders involved in gully monitoring, modelling and management, both in Australia, and internationally.

Acknowledgements
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XII INTERNATIONAL RANGELAND CONGRESS AUSTRALIA 2025

FIREGRAZE: Using strategic patch burning to influence cattle grazing behaviour and improve land condition.

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Key words: fire; grazing distribution; land condition

Abstract

Managing grazing distribution in large, diverse paddocks is a key challenge in the tropical rangelands of northern Australia. These landscapes consist of varying land types, ranging from fertile alluvial clays to rugged, skeletal red earths, leading to uneven grazing patterns as cattle favour areas with higher-quality forage. Overgrazing of preferred land types can degrade soil health and pasture composition, while underutilized areas contribute less to overall paddock productivity.

This study investigated whether burning underutilized areas could attract cattle and redistribute grazing pressure. Conducted at Victoria River Research Station, Northern Territory, two areas of 2.3 km² and 3.3 km² were burned. Global Navigation Satellite System (GNSS) collars tracked cattle movements across burnt and unburnt land types. There was increased cattle activity in burnt areas during the wet season following burning, with reduced grazing pressure on productive grey clays and vulnerable red earths.

The findings suggest that targeted burning can effectively redirect grazing pressure, enhancing the use of underutilized areas and promoting more sustainable land management in heterogeneous rangelands.

Introduction

The average size of a cattle station in the Victoria River District in the northwest of the Northern Territory is 3,377km² with a median paddock size of 120km² (Cowley 2014). These vast grazing lands are a mosaic of land types with unique topography, soil characteristics and pasture composition. Within paddocks, productive alluvial clay soils may sit juxtaposed with skeletal red earths, creating stark contrasts in grazing value and preference. This patchiness is both an opportunity and a challenge; while it provides diverse resources for cattle, it also leads to uneven grazing patterns as cattle instinctively favour areas with higher-quality forage (Tomkins and O'Reagain 2007).

Overuse of productive land types can lead to a decline in desirable palatable perennial pastures and soil health. At the same time, less fertile or areas further from a water source are often underutilised, reducing their contribution to overall paddock productivity. One strategic management tool to address this imbalance and improve grazing distribution across a paddock is the use of fire to stimulate regrowth in less-used areas.

Cattle are strongly attracted to post-fire regrowth, which is high in protein and digestible energy (Reid, 2022, Andrew 1986) offering a natural and low input method to redirect grazing pressure and promote more even utilisation of the land.

This study aimed to investigate if burning less preferred, underutilised areas within a paddock can attract cattle to these areas, thereby reducing grazing pressure on more preferred areas to improve overall paddock productivity.

Methods

The study was conducted at Victoria River Research Station (VRRS), 220 km south-west of Katherine in the Victoria River District of the Northern Territory. The climate is tropical with a median rainfall of 793mm, with the majority of rain falling between October and April. The study sites were in Conkerberry paddock (17km^2) and Box paddock (21km^2). The study sites were broadly a mix of alluvial grey clays dominated by ribbon grass (*Chrysopogon fallax*) and Flemings bush (*Flemingia pauciflora*) and calcareous red earths dominated by black spear grass (*Heteropogon contortus*) and white grass (*Sehima nervosum*). Land unit mapping at 1:30,000 scale of Kidman Springs (Forster 1972) defines 5 land units consistent across both paddocks: 4a and 4b (gently undulating to flat plains with grey, brown and red clays), 5a (Gently undulating to flat plains with a mix of calcareous red earths and grey, brown and red clays), 3a, 3b and 3c (undulating plains with calcareous red earths) and 7b (creeklines). Land unit 2a (Rugged undulating terrain on limestone with shallow skeletal soils) only occurred in Box paddock and 6d (severly eroded red earths) only occurred in Conkerberry paddock.

An underutilised area in each paddock was selected for burning. In October 2022, a 2.3km^2 area of Conkerberry was burnt (12% of paddock). In October 2023 a 3.3km^2 area of Box paddock was burnt (15% of the padddock). The burnt areas were predominately 2a and 3b land unit in Box paddock and a mix of 3a, 5a and 4b in Conkerberry paddock. Land units were combined into broad land types for analysis. 4a and 4b were combined into grey clays. 5a, 2a, 3a, 3b, 3c and 6d were combined into red earths.

The paddocks were stocked to long-term carrying capacity. All cattle were fed a standard supplement of urea in the dry season and phosphorus in the wet season. Twenty GNSS collars were deployed randomly in a mob of 76 pregnant Brahman cows in Conkerberry paddock in September 2022, and 24 GNSS collars were deployed randomly in a mob of 75 pregnant Brahman cows in Box paddock in May 2023.

The collars comprised a 61mm x 89mm x 89mm IP68 rated plastic shell, with a metal, wide “U” shaped bracket bolted to the top and PVC webbing used as straps to attach around the neck of the animal. A GNSS logger inside the shell from IGotU (GT600) recorded GNSS location every 10 minutes.

GNSS loggers were downloaded at each muster (May and September). GNSS data was analysed using QGIS plug ins to calculate total GNSS pings across the paddock and within different land types. GNSS pings were converted to relative time spent to allow for comparison between land types of different sizes. A selection index for time spent per land type was calculated as the proportion of time spent in a land type / the proportion of the paddock of that land type. GNSS pings around water points were omitted where cattle were known to rest for long periods.

Repeat photo monitoring sites marked with metal pickets were established in burnt areas prior to burning. Photos were taken at the picket before and after burning and through the study period facing north, east, south and west.

Results

There was a significant increase in animal presence within the burnt areas in both paddocks following fire once wet season rainfall occurred. The preference for the burnt areas in the wet season immediately after burning was higher in Conkerberry paddock (Fig. 1) than in Box paddock (Fig. 2). A preference for burnt areas continued throughout the wet season (November to April) in both paddocks.

The time spent on grey clays decreased during the wet season in both paddocks in both burn and no burn years, however in Conkerberry paddock cattle spent less time on the grey clays in the year burning occurred (0.7 relative time spent) compared with the following year without burning (0.9 relative time spent).

The relative time cattle spent on erodible red earths (6d) in Conkerberry paddock between November and April was significantly higher in the non-burn year (3.4 relative time spent) compared to the burn year (Fig. 3, 1.9 relative time spent).

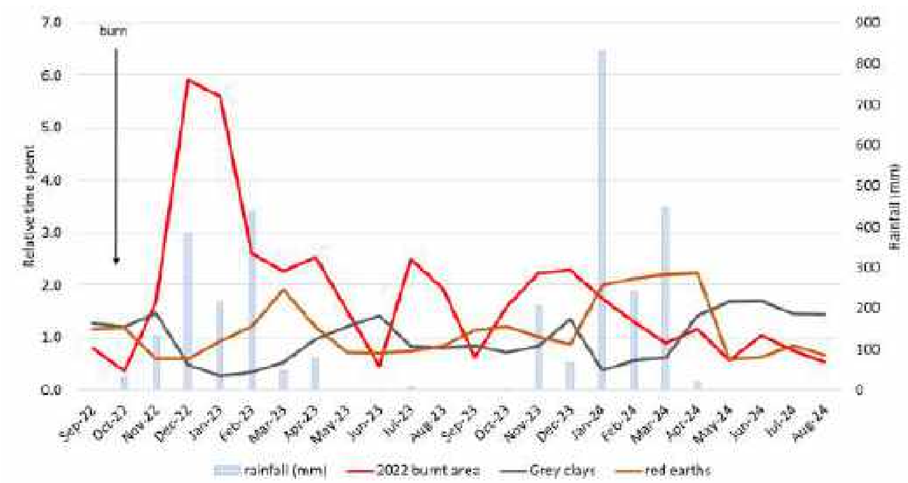

Figure 1. Relative time spent (averaged monthly) following fire on different land types and burnt areas in Conkerberry paddock

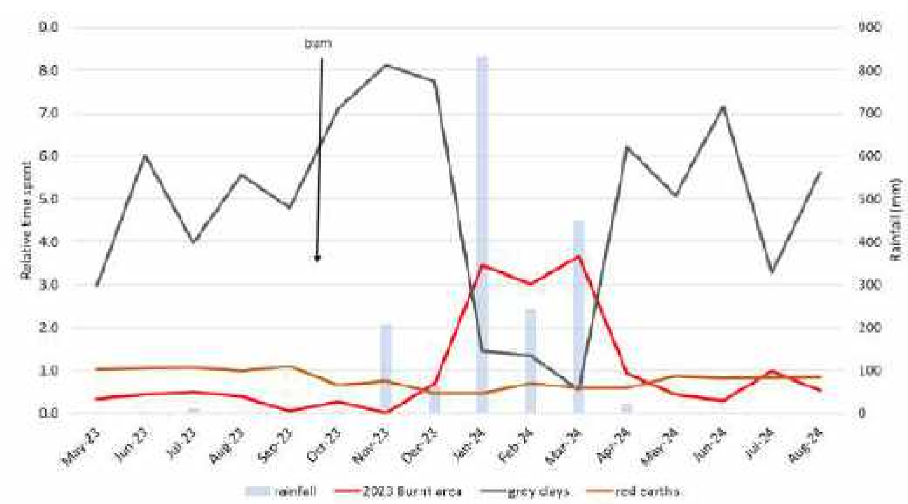

Figure 2. Relative time spent (averaged monthly) before and after fire on different land types and burnt areas in Box paddock

Figure 3. Relative time spent (averaged monthly) following fire on erodible red earths (6d) compared to burnt area in Conkerberry paddock.

Discussion

Cattle are known to prefer red soil areas during the wet season to avoid boggy conditions on the black and grey clays (Hunt et al. 2007), so it is unclear if the preference for red soil areas in the second wet season after fire in Conkerberry paddock was what occurs naturally, or if there was still some lagging effect of the previous years burn on cattle preference. Further monitoring of landscape preference in both paddocks over time will help to distinguish background versus burn driven landscape preferences.

The significant increase in cattle presence within the burnt areas during the wet season suggests that fire-stimulated regrowth attracts cattle, aligning with previous studies highlighting the nutritional appeal of post-fire vegetation (Reid 2022). Similarly, Fuhlendorf and Engle (2004) found that integrating fire and grazing can create a dynamic forage mosaic that redirects grazing activity and balances land use across heterogeneous landscapes.

Burning also reduced grazing pressure on more productive grey clays, particularly in the year there was fire introduced to the paddock. This outcome supports the hypothesis that pyric herbivory can mitigate overgrazing in high-value areas, increasing the potential for recovery. Moreover, the reduced time spent on erodible red earths (6d) during the burn year highlights the potential of fire to divert grazing pressure from ecologically vulnerable areas. Grazing in these areas during non-burn years likely exacerbates soil erosion and pasture degradation, a concern corroborated by Mott (1986), who linked uneven grazing patterns to environmental decline.

The strong preference for burnt country by cattle highlights the potential for overgrazing. It is important that the patch burn area is large enough to not be too heavily grazed but small enough to ensure some parts of the paddock are rested. Stocking rates should also be adjusted to match the carrying capacity of the paddock.

It is difficult to assess changes in land condition over short periods of time however photo monitoring points and regular pasture monitoring will continue to measure the effects of patch burning within the burn area and surrounding land types.

The findings of this study suggest pyric herbivory can be effective in redistributing grazing pressure and enhancing the utilisation of underused areas in tropical rangelands.

Acknowledgements
Thanks to the staff at Victoria River Research Station for assistance with burning and animal management.

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Rehabilitation planning at the landscape scale. The Martin Fire as a case study

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Key words: Restoration planning; Wildfire rehabilitation, Spatial mapping

Abstract:
The Martin Fire, which ignited on July 5, 2018, in Nevada's Great Basin, burned over 177,750 hectares of shrubland, profoundly impacting rangeland ecosystems and wildlife habitats. This case study examines the methods and spatial datasets used to inform post-fire rehabilitation efforts, providing a framework for large-scale landscape restoration. Legacy grazing practices, compounded by an Aroga moth infestation, had degraded the herbaceous understory and increased fuel loads, further challenging recovery. Within the Bureau of Land Management's (BLM) 30-day Emergency Stabilization and Rehabilitation (ESR) planning window, tools were employed to evaluate pre-fire conditions, assess resilience, and prioritize rehabilitation needs.

Key methods included the use of Disturbance Response Groups (DRGs) to classify plant communities by their response to disturbances and the integration of remote sensing and ground-based vegetation data to map plant functional group cover. Near-real-time annual grass mapping, validated against ground measurements, highlighted areas prone to invasive species dominance, while soil texture and precipitation data-informed microclimate resilience assessments. Historical wildfire data provided context for evaluating past rehabilitation outcomes, and guiding strategies for the current fire rehabilitation effort.

Results revealed substantial variability in vegetation recovery, influenced by pre-disturbance conditions and environmental factors. Areas with resilient soils and adequate herbaceous cover recovered well, while those dominated by invasive annual grasses or dry fuels exhibited poor recovery. Herbicide treatments showed a notable reduction in bare ground and a temporary increase in annual vegetation, emphasizing the role of targeted interventions.

This study demonstrates the utility of spatial datasets and collaborative planning in addressing large-scale disturbances. While implementation remains complex, the lessons learned from the Martin Fire provide valuable insights for improving future wildfire rehabilitation strategies, emphasizing the importance of integrating ecological data to support decision-making at the landscape scale.

Introduction

On July 5, 2018, the Martin Fire ignited near Paradise Valley, Nevada, and over the course of several days, it consumed approximately 177,750 hectares of shrubland in the Great Basin, USA. Driven by strong winds, the fire devastated iconic landscapes and wildlife habitats. The affected area included the Owyhee High Plateau, a historically productive ranching region where plant communities had become dominated by woody vegetation. Legacy grazing practices had diminished the herbaceous understory, reducing its resilience to fire. Compounding the issue, a recent Aroga moth (*Aroga websteri*) infestation had defoliated and killed large portions of sagebrush across the region, leaving abundant dry fuel and a depleted seedbed for post-fire recovery.

This paper discusses the strategies and tools used to advise and support post-fire rehabilitation efforts in the wake of this disaster. Effective rehabilitation at this scale requires tools to assess pre-disturbance conditions, map plant communities, group areas by their disturbance response, evaluate the likelihood of natural recovery without intervention, and identify the most effective rehabilitation techniques. Within the 30-day window mandated by the Bureau of Land Management (BLM) for developing a rehabilitation plan and applying for Emergency Stabilization and Rehabilitation (ESR) funding, we aimed to provide a straightforward and effective framework for addressing this challenge.

The BLM's rehabilitation planning process was highly collaborative, incorporating input from local landowners, stakeholders, ranchers, wildlife managers, and rangeland professionals. The Stringham Rangeland Ecology Laboratory contributed resources to this effort, and this paper shares the datasets and visualization techniques employed during the planning process. While the efficacy of some rehabilitation measures is evaluated, the primary focus is on demonstrating how existing datasets can be integrated to enable rapid assessment and planning at such a large scale.

The tools developed by the Stringham Rangeland Ecology Laboratory, including Disturbance Response Groups (DRGs) as described in Stringham et al. (2016) and later works (Phipps and Stringham, 2024), were instrumental in assessing rangeland response to disturbances of this magnitude. These tools provided a framework for prioritizing resources and efforts in a triage-like manner, given the limited resources available for rehabilitating the entire burn area.

While numerous physical and political challenges influenced the implementation of the rehabilitation plan, this case study demonstrates the value of collaborative efforts and the practical application of these tools in addressing large-scale disturbances. As wildfires of this scale become increasingly common, the lessons learned from the Martin Fire rehabilitation process can inform future disaster response and landscape restoration efforts.

Methods

Once the Martin Fire was extinguished by regional wildland firefighters, the Bureau of Land Management (BLM) fire management teams provided final fire extent mapping (Personal communication, Phipps, 2018). To evaluate fire intensity, the BLM collected additional imagery and produced Burned Area Reflectance Classification (BARC) data. Using ArcGIS, the fire boundary was overlaid onto spatial datasets to guide response planning and assess pre-fire conditions. Relevant base data, including political boundaries and geographic information, were compiled to support subsequent analyses.

Disturbance Response Groups

Disturbance Response Groups (DRGs), as described by Stringham (2016), were clipped to the fire boundary to identify plant communities likely to exhibit similar post-fire responses. DRGs are based on Ecological

Sites, which are defined as "a distinctive kind of land with specific characteristics that differs from other kinds of land in its ability to produce a distinctive kind and amount of vegetation" (NRCS, 2024). These groups cluster Ecological Sites by their resilience and response to disturbances such as wildfire. For example, areas dominated by plants capable of resprouting after fire are grouped together, while areas prone to invasive annual grass proliferation are classified separately. This analysis helped prioritize areas within the burn perimeter requiring stronger intervention and areas that may recover well without intervention.

Vegetation Monitoring Data

Pre-existing vegetation monitoring data were compiled across the burn area, including data from State-and-Transition Modeling, annual ranch monitoring, and national-scale efforts like the BLM's Assessment, Inventory, and Monitoring (AIM) dataset and the NRCS National Resource Inventory (NRI). These datasets were normalized to display plant functional group and ground cover percentages, including categories such as annual grass, perennial grass, annual forbs, perennial forbs, shrubs, rock, litter, and bare ground. The point-based data were visualized in GIS, mapped to soil types and plant communities, and scaled using color ramps to highlight the relative dominance of functional groups.

Annual Grass Monitoring

Annual grass, a serious concern in the Great Basin, was of particular focus. Its presence increases wildfire spread and hinders post-fire recovery due to localized seedbeds that expand after disturbances. Near-real-time annual grass cover data (Boyte & Wylie, 2016) were used to map current grass cover across the burn area. Ground-based measurements collected using the Line-Point-Intercept method were assessed alongside remote sensing data to examine trends, revealing that remote sensing often underestimated annual grass cover. These comparisons informed adjustments and validated the data's utility for large-scale assessments.

Multi-Source Remote Sensing Integration

The Multi-Resolution Land Cover Consortium (MRLC) Rangeland Condition Monitoring Assessment and Projection (RCMAP) products (Shi et al., 2022) were used to map plant functional group cover across the burn area. Ground-based data were compared to remote sensing values, and discrepancies were noted to interpret patterns across the larger landscape. Color-ramped visualizations of plant functional group cover allowed for efficient spatial assessments.

Precipitation and Soil Analysis

Annual precipitation strongly influences rangeland resilience (Chambers et al. 2013). However, the study area's remoteness limited access to on-site weather station data. Instead, precipitation data from PRISM (Daly et al., 2013) were modeled and categorized into zones familiar to resource managers. Recognizing PRISM's limitations in capturing microclimates within the Basin and Range topography, the raster data were vectorized to better inform planning.

Soil characteristics, including texture and chemical properties, were analyzed using remotely sensed datasets (Chaney et al., 2016; Nauman et al. 2024). These datasets highlighted areas with high clay content, which retain water and support specific vegetation types, and regions with high pH levels, which may affect the efficacy of post-fire herbicide treatments like Imazapic.

Historical Wildfire Data

Historical wildfire perimeters from the U.S. National Interagency Fire Center were mapped and compared with annual grass cover data to evaluate past fire responses and rehabilitation outcomes. This overlay provided insights into the effectiveness of previous restoration efforts and informed current strategies.

Application to State-and-Transition Models

Plant functional group cover data were integrated with State-and-Transition models (Stringham and Snyder, 2017) to assess the likely post-fire trajectories of different areas. Areas with intact perennial bunchgrass understories were identified as more likely to recover without additional intervention due to a generally positive response to fire from perennial grasses, while shrub-dominated areas with limited herbaceous cover were flagged as at risk of transitioning to annual grass dominance.

This comprehensive, multi-scale analysis informed targeted rehabilitation strategies to optimize resource allocation and address post-fire challenges effectively.

Results

Variation in vegetation response was observed across the study area. Areas with poor pre-disturbance conditions, characterized by low perennial herbaceous biomass and abundant dry fuels such as Aroga moth (*Aroga websteri*)-killed stands of Wyoming Big Sagebrush (*Artemisia tridentata var. wyomingensis*), have visibly shown limited recovery. In contrast, areas with more resilient soils and favorable pre-disturbance conditions exhibited visibly better plant community recovery, often independent of rehabilitation efforts.

Visual observation of the remotely sensed cover data by plant functional groups appears to show evidence of the application of pre-emergent herbicides. Approximately three years after herbicide treatment, corresponding to the duration the chemical remains active in the soil, a clear pattern emerged: bare ground appears to have decreased while annual vegetation increased. These trends are visibly apparent in the data, and were not remeasured due to lack of funding, but are consistent with measurements acquired by other groups and local knowledge of the area.

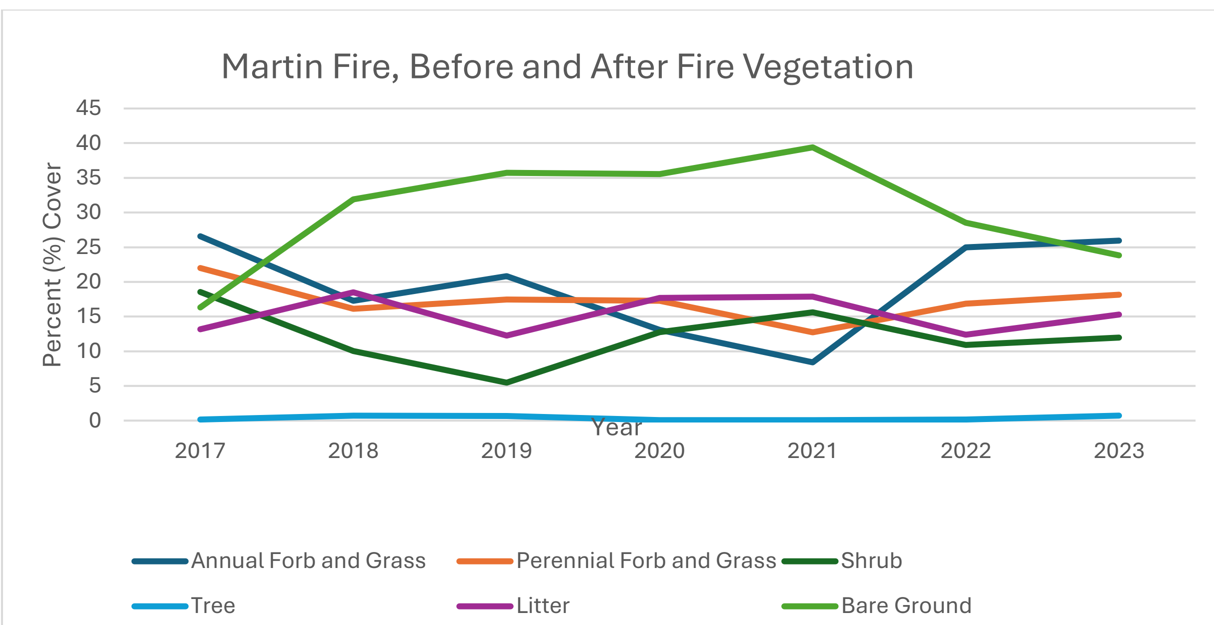

Figure 1: Data from the Rangeland Analysis Platform (RAP) summarizes vegetation response across the entire Martin Fire perimeter. These results average diverse plant community responses before and after the fire, capturing the variability across the landscape.

During site tours following the fire, it was visibly evident that perennial bunchgrass establishment was particularly evident in the southern portion of the study area, where aggressive cultivars like crested wheatgrass (*Agropyron cristatum*) performed well. Areas receiving additional soil moisture, such as drainages or slopes with reduced evaporation and solar gain (north- and northeast-facing aspects), also demonstrated stronger recovery of native vegetation which is dramatically visible on the landscape due to increased resilience in these microclimates.

Maps generated during the study, included in Appendix A, supported the development of a restoration plan by the BLM's Elko District Emergency Stabilization and Rehabilitation (ESR) Coordinator, Marissa Murphy. Her collaborative approach incorporated input from diverse stakeholders, which not only enhanced the plan's quality but also facilitated broader stakeholder support.

These findings highlight the importance of integrating vegetation, herbicide, and soil data to understand post-fire recovery dynamics and inform future rehabilitation efforts.

Discussion [Conclusions/Implications]

This case study highlights the use of spatial datasets and methods for post-wildfire rehabilitation assessment and planning, with a focus on their application across large spatial scales. The purpose of this discussion is to provide illustrative examples of these tools and techniques rather than to test specific hypotheses. Additional maps and spatial analyses will be included in the accompanying poster to be presented at IRC 2025.

While the implementation and success of post-wildfire rehabilitation involve a complex interplay of variables, many of which are beyond control, this study emphasizes the potential of emerging datasets and spatial methods to support effective planning. By demonstrating how these tools can be applied to large-scale rehabilitation efforts, we aim to contribute to the development of more efficient and informed decision-making processes in post-fire recovery.

The authors are actively engaged in further advancing this field and are working on additional tools to enhance rehabilitation planning at landscape scales. We welcome continued dialogue on this topic and encourage interested readers to contact us using the provided email addresses for further discussion.

Acknowledgements

A very special thank you to Marissa Muphy with the BLM for allowing such a collaborative effort in rehabilitation planning on the Elko District portion of the wildfire. Thank you to everyone who contributed, including all the datasets provided to help in the generation of this mapping effort.

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Moderate defoliation improves Mitchell Grass leaf, tiller and inflorescence production

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Key words: drought recovery; drought resilience; perennial tussock grass; Astrebla

Abstract
The Mitchell grasslands are unique to Australia and make important contributions to grazing, conservation, cultural heritage, and rural socioeconomics.

Previous studies suggest there is an optimal range of 15-20cm defoliation height to promote Mitchell grass (*Astrebla* spp.) leaf, tiller and inflorescence production during average to above average rainfall periods. However, there is evidence that a different defoliation height and frequency is needed to increase the responsiveness of Mitchell grass leading into, during, and exiting drought.

A long-term drought resilience experiment commenced in December 2021 at Longreach, Queensland to determine the interaction between defoliation height and frequency and water stress on Mitchell grass response to rainfall.

Treatments commenced in October 2022 once establishing plants reached maturity. The main effect of water stress is induced through rainfall received or alleviated through supplementary irrigation. Treatment interaction is applied through defoliation height (15cm or 0cm) and frequency (never, annually or biennially) at the end of the dry season (early October). Soil moisture and key plant parameters are monitored monthly and quarterly respectively.

Preliminary findings of plant recovery from the initial two defoliations indicate that cutting: increased end-of-wet-season photosynthetic area at both heights; increased tiller and inflorescence production and canopy area at 15cm height; but reduced tiller and inflorescence production at 0cm.

These early results support previous studies that Mitchell grass responds positively to ‘moderate’—but negatively to severe—defoliation. The current study has been during average to above-average rainfall. Further papers will report longer-term results that will begin to reflect drought conditions.

Investment into long-term research is needed to continuously improve our understanding of perennial grass species management as a changing climate brings new challenges through increased temperature and

rainfall variability. The ultra long-lived (>20 years) *Astrebla* spp. are an excellent model species for this purpose.

Introduction

Astrebla spp (Mitchell grasses) are tropical tussock grasses which are endemic to Australia. They are very long-lived perennials (>20 year life span, Orr and Phelps 2013), and produce relatively high levels of palatable forage. They grow predominantly on clay soils in arid to semi-arid regions, on naturally tree-less rolling downs and plains. These grasslands make important contributions to pastoralism, conservation, cultural heritage, and rural socioeconomics. Previous studies suggest there is an optimal range of defoliation height and frequency which can increase the responsiveness and resilience of Mitchell grass leading into, during, and exiting drought. Globally, defoliation frequency and height is recorded as impacting photosynthetic capacity (Cullen et al. 2006), tiller dynamics and dry matter yield (Kaufononga et al. 2017), and interacts with drought to increase mortality (Hacker et al. 2006) in perennial grasses. Studies of Astrebla spp can therefore contribute to the international understanding of perennial grass management.

Methods

A long-term drought resilience experiment commenced in Longreach in December 2021 to determine the role of defoliation and water stress on *Astrebla lappaecea* (Curley Mitchell grass) response to rain. The main treatment is a) exposure or b) non-exposure to drought water stress, achieved by a) relying on rainfall received or b) supplementary irrigation to match monthly average rainfall. Sub-treatments are annual or biennial clipping to remove a) all tiller nodes (1-2 cm height) b) all but 3-4 tiller nodes (15 cm height) and c) an unclipped control. Clipping occurs at the end of the dry season (October). Plots and plants were allocated randomly with a split-plot design with four replicates. Five plants are arranged in the corners and centre of each of eight 0.7m x 0.7 m sized plots, with a 0.3m access path between each plot.

Forty plants were established over December 2021-March 2022, and irrigated until all plants had reached maturity in October 2022. During this time, heatwaves and insect incursions killed many young seedlings which were replaced with newly germinated seedlings, and set-back the growth of others. Emergent tillers were tagged in control plants during the establishment phase to track survival.

Soil moisture is recorded monthly through a DeltaT PR2 probe, with two access tubes installed per plot and 10 access tubes within walkways to monitor for the possibility of lateral flow from irrigated to non-irrigated plots. Plants are recorded daily, weekly, monthly, quarterly, or biannually depending on the parameter (Table 1). No statistical analysis is reported for these preliminary results.

Results

The Longreach region was drought declared from December 2021 to May 2023 (LongPaddock 2024). Heatwaves, high evapotranspiration, and insect incursions killed many of the young seedlings and set-back the growth of others during the establishment phase (Dec. 2021 to Jan. 2022; days 0-90; Fig. 1a). Nevertheless, soil moisture levels were relatively consistent at depth (600-1000mm) and more dynamic in response to rainfall events within the soil cracking zone (0-400mm, Fig. 1b).

The preliminary trends for plant recovery from a single defoliation indicate that clipping: increased end-of-wet-season photosynthetic area at both heights; increased tiller production, basal area and canopy area at 15cm height but; reduced tiller production and basal area at 0cm. In contrast with other studies, defoliation did not increase inflorescence production. Drought exposed plants tended towards reduced photosynthetic area compared with non-exposed (irrigated) plants within every clipping sub-treatment (Fig. 2).

Table 1. Frequency of plant parameter measurements.

Frequency	Parameter	Method
Daily-weekly	Visual overview	Photographic record
Weekly-monthly	Plant height	Direct measurement (cm)
Monthly-quarterly	Photosynthetic area	Number of green leaves, direct measurement of representative leaf length and width (mm)
	Tiller number (primary and axillary)	Direct count
	Inflorescence number (primary and axillary)	Direct count
	Rhizome emergence	Direct count
	Canopy area	Direct measurement of perpendicular widths (leaf tip to leaf tip, cm)
Quarterly-biannually	Basal area	Direct measurement of perpendicular widths (mm)
	Node number per tiller	Direct count of 10 random tillers
	Tiller lifecycle	Direct estimate of live, senescent and dead tillers; counts of tagged tillers emerged in first year
	Leaf lifecycle	Direct estimate of live, senescent and decaying leaves
Annual- biennial	Biomass	Weight of harvested material (dry matter, g)

One of the 1-2 cm height clipped plants has died, and all have greatly reduced basal area (data not presented). One of the unclipped control plants is dominated by dead tillers and leaves, with very little new growth. Other control plants are starting to show similar signs of reduced vigour. Tagged tiller mortality reached 46% after 11 months, and 93% by 29 months after emergence. By April 2024, the majority (60%) of control plants' total primary tillers were dead.

Discussion

High mortality of seedlings during the summer establishment phase suggests that mid-summer conditions may not be conducive to *Astrebla* seedling establishment. This potentially contradicts earlier findings that seedling recruitment occurs any time during the wet season (Orr and Phelps 2013) but may also reflect the drought and heatwave conditions experienced over the 2021-22 summer at Longreach.

The early results of clipping support previous studies that Mitchell grass responds positively to 'light'—but negatively to severe—defoliation. Despite challenging drought conditions during the establishment phase of this experiment, subsequent average to above-average rainfall conditions have led to relatively reliable soil moisture and a lack of exposure to drought since the initiation of clipping.

Further papers will report longer-term results that include drought and hence water stress conditions. The key question that remains to be answered is whether there is an optimal defoliation height and frequency which increases the responsiveness and resilience of Mitchell grass during and exiting drought.

The high mortality of the first years' tagged tillers in unclipped control plants, supported by high overall primary tiller mortality, suggests old tillers will dominate the demographics of clipped plants. This is likely to reduce the potential for recovery compared with tiller demography dominated by younger tillers. Clipping to 1-2cm height forced regrowth as primary tillers from the crown, as all nodes that could initiate growth are removed. Clipping to 15cm height retains 3-4 nodes where leaves and axillary tiller growth can initiate from. It remains to be seen if clipping to force consistently younger primary (annual or biennial 1-2cm clipping) or axillary (annual or biennial 15cm clipping) tillers will promote growth during drought recovery, or if reduced basal area and reduced overall tiller number will impede growth.

Investment into long-term research is needed to continuously improve our understanding of Mitchell grass as a changing climate brings new challenges through increased temperature and potentially more variable rainfall conditions.

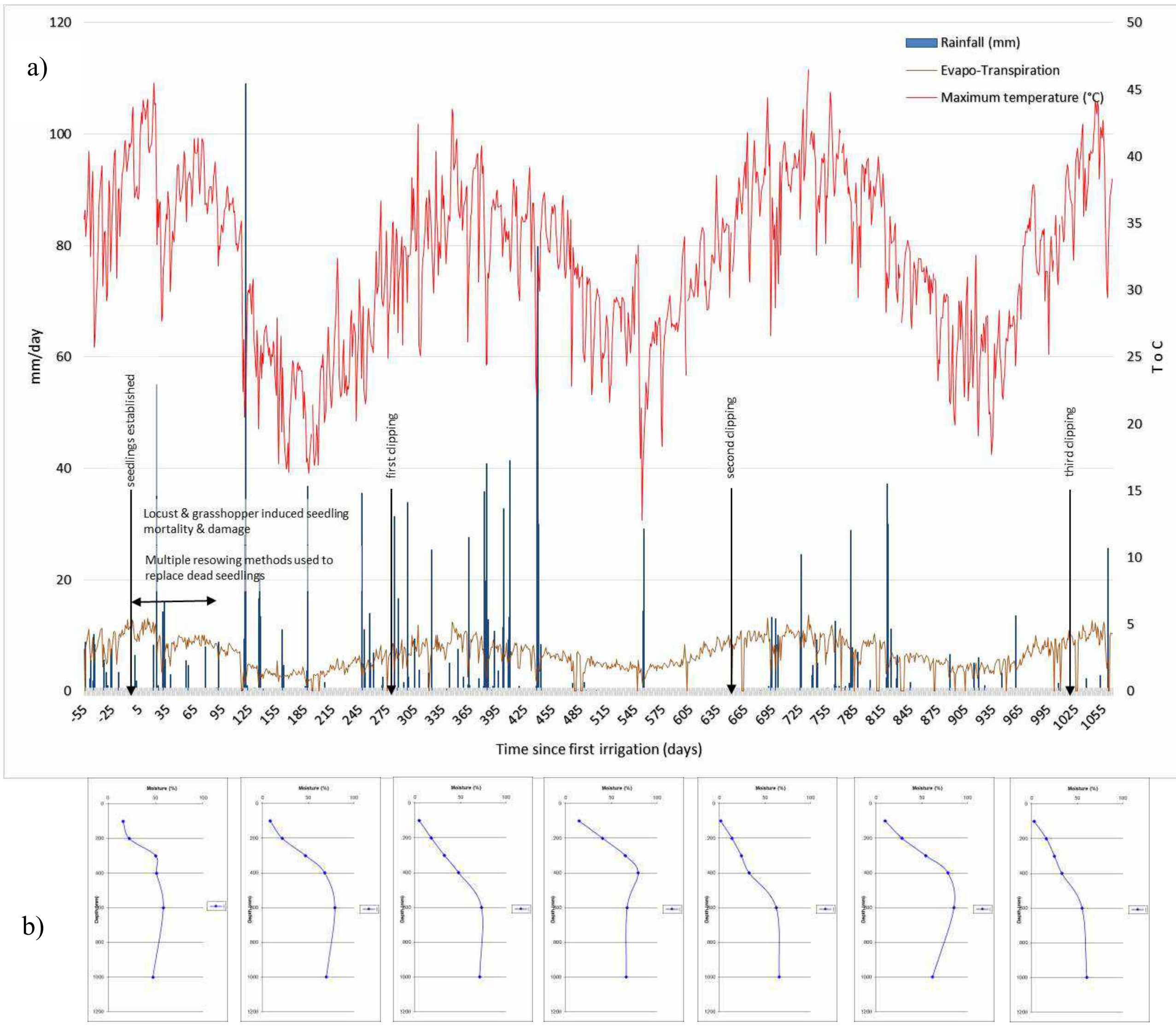

Fig. 1. a) Seedling establishment phase and clipping events in relation to maximum temperature, evapotranspiration and insect incursions throughout the experiment; b) plot level soil moisture levels at days 7, 140, 315, 444, 686, 825, and 1027.

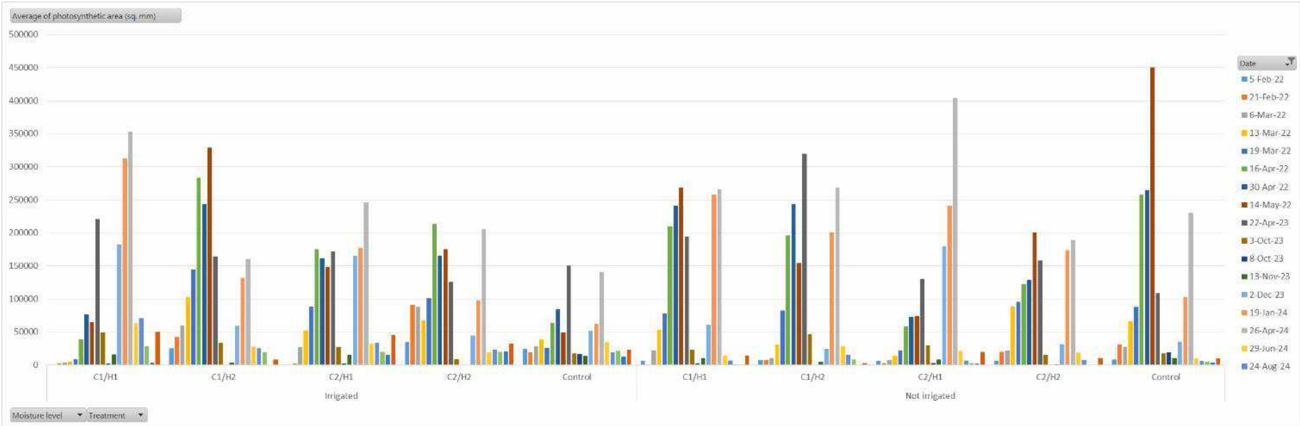

Fig. 2. Photosynthetic area (sq mm/plant) over time under drought and non-drought conditions and at five clipping intensities.

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Trends in avian diversity and abundance in remnant vegetation in inland eastern Australian farmland between 2014 and 2023

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Key words: climatically driven variability; Common Myna; declining woodland birds; floodplain vegetation; rainfall; threatened species

Abstract

Australian bird communities fluctuate greatly in composition and abundance in response to rainfall. At the same time, increasing numbers of threatened bird species are declining in abundance and range, due to various threatening processes. An opportunity to study the dynamics of avian communities in inland eastern Australia arose when birds were surveyed in remnant floodplain vegetation on cotton farms in spring (September–November) 2014 and again in spring 2023, mostly at the same sites (197 sites in 2014, 195 in 2023 and 167 in common). Sites were censused twice on different mornings by separate observers in both years, with 133 diurnal landbird species and 4384 individuals recorded in 2014, and 151 species and 8227 individuals in 2023. Mean (± SE) species richness and total abundance of landbirds were 10.9 ± 0.03 and 22.3 ± 0.08 per 2-ha site, respectively, in 2014, and 17.8 ± 0.04 and 42.4 ± 0.13 per site, respectively, in 2023. Birds were almost twice as abundant in 2023 as 2014, likely attributable to 3 years of above-average rainfall in 2020–22. By contrast, the 2014 surveys were preceded by 1.5 years of average or below-average rainfall. Most (104) of the 126 species recorded in both years were more frequent in 2023 than 2014. Of concern, however, were four sedentary and 'declining' woodland species in south-eastern Australia that were either not recorded in 2023 or were less widespread or abundant than in 2014: Speckled Warbler,* Varied Sittella, Crested Shriketit and Crested Bellbird. Introduced species were also more prevalent in 2023 than 2014, with Common Myna increasing greatly in the intervening 9 years. Our findings accord with the rainfall-driven variability of Australian bird communities, help prioritise the species most in need of recovery interventions, and focus attention on the impact of the rapid increase of the Common Myna in inland eastern Australia.

* Latin names in Table 1 at end of this paper.

Introduction

Australian inland woodland, shrubland and grassland bird communities fluctuate greatly in composition and abundance in response to variable rainfall, increasing in abundance and richness in wet periods (Pascoe et al. 2021; Recher and Davis 2014; Reid et al. 2024; Smith 2015). The recent unusual triple La Niña in 2020–2022 (Voiland 2023) presented an opportunity to compare the impact of this 3-year wet period on the bird community in remnant semiarid woodland and grassland floodplain vegetation in inland eastern Australia, with a similar survey conducted in 2014 after a 20-month dry period. At the same time, increasing numbers of bird species are being listed under state and Commonwealth legislation as threatened with extinction. In addition, many woodland bird species in south-eastern Australia have been identified as ‘declining’ (Reid 1999). Not only is the number of threatened bird species in Australia steadily increasing but, between 1985 and 2018, the relative abundance of threatened bird species decreased by an average of 60% (Cresswell et al. 2021). Of interest, therefore, is whether populations of threatened and declining bird species are able to recover during wet periods such as the recent triple La Niña. Also of interest is whether wet periods are similarly advantageous to introduced bird species, since invasive species are the principal threat to flora and fauna species listed as threatened under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act; Cresswell et al. 2021).

This paper reports the abundance and richness of birds in remnant floodplain vegetation in inland eastern Australia resulting from two surveys, one in 2014 and the second in 2023, with a particular focus on threatened and declining species, as well as introduced species.

Methods

Birds were surveyed in remnant vegetation (riparian forests, woodlands, tall shrublands and native and derived grasslands) and in native revegetation on floodplain cotton farms from central Queensland to southern New South Wales between 25 September and 29 November 2014, and between 22 September and 22 November 2023. Farms were clustered in four zones (from north to south): (1) central Queensland (Fitzroy River basin) in the Emerald district; (2) Border Rivers, comprising the Condamine–Culgoa River basin in southern Qld and the Macintyre, Gwydir and Namoi River catchments in north-western NSW, centred on Moree; (3) Macquarie River basin in central NSW around Trangie, and (4) southern NSW consisting of the Lachlan and Murrumbidgee catchments, centred around Griffith. A distance of approximately 1300 km separated the northern sites near Emerald in central Qld and the southern sites near Coleambally in southern NSW.

The climate of the three northern zones is humid subtropical (Cfa) grading into semiarid (BSh) in the Köppen–Geiger system, whereas the southern NSW zone is cold semiarid (BSk; Peel et al. 2007). Mean annual rainfall between 2000 and 2023 varied from 567 mm and 564 mm at Emerald and Moree, respectively, to 471 mm at Trangie and 289 mm in Griffith. By analysing Bureau of Meteorology rainfall data for weather stations in each zone in survey years and the 3 preceding years, we determined that both survey years were similarly dry (38–72% and 35–76% of mean annual rainfall falling in the 8 months prior to the September–November survey period in 2014 and 2023, respectively). However, seasonal conditions in the 3 years preceding the survey years differed. Annual rainfall across the region was 98–116% of mean annual rainfall in 2011–13 compared to 115–156% in 2020–22. The latter was an unusual 3-year ‘Triple-Dip La Niña’ wet period (Voiland 2023).

Land use in all four zones is predominantly irrigated and dryland cropping and extensive livestock grazing of native pastures and woodlands, although some remnant vegetation on irrigated farms in all zones is ungrazed by domestic livestock. In 2014, the 197 sites surveyed were all on cotton farms, whereas 22 of the 195 sites surveyed in 2023 were on public land (travelling stock routes, national parks, nature reserves). These and six other sites on cotton farms were substituted for sites that were unable to be surveyed in 2023 due to changes in ownership or vegetation clearance, and were selected to sample vegetation types more evenly; 167 sites were common to both surveys.

Sites were classified into nine types by vegetation structure, dominant plant species and as remnant native vegetation or native (planted) revegetation: (1) river red gum (*Eucalyptus camaldulensis*) forest and woodland; (2) coolibah (*E. coolabah*) woodland; (3) black box (*E. largiflorens*) woodland; (4) poplar box (*E. populnea*) woodland; (5) myall (*Acacia pendula*) tall open shrubland; (6) belah (*Casuarina cristata*) forest and low-forest; (7) brigalow (*A. harpopyhlla*) low-forest; (8) grassland; (9) native revegetation of trees or trees and shrubs (planted 2–35 years ago). The structure and composition of each vegetation type is described in more detail by Smith et al. (2019).

Sites consisted of a 2-ha (generally 200 × 100 m) quadrat in a target vegetation type, generally contiguous with similar vegetation on at least two sides and sometimes all four. Birds at each site were censused twice on different mornings for 20 mins between sunrise and 11:00 hrs by separate observers in 2014 (JR and S. Green) and 2023 (JR and NR). Weather conditions were generally fine and sunny or overcast and still or with a breeze or light wind during both survey periods. Very windy conditions and rain were avoided. All birds seen or heard in the 2-ha quadrat were recorded. Data were averaged over the two censuses per quadrat in each survey period. Avian nomenclature follows Christidis and Boles (2008), and threatened bird species categories were as per Commonwealth and NSW legislation in December 2024, and applied retrospectively to species recorded in the 2014 and 2023 surveys.

Results

Some 133 diurnal landbird species and 4384 individuals were recorded in 2014, and 151 species and 8227 individuals in 2023 (Table 1). Mean (± SE) species richness and total abundance of landbirds were 10.9 ± 0.03 and 22.3 ± 0.08 per site, respectively, in 2014, and 17.8 ± 0.04 and 42.4 ± 0.13 per site, respectively, in 2023. Birds were almost twice as abundant in 2023 as 2014, and mean species richness one and half times greater in 2023 than 2014. Seven species were recorded in 2014 but not 2023: Scaly-breasted Lorikeet, Budgerigar, Pallid Cuckoo, White-fronted Honeyeater, Varied Sittella, Rufous Fantail and Little Crow. By contrast, 25 species were recorded in 2023 but not 2014. Most (126) species were recorded in both years, and 82 of these species were recorded in at least three more sites in 2023 than in 2014. By contrast, only six species were recorded in at least three more sites in 2014 than in 2023.

Consistent with the results for native species, introduced bird species were more widespread and abundant in 2023 than 2014 (Table 1). Only three introduced species were recorded in 2014: Rock Dove ($n = 2$ sites), Common Starling (11) and Common Myna (1). These species were recorded in many more sites in 2023 (10, 26 and 24 sites, respectively), particularly Common Myna. Spotted Dove, Common Blackbird and House Sparrow were also recorded in one or two sites each in 2023.

Also consistent with avian diversity and abundance comparisons between the 2 years, most threatened and declining woodland bird species were more diverse, frequent and abundant in 2023 than 2014 (Table 1). Fourteen species listed as Vulnerable or Endangered under the *Biodiversity Conservation Act 2016* (NSW) or the EPBC Act (Cwth), or both, were recorded in 2023 compared to 13 in 2014. Two listed species were recorded in 2023 but not in 2014 (Little Lorikeet, White-fronted Chat), whereas only one listed species was recorded in 2014 but not 2023 (Varied Sittella). Ten of the 12 listed species recorded in both years were both more frequent and abundant in 2023 than 2014, and paired t-tests comparing both the frequency and abundance (log-transformed) of the 12 species in the 2 years were significant (P = 0.009 and P = 0.002, respectively).

Twenty-seven declining woodland bird species were recorded in the two surveys (including seven of the listed species mentioned above). Twenty-six declining woodland species were recorded in 2023 compared to only 23 species in 2014 (Table 1). Eighteen of the 22 declining species recorded in both years were both more frequent and more abundant in 2023 than 2014. Paired t-tests comparing both the frequency and abundance (log-transformed) of the 22 species between the two years were significant (P = 0.002 and P = 0.004, respectively).

Discussion

We attribute the large increase in local and subcontinental-scale species richness and abundance of birds in 2023 compared to 2014 to the three La Niña years of above-average rainfall in 2020–22. Rainfall was well above average in the three southern zones in all 3 years between 2020 and 2022 (115–219% of mean annual rainfall), with only the 2021 rainfall at Emerald falling below average (90% of mean annual rainfall). By contrast, and despite above-average rainfall in 2011 and 2012 throughout all four zones (110–149% and 105–143% of mean annual rainfall, respectively), rainfall was well below average in 2013 (69–88%) in the year preceding the 2014 survey. The dry conditions from January to August in 2014 preceding the survey, coupled with the dry 2013, were sufficient to suppress avian abundance and diversity, whereas the dry start to 2023 was insufficient to dampen the increased population sizes and habitat spill-overs evident in the 2023 surveys. The general increases in population abundances and habitat spill-overs in these semi-arid woodland and grassland habitats in 2023 were likely due to increased food abundance, breeding and breeding success in 2020–22 compared to 2013–14 (Recher and Davis 2014; Smith 2015; Stevens and Watson 2013).

Of interest are the seven species recorded in both years that were not more abundant and widely dispersed in 2023 than 2014: Australian Hobby, Nankeen Kestrel, Horsfield's Bronze-Cuckoo, Crested Bellbird, Little Crow, Zebra Finch and Australasian Pipit. Several of these are mobile species often found commonly in arid Australia in good seasons and prefer some non-vegetated ground for foraging; hence part or all of the kestrel, cuckoo, crow, finch and pipit populations might have relocated inland during the three La Niña years and continued to reside there during the 2023 survey.

The increase in avian abundance and local species richness in 2023 was generally evident among listed and declining woodland bird species, indicating that the excellent seasonal conditions in 2020–22 counteracted the various threatening processes responsible for these species' declines in historical times. However, eight threatened and/or declining species recorded in 2014 were either not recorded in 2023, or were less abundant or frequent in 2023 than 2014: Spotted Harrier, Superb Parrot, Horsfield's Bronze-Cuckoo, Speckled Warbler, Painted Honeyeater, Varied Sittella, Crested Shriketit and Crested Bellbird. While part of the populations of some of these species may have resided further inland in more arid habitats in 2023 for the reasons mentioned above (harrier, parrot, cuckoo), the reduced abundance or frequency of the more sedentary species (warbler, sittella, shriketit, bellbird) is a concern. It could indicate that the threatening processes contributing to their decline are having a greater influence than the positive effect of prolonged high rainfall. As the Painted Honeyeater is dependent on mistletoe fruit for food, part of its population, too, may have relocated to more arid habitats in 2023 if excellent seasonal conditions promoted an unusually large fruit resource further inland.

Although introduced bird species were more frequent or abundant in 2023 than 2014, in common with most other species, the increase in Common Mynas was startling. Only two birds were recorded in one site in

2014, whereas 102 birds were recorded across 26 sites in 2023. The Invasive Species Specialist Group, a specialist group of the Species Survival Commission of the World Conservation Union, declared this species to be one of the world's most invasive species, listing it with only two other bird species in '100 of the World's Worst Invasive Species' (Lowe et al. 2004). The species is spreading rapidly in inland eastern Australia.

Conclusions/Implications

Our findings support the notion that above-average rainfall is an important driver of breeding success and population increase in semi-arid Australian bird communities. The threatened and declining sedentary species that showed the reverse trend (Speckled Warbler, Varied Sittella, Crested Shriketit, Crested Bellbird) deserve special conservation attention. Research is also required to assess the environmental impact of the rapid expansion of the Common Myna in inland eastern Australia.

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Table 1. The frequency (Freq), total number (Total no.) and conservation status of diurnal landbirds recorded in censuses in native floodplain vegetation in inland eastern Australian farmland in September–November 2014 and 2023. Frequency is the per cent occurrence of species across all sites in 2014 (n = 197 sites) and 2023 (n = 195).

English name	Scientific name	Conservation status*	2014		2023	
			Freq (%)	Total no.	Freq (%)	Total no.
Emu	*Dromaius novaehollandiae*	D	0.0	0	0.5	2
Australian Brush-turkey	*Alectura lathami*		0.0	0	0.5	1
Stubble Quail	*Coturnix pectoralis*		0.0	0	3.6	22
Brown Quail	*Coturnix ypsilophora*		0.5	2	10.8	116
**Rock Dove	*Columba livia*		1.0	9	5.1	45
**Spotted Dove	*Streptopelia chinensis*		0.0	0	1.0	6
Common Bronzewing	*Phaps chalcoptera*		1.5	4	5.1	25
Crested Pigeon	*Ocyphaps lophotes*		56.3	410	56.4	436
Diamond Dove	*Geopelia cuneata*		0.0	0	1.0	9
Peaceful Dove	*Geopelia striata*	D	14.2	62	23.6	225
Bar-shouldered Dove	*Geopelia humeralis*		4.6	14	12.8	60
Black-shouldered Kite	*Elanus axillaris*		3.0	11	7.7	21
Pacific Baza	*Aviceda subcristata*		0.5	1	1.0	3
White-bellied Sea-Eagle	*Haliaeetus leucogaster*	V	0.5	1	1.5	5
Whistling Kite	*Haliastur sphenurus*	D	10.7	36	14.9	53
Black Kite	*Milvus migrans*		8.6	31	13.8	47
Brown Goshawk	*Accipiter fasciatus*		0.5	2	2.1	5
Collared Sparrowhawk	*Accipiter cirrocephalus*		0.5	1	1.5	4
Spotted Harrier	*Circus assimilis*	V	0.5	1	0.5	1
Wedge-tailed Eagle	*Aquila audax*		1.5	4	2.1	4
Nankeen Kestrel	*Falco cenchroides*		12.2	31	9.2	26
Brown Falcon	*Falco berigora*		1.5	3	2.1	6
Australian Hobby	*Falco longipennis*		3.6	7	2.1	4
Black Falcon	*Falco subniger*	V	0.5	1	1.0	3
Painted Button-quail	*Turnix varius*	D	0.0	0	0.5	1
Little Button-quail	*Turnix velox*		0.0	0	1.0	2
Galah	*Eolophus roseicapillus*		34.0	382	41.5	515
Long-billed Corella	*Cacatua tenuirostris*		0.0	0	0.5	4
Little Corella	*Cacatua sanguinea*		4.1	46	13.8	133
Sulphur-crested Cockatoo	*Cacatua galerita*		24.4	383	42.1	650
Cockatiel	*Nymphicus hollandicus*		6.6	40	33.8	280
Rainbow Lorikeet	*Trichoglossus haematodus*		1.0	7	4.6	60
Scaly-breasted Lorikeet	*Trichoglossus chlorolepidotus*		0.5	2	0.0	0
Musk Lorikeet	*Glossopsitta concinna*		2.0	59	1.0	4
Little Lorikeet	*Glossopsitta pusilla*	V	0.0	0	0.5	6
Australian King-Parrot	*Alisterus scapularis*		0.5	2	1.0	6
Red-winged Parrot	*Aprosmictus erythropterus*		7.6	28	12.3	40
Superb Parrot	*Polytelis swainsonii*	V, VN	2.5	97	6.2	70
Yellow Rosella	*Platycercus flaveolus*		1.0	12	3.6	29
Eastern Rosella	*Platycercus eximius*		9.6	82	18.5	167
Pale-headed Rosella	*Platycercus adscitus*		14.2	56	29.2	157
Australian Ringneck	*Barnardius zonarius*		11.2	68	14.9	95
Blue Bonnet	*Northiella haematogaster*		18.3	224	23.1	200
Red-rumped Parrot	*Psephotus haematonotus*		24.9	225	28.7	336
Mulga Parrot	*Psephotus varius*		0.0	0	1.0	4
Budgerigar	*Melopsittacus undulatus*		1.0	4	0.0	0
Pheasant Coucal	*Centropus phasianinus*		2.0	4	4.1	11

Channel-billed Cuckoo	*Scythrops novaehollandiae*		0.5	2	3.6	9
Horsfield's Bronze-Cuckoo	*Chalcites basalis*	D	5.6	12	2.6	6
Shining Bronze-Cuckoo	*Chalcites lucidus*		0.5	1	0.5	1
Little Bronze-Cuckoo	*Chalcites minutillus*		1.0	2	1.0	2
Pallid Cuckoo	*Cacomantis pallidus*		0.5	1	0.0	0
Fan-tailed Cuckoo	*Cacomantis flabelliformis*	D	0.0	0	0.5	1
Laughing Kookaburra	*Dacelo novaeguineae*		12.2	39	15.9	55
Blue-winged Kookaburra	*Dacelo leachii*		0.5	1	1.5	9
Forest Kingfisher	*Todiramphus macleayii*		0.5	2	2.1	7
Sacred Kingfisher	*Todiramphus sanctus*		17.8	97	24.6	153
Rainbow Bee-eater	*Merops ornatus*		1.0	2	8.2	43
Dollarbird	*Eurystomus orientalis*		4.1	16	4.6	17
Brown Treecreeper	*Climacteris picumnus*	V, VN, D	8.1	64	13.8	117
Spotted Bowerbird	*Ptilonorhynchus maculatus*		2.5	6	5.6	11
Superb Fairy-wren	*Malurus cyaneus*		18.3	338	37.4	827
Red-backed Fairy-wren	*Malurus melanocephalus*		6.1	72	7.2	113
White-winged Fairy-wren	*Malurus leucopterus*		8.1	96	23.6	300
Purple-backed Fairy-wren	*Malurus assimilis*		22.8	292	42.6	637
White-browed Scrubwren	*Sericornis frontalis*		0.5	8	1.0	10
Speckled Warbler	*Chthonicola sagittata*	V, D	1.5	6	1.5	6
Weebill	*Smicrornis brevirostris*		24.4	204	24.6	281
Western Gerygone	*Gerygone fusca*		6.6	28	14.4	71
White-throated Gerygone	*Gerygone albogularis*		2.5	9	8.2	27
Yellow Thornbill	*Acanthiza nana*		10.2	146	14.9	165
Yellow-rumped Thornbill	*Acanthiza chrysorrhoa*		10.7	102	14.4	102
Chestnut-rumped Thornbill	*Acanthiza uropygialis*	D	4.6	57	10.8	62
Buff-rumped Thornbill	*Acanthiza reguloides*	D	0.0	0	0.5	2
Inland Thornbill	*Acanthiza apicalis*		2.0	20	1.5	9
Brown Thornbill	*Acanthiza pusilla*		0.0	0	1.0	2
Southern Whiteface	*Aphelocephala leucopsis*	V, VN, D	0.5	2	1.0	4
Spotted Pardalote	*Pardalotus punctatus*		0.5	1	1.0	5
Striated Pardalote	*Pardalotus striatus*		25.4	116	39.5	278
Lewin's Honeyeater	*Meliphaga lewinii*		0.0	0	3.1	13
Singing Honeyeater	*Lichenostomus virescens*		8.1	50	15.4	180
White-plumed Honeyeater	*Lichenostomus penicillatus*		28.4	511	34.4	855
White-fronted Honeyeater	*Purnella albifrons*		0.5	2	0.0	0
Noisy Miner	*Manorina melanocephala*		28.9	627	37.9	1140
Yellow-throated Miner	*Manorina flavigula*		32.0	416	36.9	781
Spiny-cheeked Honeyeater	*Acanthagenys rufogularis*		10.7	49	11.8	65
Crimson Chat	*Epthianura tricolor*		0.0	0	1.0	14
White-fronted Chat	*Epthianura albifrons*	V	0.0	0	0.5	13
Brown Honeyeater	*Lichmera indistincta*		4.1	24	10.8	90
Black-chinned Honeyeater	*Melithreptus gularis*	V	0.5	2	1.0	4
Brown-headed Honeyeater	*Melithreptus brevirostris*		0.5	3	1.5	8
White-throated Honeyeater	*Melithreptus albogularis*		3.0	32	4.6	70
Blue-faced Honeyeater	*Entomyzon cyanotis*		10.2	41	20.5	100
Noisy Friarbird	*Philemon corniculatus*		6.6	21	10.8	112
Little Friarbird	*Philemon citreogularis*		32.0	299	43.1	457
Striped Honeyeater	*Plectorhyncha lanceolata*		9.6	41	26.7	175
Painted Honeyeater	*Grantiella picta*	V, VN	3.6	13	3.6	15
Grey-crowned Babbler	*Pomatostomus temporalis*	V, D	9.6	85	13.3	118
Varied Sittella	*Daphoenositta chrysoptera*	V, D	0.5	5	0.0	0
Ground Cuckoo-shrike	*Coracina maxima*	D	0.5	1	1.0	6
Black-faced Cuckoo-shrike	*Coracina novaehollandiae*		24.4	80	44.6	221
White-bellied Cuckoo-shrike	*Coracina papuensis*	D	4.1	11	4.6	16
White-winged Triller	*Lalage sueurii*	D	9.6	28	10.3	36
Crested Shrike-tit	*Falcunculus frontatus*	D	2.0	7	2.1	4

Golden Whistler	*Pachycephala pectoralis*		1.0	2	1.0	3
Rufous Whistler	*Pachycephala rufiventris*	D	12.7	72	31.8	156
Grey Shrike-thrush	*Colluricincla harmonica*		16.8	57	26.7	126
Crested Bellbird	*Oreoica gutturalis*	D	2.0	5	0.5	1
Australasian Figbird	*Sphecotheres vieilloti*		0.5	1	0.5	11
Olive-backed Oriole	*Oriolus sagittatus*		5.6	18	7.2	18
White-breasted Woodswallow	*Artamus leucorynchus*		10.7	54	12.3	58
Masked Woodswallow	*Artamus personatus*		2.5	14	3.6	53
White-browed Woodswallow	*Artamus superciliosus*	D	5.1	82	7.7	180
Black-faced Woodswallow	*Artamus cinereus*		0.5	5	1.5	5
Dusky Woodswallow	*Artamus cyanopterus*	V, D	3.0	9	4.6	18
Little Woodswallow	*Artamus minor*		0.0	0	1.5	7
Grey Butcherbird	*Cracticus torquatus*		23.4	101	32.3	176
Pied Butcherbird	*Cracticus nigrogularis*		32.0	156	45.1	205
Australian Magpie	*Cracticus tibicen*		37.6	188	49.2	271
Pied Currawong	*Strepera graculina*		0.5	1	0.5	1
Spangled Drongo	*Dicrurus bracteatus*		0.0	0	0.5	1
Rufous Fantail	*Rhipidura rufifrons*		0.5	1	0.0	0
Grey Fantail	*Rhipidura albiscapa*		3.6	13	10.3	35
Willie Wagtail	*Rhipidura leucophrys*		32.0	225	47.2	379
Australian Raven	*Corvus coronoides*		20.8	91	44.1	200
Little Raven	*Corvus mellori*		3.0	10	13.3	79
Little Crow	*Corvus bennetti*		1.5	9	0.0	0
Torresian Crow	*Corvus orru*		8.1	30	16.4	77
Leaden Flycatcher	*Myiagra rubecula*		1.0	3	4.6	25
Restless Flycatcher	*Myiagra inquieta*	D	6.6	22	12.8	62
Magpie-lark	*Grallina cyanoleuca*		35.0	183	52.3	297
White-winged Chough	*Corcorax melanorhamphos*		7.6	89	7.7	203
Apostlebird	*Struthidea cinerea*		11.7	224	12.8	361
Jacky Winter	*Microeca fascinans*	D	9.1	29	14.9	89
Red-capped Robin	*Petroica goodenovii*	D	1.5	4	5.6	29
Hooded Robin	*Melanodryas cucullata*	E, EN, D	0.5	3	2.6	11
Eastern Yellow Robin	*Eopsaltria australis*	D	3.0	17	4.6	27
Horsfield’s Bushlark	*Mirafra javanica*		3.0	24	2.6	9
Golden-headed Cisticola	*Cisticola exilis*		0.5	4	4.6	39
Australian Reed-Warbler	*Acrocephalus australis*		0.0	0	0.5	2
Tawny Grassbird	*Megalurus timoriensis*		0.0	0	4.6	14
Rufous Songlark	*Cincloramphus mathewsi*		2.5	16	6.2	23
Brown Songlark	*Cincloramphus cruralis*		0.0	0	1.5	5
Silvereye	*Zosterops lateralis*		2.5	47	7.7	56
Welcome Swallow	*Hirundo neoxena*		5.1	23	15.9	66
Fairy Martin	*Petrochelidon ariel*		7.6	75	17.4	247
Tree Martin	*Petrochelidon nigricans*	D	9.1	91	22.6	335
**Common Blackbird	*Turdus merula*		0.0	0	0.5	1
**Common Starling	*Sturnus vulgaris*		5.6	74	12.3	136
**Common Myna	*Sturnus tristis*		0.5	2	13.3	102
Mistletoebird	*Dicaeum hirundinaceum*		24.4	141	33.3	200
Zebra Finch	*Taeniopygia guttata*		4.1	47	2.6	41
Double-barred Finch	*Taeniopygia bichenovii*		5.6	50	7.7	105
Plum-headed Finch	*Neochmia modesta*	D	0.0	0	2.6	67
Red-browed Finch	*Neochmia temporalis*		0.0	0	0.5	3
Chestnut-breasted Mannikin	*Lonchura castaneothorax*		0.5	2	0.5	30
**House Sparrow	*Passer domesticus*		0.0	0	0.5	1
Australasian Pipit	*Anthus novaeseelandiae*		4.1	12	1.5	3

* Conservation status: D, declining (Reid 1999); E, Endangered, and V, Vulnerable in NSW (NSW Biodiversity Conservation Act); EN, Endangered nationally, and VN, Vulnerable nationally (Cwth EPBC Act 1999)
** Introduced species

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Ecology of *Festuca karatavica*, a promising tussock grass for restoration of alpine rangelands

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Keywords: Altitudinal gradient, Nutrient value, Phenological stages , Plant Ecology, Tussock grass

Abstract

Alpine ecosystems are characterized by extreme environmental conditions, including cold temperatures, low rainfall, poor soils, and high winds, which severely constrain plant growth and establishment. Despite these challenges, keystone plant species native to these habitats play a vital role in ecosystem restoration and conservation. One such species is *Festuca karatavica* (Bunge), a tussock grass native to alpine regions of northern Iran and Central Asia, found at elevations ranging from 1800 to 3100 m.a.s.l. This species is particularly valuable as a source of livestock fodder and for its contributions to soil and water conservation. In this study, we investigated the phenology, nutrient content, and ecological preferences of *F. karatavica* along an altitudinal gradient in its natural habitat on Shirbad Summit, northeast Iran. We also analyzed associated plant species diversity and richness, as well as soil physical and chemical properties. The phenological cycle of *F. karatavica* begins in early April and concludes with seed shedding by September, with seasonal variations influenced by annual rainfall. Crude protein content, acid detergent fiber (ADF), and neutral detergent fiber (NDF) were highest during early growth stages but declined over the growing season. Its seeds germinate easily without dormancy, suggesting strong regenerative potential. Soil conditions vary across the altitudinal gradient, with sandy loam textures and the highest pH (7.4) and electrical conductivity (EC) observed at the summit, decreasing at lower elevations. Species diversity peaked at mid-elevation (2831 m.a.s.l.), while species richness and evenness were highest at higher (3050 m.a.s.l.) and lower (2720 m.a.s.l.) elevations, respectively. The most favorable habitat for *F. karatavica* was identified at mid-elevation, where optimal soil nutrients (N, P, and organic C) and mycorrhizal associations supported its growth. Growth at higher altitudes is constrained by poor soil conditions and harsh climatic factors, whereas competition, intensive grazing, and erosion limit its success at lower altitudes.

Introduction

Festuca karatavica (Bunge), is a perennial native grass. It grows in alpine habitats and provides a reliable source of fodder for livestock and wildlife. It is also important for soil and water conservation in alpine ecosystems with harsh climates. Intense livestock grazing and possible climate change effects have led to the replacement of *F. karatavica* by *F.sclerophylla,* a closely related species whose distribution range extends through Alborz and central Zagros toward north-eastern Turkey and Caucasian mountains(Memariani and Arjmandi, 2013). According to the extent of its occurrence and its very peculiar habitats, which are highly sensitive to climate change, *F. karatavica* is evaluated as an endangered (EN, B1ab (ii, iii)) species in Iran (Memariani and Arjmandi, 2013). In this study, we investigated the ecological conditions and phenology of *F. karatavica* at Shirbad, the tallest summit of the Binalud Mountain range in northeast Iran.

F. karatavica(Bunge) B. Fedtsch. Turkest. (Fig1). It is densely tufted. Culms 50-100 (-140) cm, glabrous, at base tightly enveloped by brownish butt sheaths. Leaf sheaths glabrous on surface; ligule an eciliate membrane, truncate, 1.5-5 mm long (Memariani and Arjmandi, 2013).

Fig 1. *Festuca karatavica* in Flora of Khorasanica

Phytogeography and ecology

The general distribution of this Irano- Turanian species is from western Tian Shan, southwestern Pamir-Alay, to northeastern and northcentral parts of Afghanistan, and the newly recorded specimens from Binalood Mountains extend the distribution range of *F. karatavica* more westward to NE Iran. Ecologically, it grows in higher mountain and alpine areas on stony slopes, rocks, and screes. In the Binalood mountain ranges, its habitat is usually on metamorphic schistose rocks at high elevations between 1800 to 3000 m. From westward, in calcareous rocky slopes of the North Khorassan Province (Aladagh and Salook and Shah-Jahan Mts.) (Memariani and Arjmandi, 2013).

Methodology

The investigated area was determined by the priority of the presence of *F. karatavica*; in three altitudes, the first elevation was 3050 meters with the coordinates of 36º17"35' North and 59º05"40' East, the second is located at the height of 2831 meters of 36º17"27'N and 59º05"49.49' E. The third altitude was at 2720 meters of 36º17"20.6' N and 59 º 05"3.40' E.

In each elevation, three transects were established, in which 5 quadrats of one square meter were placed randomly. The abundance and canopy cover of *F. karatavica* and all other plant species were measured within quadrats.

Forage quality was monitored by measuring crude protein (nitrogen), ADF (Acid Detergent Fiber), NDF (Neutral Detergent Fiber) and DMD (Digestible Dry Matter). The formula provided by Oddy *et al*.,1983 was used: **DMD$^{\%10}$ = 83/56-0/824 ADF ٪+ 2/626 N٪**

Metabolic energy was calculated after calculating the digestibility percentage of dry matter from the equation provided by “Deutsches Institut für Normung” (DIN): **ME^{2} (MJ/Kg) = 0.17 DMD%– 2**

The SPSS software was used to analyze the data. The nutritive values of plant samples from different elevations were compared at different phenological stages using one-way analysis of variation.

To determine the phenological stages, 10 individuals *of F. karatavica* were selected from each elevation class. Phenological growth stages were recorded every 20 days from April to July in 2015 and 2016.

Results and discussion

Forage quality changes were compared according to NDF, ADF and protein (Fig 2). The amount of NDF increased (P=<0.00001) by increasing plant phenological stages from early emergence to seed shedding. Consistent with other studies on native grasses of Iran (Arzani et al., 2004), the highest amount of NDF was in the seed ripening stage and the lowest amount was in the early growth season, conversely protein content was reduced from the early growth towards the seed ripening stage. The critical limit of protein is shown as a line, which is defined as the critical level that is needed to keep the grazing livestock alive.

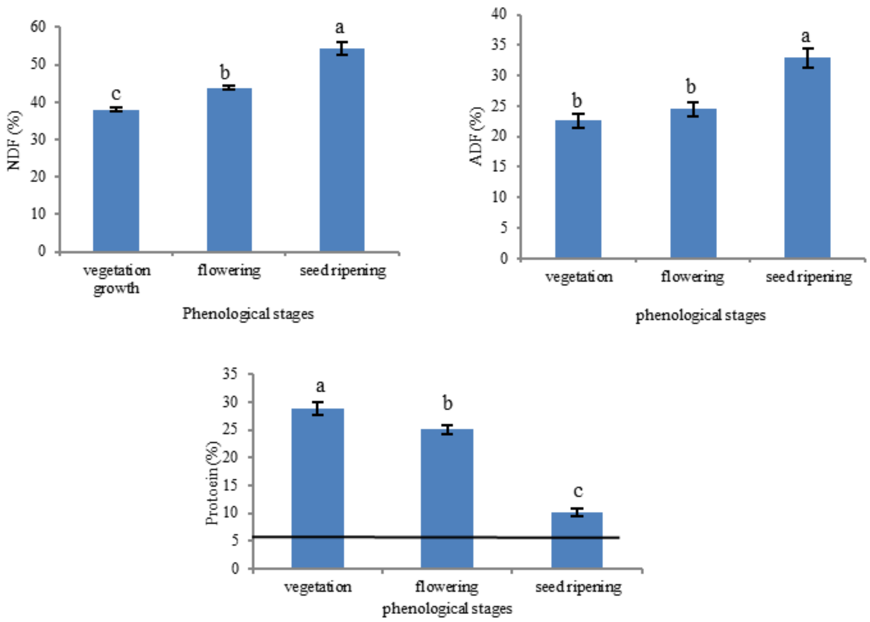

Fig 2. Effect of Phenologcal stages on Nutrition qualification factors

The results of the plant phenology in 2015 showed that growth initiation in high-altitude were from the end of April to the mid-May. Phenological stages commenced a week earlier in the mid and low elevations that the summit site. A dry spring in 2016 led to an earlier growth stages as compared the those we had recorded for 2015 as a normal year (Fig3).

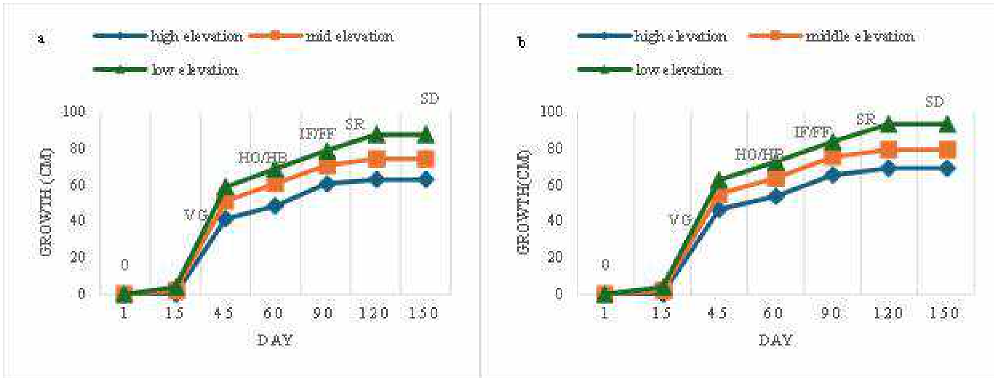

Fig 3. Phenological stages in different elevation in a normal (2015) and a dry (2016) year.

By increasing the elevation, mycorrhiza spore counts and the inoculation rate were reduced, similar to the changes observed for soil moisture (Fig4).

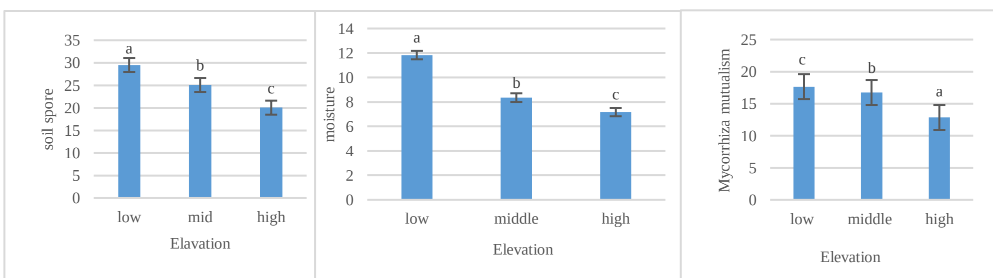

Fig 4. Changes in Spore, Moisture and Mycorrhiza in different states of study elevation.

The soil texture in each altitudinal habitat was loamy. Silt, nitrogen, and phosphorous levels were higher at lower altitudes, whereas clay and EC levels were higher at higher elevation. (Table1).

Table 1. Soil properties in three elevation

Index	Low Elevation	Mid Elevation	High Elevation
Sand (%)	43.75±0.79	57.5±2.62	46.75[a] ±1.75
Silt (%)	40.25±0.74	28.25±1.89	31.5±1.80
Clay (%)	16±0.35	14.25±1.35	20.75±1.43
Texture	loamy	loamy	loamy
EC (µs/cm)	1826±0.35	1824.50±1.35	1823.25±1.63
Ca (meq/lit)	140.5±0.55	124.5±1.01	108±1.25
N (ppm)	2129±0.93	2074.75±1.27	2021±1.75
pH	7.40±0.004	7.36±0.03	7.32±0.03
Organic matter (%)	2.82±.58	2.77±0.21	2.95±0.21
Phosphorus (ppm)	32.65±0.68	28.32±0.69	24.02±0.92

The habitats of *F. karatavica* differed in plant community indices, with mid-altitude habitats showing the highest species diversity and richness but the lowest evenness compared to high- and low-altitude habitats(Table2).

Table 2. Biodiversity indexes in different studied altitude

Elevation / Index	Index	Low	Middle	High
Diversity	Shannon-Wiener	2.490	2.695	2.518
	Simpson	0.819	0.831	0.792
	Hill) N2(	4.964	5.577	4.640
	Hill) N1(	5.65	6.50	5.76
	Brillouin	2.125	2.431	2.274
Evenness	Camargo	0.525	0.573	0.536
	Simpson revers	0.682	0.608	0.549
	Modified Knee	0.227	0.165	0.187
Richness	Number of species	8	10	9
	Jack Knife	12.4	15.3	10.8

Conclusion

In this study, we provided detailed insights into the phenological growth stages, nutritive value, soil characteristics, mycorrhizal symbiosis, and plant community indices of *Festuca karatavika*, a keystone species native to the alpine ecosystems of northeast Iran. Our findings shed light on the environmental constraints limiting the distribution of this species and contributing to its classification as endangered. At lower elevations, higher soil organic matter and nutrient levels likely promote greater mycorrhizal symbiosis. However, more intense livestock grazing and competition from invasive species like *Eremurus olgae* may reduce its abundance in these areas. Conversely, harsh microhabitat conditions, such as low soil moisture, poor nutrient availability, and extreme climate, may account for its low abundance at higher elevations. Our results suggest that the mid-altitude zone of Shirbad Mountain provides the most suitable habitat for *Festuca karatavika*, offering a balance between protection from harsh upper-elevation conditions and reduced grazing pressure.

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Synergizing livestock management and grassland ecology for enhanced biodiversity and soil health

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Key words: bird diversity; grassland conservation index (GCI); soil microorganism; active carbon; phosphatase activity

Abstract

This study investigated the relationship between soil health and biodiversity in grasslands, under the hypothesis that better livestock management practices result in a healthier balance between fungi and bacteria, greater carbon sequestration potential, higher bird diversity, and better coverage of forage species. Six farms were selected, and within each, variables were determined at farm and paddock level. At farm level, floristic variables related to pasture degradation as coverage of forage species, coverage of invasive exotic species, proportion and height of the upper stratum were assessed to form the Grassland Conservation Index (GCI) and Bird Monitoring Strategy. At paddock level, a representative pasture was chosen based on the dominant soil group. Two transects were established in these pastures along which soil was sampled for analyses of microbiologically, chemical and physical attributes. Fungal abundance, the fungi-to-bacteria ratio (F), enzymatic activities (beta-glucosidase and phosphatase), and active carbon (AC) were determined. These variables were used to construct the Microbiological Soil Health Index. Chemical analyses included nutrient content, micronutrients, pH, and bases. At the farm level, principal component analysis (PCA) revealed that the main and the second axis explained 39,4% and 24% respectively, of the variability, distinguishing two samples. AC and phosphatase, crucial for the soil health index, were determinant in this separation. These two samples showed higher total phosphorus (P total), AC, and phosphatase activity, suggesting that soils rich in total P can sustain a greater abundance of P-solubilizing microorganisms. Although the number is low and much more studies are needed to correlate the ecosystemic trophic chains and their relationships, this case study leaves lessons learned and trends of the relationships between ecosystemic services of rangelands.

Introduction

The Río de la Plata grasslands are among the largest, most diverse, and least transformed temperate subhumid to subtropical grasslands in the world, spanning central-eastern Argentina, Uruguay and southern Brazil (Soriano et al. 1991; Paruelo et al. 2022). These grasslands provide crucial ecosystem services, including food provisioning, biodiversity conservation (Bilenca and Miñarro 2004; Medan et al. 2011), and carbon sequestration (Modernel et al. 2016). Given climate change and increasing market demands, there is an urgent need to identify indicators that reconcile livestock production with environmental protection.

Evidence suggests that biological indicators, such as bird species richness and microbiological and biochemical indicators, offer a more precise assessment of soil health and functional potential than physicochemical indicators. Soil microorganisms perform essential functions for plants (Newsham et al. 1995; Smith and Read 2008; Mendes et al. 2013; Rillig et al. 2016) and serve as valuable bio-indicators. These include the abundance of beneficial organisms, the fungi-to-bacteria biomass ratio (H:B), enzyme activity crucial for nutrient cycling (Pérez Guzmán et al. 2021), and active carbon content, which reflects the carbon available to microorganisms and is sensitive to practices that sequester carbon in the soil (Hurisso et al. 2016).

Within Uruguay, El Paso Centurión and Sierra de Ríos is a protected landscape important for biodiversity. The main activity here is livestock farming on natural grasslands, which requires effective management based on scientific data. Our approach emphasizes that healthier soils promote better plant growth, that supports livestock production and plant diversity, which in turn sustains greater bird diversity and serves as bioindicators of environmental health.

Our main objective was to establish a baseline of environmental health indicators in the Paso Centurión and Sierra de Ríos Protected Landscape, generating information to propose management recommendations for biodiversity conservation. Specifically, we aimed to assess i) the health status of six livestock farms using soil, vegetation, and bird health indicators, and ii) the correlation between these health indicators at different spatial scales (farm and paddock).

Methods

This study was carried out in Paso Centurión and Sierra de Ríos, a protected landscape which is in the northeast of Uruguay. In November 2023 we selected 6 livestock establishments (named from A to F). At farm spatial scale we study percentage of natural pasture, vegetation cover index by satellite, bird abundance, bird richness species.

At the paddock spatial scale, two representative points within the dominant soil type were sampled in each establishment. For the study of chemical, physical and biological indicators of the soil, two composite soil samples from the first 15cm were taken, following two 60 m transects. We determined total P, micronutrients, total bases and organic matter according to MEHLICH - I; Sulfochromic Oxidation and soil physical analysis were performed with Bouyoucos Densimeter. In laboratorio Sosei we estimated biological variables such as Fungi and bacterial biomass to estimate the H:B ratio, and abundance of protozoa were determined by direct microscopy; phosphatase activity and betaglucosidase activity were measured by spectrophotometry and active carbon was determined by oxidation of potassium permanganate. To investigate the health of the vegetation, the cover of forage species, the cover of exotic species and the structural heterogeneity were assessed in these sample points. Using vegetation variables, we construct the Grassland Conservation Index at farm scale, which represents individual contribution of producers (at the level of rural establishments) to the conservation of natural grasslands. Integrating data of functional microbiological variables, the Microbiological soil health Index (MSHI) was constructed. To study the correlation between the different indicators at paddock scale, simple linear regression analyses were carried out between the different variables studied, as principal component analysis (PCA), standardizing different variables at paddock scales.

Results

Results at farm scale

Site C had the lowest ICP and, together with site F had a low number of birds compared to the other sites surveyed (Figure 1)

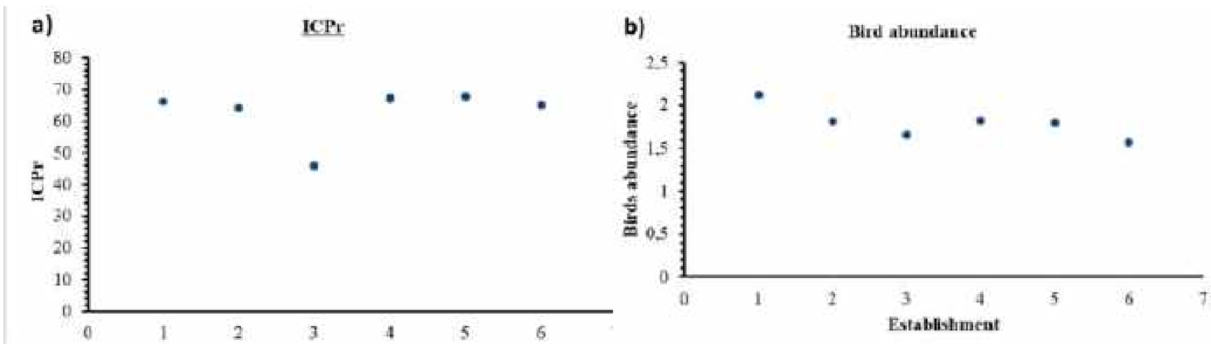

Figure 1. ICP value (a) and bird abundance (b) in the establishments studied.

Results at paddock scale

The abundance of the different microbial groups and as the H:B ratio, was relatively homogeneous among study sites (ranged 0.01-0.4). We found differences in soil microorganism functioning variables between sampled points. The principal component analysis separated samples A1 and C2 (samples with greatest MSHI) from the rest at paddock scale. The active carbon, phosphatase activity and total P in soil were important in explaining this grouping of sample points. (Figure 2).

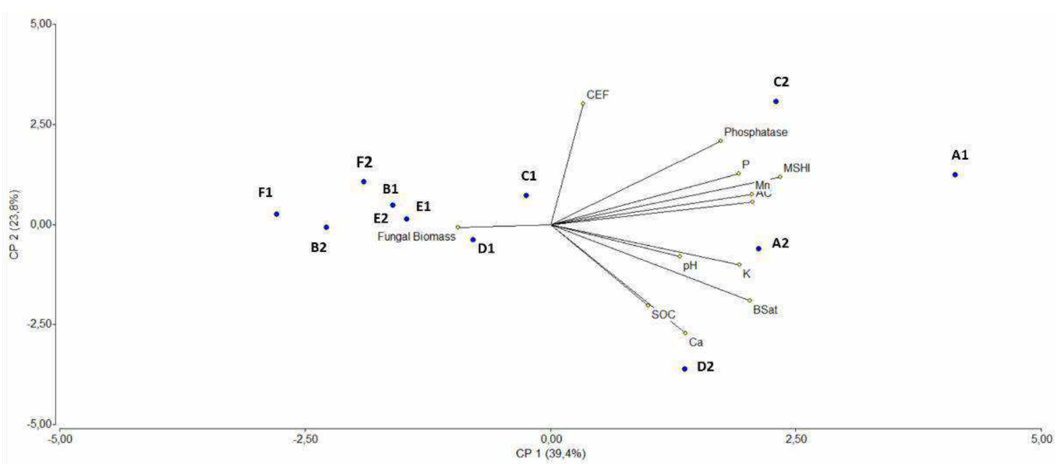

Figure 2. Principal component analysis performed with variables standardized at paddock scale. A1 and A to F1 and F2 are points 1 and respectively sampled and within paddock A to paddock F; MSHI: Microbiological soil health Index; AC: active carbon; Bsat: bases saturation; SOC: soil organic carbon; CEF: coverage of forage species.

In terms of grassland vegetation, all sites had a high total ground cover (70-98%), an índex of forage species cover between 1.6 -3.4 and no exotic species were recorded. Contrary we expected, the relationship between MSHI and forage species cover was weak (Fig 3).

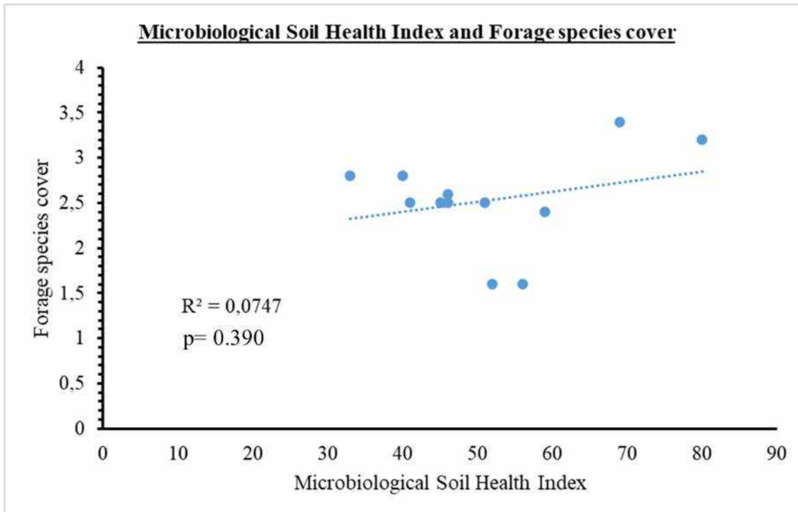

Figure 3. Relationship between the Microbiological soil health Index and coverage of forage species.

Discussion

Our research is the first to report values for soil microbial indicators in grasslands and shows that exist an association between soil and vegetation health in this ecosystem. The points with the highest MSHI were those with the highest levels of total P. This could be explained due to soils with more total P could support a greater abundance of P-solubilising microorganisms, as evidenced by a higher activity of the enzyme phosphatase. Contrary we expected we did not find a relationship between the MSHI and forage species cover, probably due to the small number of replications. Larger sampling efforts would be needed to explore this relationship further. A more comprehensive avian survey, including statistical modelling, is needed to establish a stronger, statistically significant link between bird diversity and ecological indicators. Identifying indicators that reflect the health of the different components of the natural field and how they relate to each other under different productive management is a fundamental step in creating incentives and promoting policies for the conservation of our most important ecosystem.

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Effect of soil and subhabitat differentiation on the growth of *Tarchonanthus camphoratus* seedlings from a semi-arid savanna of South Africa

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Key words: allelopathic effect; seedling growth rate; canopied zone, uncanopied zone; nutrient status

Abstract

Large areas in the savanna of the Northern Cape Province of South Africa suffer from bush thickening, especially by species such as *Tarchonathus camphoratus*. Effective management of these areas requires an understanding of the factors such as allelopathy that can affect the establishment, survival and growth of *T. camphoratus* seedlings. The objectives of this study were to investigate whether soil originating from different subhabitats would differ in soil nutrient status and whether *T. camphoratus* exhibit allelopathic effects by affecting the survival and growth of seedlings grown in soil originating from these different subhabitats. Soil and ripe seeds were collected in the Northern Cape Province of South Africa on two sites of different soil types (deep sandy and shallow rocky) and within three subhabitats (close to the stems of mature *T. camphoratus* plants; in the middle of the canopy; and away from tree canopies in the uncanopied zone). The trial was conducted under controlled conditions in a greenhouse over a period of 18 months and consisted of six treatments with ten replications. Soil analyses, including Na, Mg, K, Ca, P and N were performed on the soil from the different subhabitats. Seeds germinated abundantly in all the soil samples, confirming that there are no allelopathic effects preventing their germination. Significantly higher ($P<0.05$) plant heights, leaf numbers and growth rates were measured in seedlings grown in the soil originating from the canopied zone compared to those grown in soil from the uncanopied zone, while no significant differences ($P>0.05$) existed between the seedlings grown in soil from the same subhabitat but different soil types. The better growth of *T. camphoratus* seedlings in soil from the canopied subhabitats can be attributed to the higher soil nutrient status in these subhabitats. This has important implications for tree thinning operations as areas where mature trees are removed, will present ideal areas for seedling establishment, survival and growth.

Introduction

Southern African savannas are water-limited ecosystems and bush thickening is considered a major factor contributing towards the low occurrence or even total absence of herbaceous plants, due to severe competition from the woody plants for available soil water (Smit et al. 1999). Large areas in the savanna of the Northern Cape Province of South Africa suffer from bush thickening, especially by species such as *Tarchonathus camphoratus*. Many studies have shown a positive response of the herbaceous layer to the partial or complete removal of woody plants (Smit 2005; Harmse et al. 2016) and the success of bush-clearing or thinning operations is often measured on the basis of the recovery, productivity and stability of the herbaceous layer. However, the re-establishment of woody plants after thinning or clearing - either by resprouting or by seedling establishment from seeds - remains a serious threat and this phenomenon has been widely reported in southern African savannas (Smit 2004; Harmse et al. 2016). It is known that some plants release allelochemicals into the soil and these metabolic secretions, including long chain fatty acids, phenolic acids, terpenoides, organic cyanides and others are known to affect seed germination and seedling emergence, mortality and growth (Ghebrehiwot et al. 2014). The objectives of this study were to investigate whether soil originating from different *T. camphoratus* subhabitats (under- and between tree canopies) would differ in soil nutrient status and whether *T. camphoratus* exhibits allelopathic effects by affecting the survival and growth of seedlings grown in soil originating from these different subhabitats.

Methods

Soil and ripe seeds of *T. camphoratus* shrubs were collected from the Rooipoort Nature Reserve approximately 60 km west of the town of Kimberley in the Northern Cape Province of South Africa. The reserve is located within the savanna biome of southern Africa and Mucina and Rutherford (2006) described the area as the Eastern Kalahari Bushveld Bioregion. Twenty free-standing *T. camphoratus* shrubs of similar size (1.5 - 2.0 m height) were randomly selected on two sites of different soil potential (deep sandy soils and shallow rocky soils). Topsoil (0 - 20 cm) was excavated from three identified subhabitats (Smit & Swart 1994), namely: (1) close to the stem ; (2) in the middle of the canopy between the stem and the canopy edge; and (3) in the open uncanopied zone between the shrubs. The bulked samples were thoroughly mixed and a subsample was taken for laboratory analyses.

Large pots (18 700 cm^3) were filled with an equal volume of soil and placed in a greenhouse located at the facilities of the University of the Free State, Bloemfontein, South Africa. This amounted to 3 subhabitats x 2 sites x 10 replications = 60 pots. *T. camphoratus* seeds were planted in the pots during September 2018. Plots were regularly watered and germination of seeds recorded. Seedling height was measured weekly. Eighteen weeks later all plants were harvested. The number of leaves per seedling, number of daughter shoots, stem diameter at the base and seedling height was recorded. The stems, leaves and roots were separated and the soil washed from the roots with medium pressure water. Thereafter all biomass fractions were oven-dried at 70°C to constant mass and then weighed. The Shapiro-Wilk test ($p > 0.05$) was used to test all variables for normal data distribution. Analysis of variance using the randomized complete block design (RCBD) was used to test the influence of subhabitat and soil on the different plant growth parameters.

Results and Discussion

Soil nutrient status

Marked differences in soil nutrient status between the uncanopied subhabitat and the two canopied subhabitats were found (Table 1). However, the extent to which each soil nutrient was affected, differed. Subhabitat differentiation significantly ($p < 0.05$) influenced soil potassium and calcium concentrations as well as total nitrogen and organic carbon percentages on both soil types and followed a clear spatial gradient with increasing distance from the stem to the open grassland subhabitat. Magnesium concentrations differed between subhabitats on the rocky soil only, while plant available phosphorus only differed between subhabitats on sandy soil. Soil pH, calcium concentration, nitrogen and organic carbon percentage were significantly ($p < 0.05$) influenced by soil potential.

Table 1 Mean ± 1 SE of all tested soil variables for two soil potentials (sandy and rocky) in three subhabitats

Site Subhabitat	Rocky stem	Rocky canopy middle	Rocky open	Sandy stem	Sandy canopy middle	Sandy open
pH(H_2O)	7.32 ± 0.06	7.59 ± 0.06	7.41 ± 0.06	7.04 ± 0.07	7.35 ± 0.08	6.88 ± 0.08
K^+ (mg kg^{-1})	244.37 ± 15.19	208.82 ± 9.98	143.47 ± 8.99	239.42 ±17.61	237.97 ± 16.50	132.96 ± 12.424
Ca^{2+} (mg kg^{-1})	475.22 ± 27.01	436.17 ± 44.25	306.80 ±18.07	339.51 ± 20.84	279.36 ± 12.11	233.98 ± 17.048
Mg^{2+} (mg kg^{-1})	95.17 ± 2.88	90.31 ± 2.49	71.22 ± 2.57	83.52 ± 3.37	91.47 ± 3.69	81.28 ± 4.609
Na^+ (mg kg^{-1})	5.10 ± 0.18	4.91 ± 0.33	4.80 ± 0.22	4.58 ± 0.10	4.72 ± 0.10	4.30 ± 0.078
P (mg kg^{-1})	6.30 ± 1.25	7.53 ± 1.11	4.52 ± 0.79	7.86 ± 1.20	4.17 ± 0.67	3.77 ± 0.699
N (%)	0.08 ± 0.01	0.05 ± 0.00	0.03 ± 0.01	0.05 ± 0.00	0.03 ± 0.00	0.02 ± 0.001
OC (%)	1.29 ± 0.27	0.829 ± 0.02	0.47 ± 0.03	0.81 ± 0.03	0.548 ± 0.00	0.35 ± 0.012
C:N	17.0:1 ± 0.60	18.4 :1 ± 0.98	20.8:1 ± 2.70	17.2:1 ± 0.49	22.0:1 ± 2.21	19.9 ± 1.127

Seed germination and growth of seedlings

Germination of the seeds commenced very slowly and only by 15 January 2019 had the majority of seeds germinated, indicating that fresh *T. camphoratus* seeds undergo some form of seed dormancy (seed rest period) for approximately three to four months. Seedlings grown in the soil originating from the sandy site differed significantly ($p < 0.05$) in height between subhabitats. Seedlings grown in the soil from the two canopied subhabitats grew significantly ($p < 0.05$) higher than the seedlings grown in the soil from the uncanopied subhabitat. In the case of the soil originating from the rocky site, only seedlings grown in the soil from the stem subhabitat grew significantly higher ($p < 0.05$) than those grown in soil from the uncanopied subhabitat (Table 2).

Seedlings grown in the soil from the two canopied subhabitats of both the sandy and the rocky site grew significantly ($P < 0.05$) thicker (stem base diameter) compared to those grown in soil from the uncanopied subhabitat. However, the stem diameters of plants grown in soil of the canopied subhabitats of both soil types did not differ significantly ($p > 0.05$) (Table 2).

The number of leaves per seedling was 138% and 88% higher for plants grown in the soil originating from the stem and canopy middle subhabitats respectively, compared to plants grown in soil from the uncanopied subhabitat of the sandy site. Similarly, plants grown in the soil from the stem and canopy middle subhabitat, had 114% and 106% more leaves respectively, than plants grown in soil from the uncanopied subhabitat of the rocky site (Table 2).

The dry mass of the seedling leaves and shoots as well as total dry mass (leaves, shoots and roots combined) yielded very similar results. Significantly ($p < 0.01$) heavier leaf dry mass, shoot dry mass and total dry mass were recorded in plants grown in the soil from the canopied subhabitats compared to plants grown in the soil from the uncanopied subhabitat. The plants grown in the soil of the two canopied subhabitats were statistically non-significant ($p > 0.05$) in leaf, shoot and total dry mass in both soils.

Table 2 Soil effect on seedling height, stem diameter, number of leaves and number of daughter shoots (mean ± SE) as per subhabitat (n=10). The same letter for each subhabitat represents statistical non-significance ($p > 0.05$).

Subhabitat	Site	Seedling height (mm)	Stem diameter (mm)	Number of leaves	Number of daughter shoots.
Stem	Sandy	683.8 ± 71.5[a]	8.2 ± 0.5[a]	243.7 ± 31.8[a]	28.3 ±4.2[a]
	Rocky	664.6 ± 84.3[a]	8.7 ± 0.5[a]	206.3 ± 25.6[a]	28.2 ± 5.3[a]
Canopy middle	Sandy	655.9 ± 49.8[a]	8.6 ± 0.4[a]	192.0 ± 13.8[a]	24.4 ± 2.8[a]
	Rocky	570.0 ± 68.2[a]	8.1 ±0.8[a]	198.4 ± 27.0[a]	21.6 ± 3.2[a]
Uncanopied	Sandy	405.7 ± 46.1[a]	5.7 ± 0.3[a]	102.3 ± 11.5[a]	8.7 ± 2.0[a]
	Rocky	418.9 ± 29.8[a]	5.8 ± 0.2[a]	96.4 ± 8.6[a]	8.0 ± 2.1[a]

The only significant ($p < 0.05$) difference in root dry mass was found between plants grown in the soil from the canopy middle and uncanopied subhabitat of the rocky site (Table 3).

Table 3 Soil effect on leaf dry mass, shoot dry mass, root length and root dry mass (mean ± SE) as per subhabitat (n=10). The same letter for each subhabitat represents statistical non-significance ($p > 0.05$).

Subhabitat	Site	Leaf dry mass (g)	Shoot dry mass (g)	Root length (mm)	Root dry mass (mm)	Total dry mass (mm)
Stem	Sandy	15.6 ± 1.8[a]	9.9 ± 1.9[a]	486.8 ± 18.3[a]	9.6 ± 1.4[a]	35.1±5.04[a]
	Rocky	13.0 ± 1.6[a]	7.8 ± 1.6[a]	454.4 ± 32.9[a]	8.3 ± 1.0[a]	29.2±3.9[a]
Canopy middle	Sandy	14.4 ± 1.2[a]	7.9 ± 0.7[a]	480.0 ± 26.3[a]	8.7 ± 0.9[a]	31.0±2.8[a]
	Rocky	13.9 ± 2.0[a]	7.5 ± 1.4[a]	449.6 ± 26.9[a]	10.3 ± 1.7[a]	31.7±4.9[a]
Uncanopied	Sandy	6.8 ± 0.6[a]	2.9 ± 0.5[a]	484.0 ± 37.1[a]	7.2 ± 0.6[a]	16.9±1.5[a]
	Rocky	6.3 ± 0.3[a]	2.3 ± 0.2[a]	417.1 ± 25.0[a]	5.9 ± 0.4[a]	14.5±0.8[a]

Conclusions

This study demonstrated the importance of *T. camphoratus* in soil enrichment and confirms the well documented development of "nutrient hotspots" under woody plant canopies. The delayed germination of ripe seed of T. *camphoratus* confirmed the existence of a dormancy period of three to four months. This is possibly an adaptation to prevent the seeds from germinating too early in the rainy season when the risk of desiccation is high.

No allelopathic effects that limit seed germination and the survival of *T. camphoratus* were observed in the soil collected from underneath their canopies. While above-ground seedling growth was generally higher in the soil from close to the stem compared to those in soil from the middle of the canopy, the differences between the two canopied subhabitats were statistically non-significant ($p > 0.05$). In contrast to the above-ground growth parameters, no statistically significant ($p < 0.05$) difference could be established between the root dry masses of seedlings grown in the soil of all three subhabitats.

Higher nutrient availability under the shrub canopy compared to the uncanopied zone is considered to be the primary cause for the observed increased above-ground growth of the *T. camphoratus* seedlings that were grown in the soil from the two canopy subhabitats. No statistically significant ($p < 0.05$) differences in any of the measured growth parameters could be identified between soil originating from the sandy or the rocky sites, clearly demonstrating the importance of *T. camphoratus* as a biological agent that is able to create islands of enhanced soil nutrients (soil enrichment), regardless of soil type. From this, it can be concluded that subhabitat differentiation has more definite effects on seedling growth than differences related to soil type. This has important implications for tree thinning operations as areas where mature trees are removed, will present ideal areas for seedling establishment, survival and growth.

Acknowledgements

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Exterminating Bohemian knotweed (*Reynoutria* × *bohemica*) propagules using thermal treatment

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Key words: knotweed; reynoutria; fallopia; polygonum; invasive

Abstract

Invasive knotweeds in North America, including Japanese knotweed (*Reynoutria japonica*), Giant knotweed (*Reynoutria sachalinensis*), and Bohemian knotweed (*Reynoutria* × *bohemica*), cause significant environmental, structural, and economic damage worldwide. These impacts have placed knotweeds among just 37 plants on the International Union for the Conservation of Nature's list of the 100 worst invasive species. Despite their profound effects, most research has focused on specific treatment methods rather than exploring the plants' physiological vulnerabilities. Our study seeks to address this gap by investigating the thermal limitations of *Reynoutria* species. Specifically, we aim to identify the temperatures and exposure durations needed to achieve 100% mortality in knotweed rhizomes and seeds. Preliminary results show that temperatures of 150°C or higher can result in complete seed mortality within 60 minutes. These findings can inform various treatment methods, including incineration, composting, microwave radiation, thermal desorption, and other novel thermal approaches.

Introduction

Knotweeds, including Japanese knotweed (*Reynoutria japonica*), Giant knotweed (*Reynoutria sachalinensis*), and their hybrid, Bohemian knotweed (*Reynoutria* × *bohemica*), have caused significant economic and ecological damage worldwide. Lowe et al. (2000) identified Japanese knotweed as one of the world's 100 "worst" invasive species on a list encompassing plants, animals, fungi, and microbes.

These challenges underscore the need for effective prevention and management strategies for invasive knotweeds. Conventional methods, such as herbicide application and mechanical treatments, have shown limited success, with only herbicide treatments consistently achieving results (Hocking et al. 2023). However, even herbicide treatments require multiple applications over several years to ensure eradication. In construction projects where knotweeds are prevalent, excavation is often necessary to prevent long-term damage to foundations or paving. Disposal of excavated material remains a challenge; while deep burial is commonly used (McHugh 2006), it is not a reliable long-term solution since knotweed propagules can remain dormant in soil for up to 20 years (Parkinson and Mangold 2010).

Excavating contaminated soils presents an opportunity to apply off-site treatments. This study aims to establish a foundational understanding of the effectiveness of heat treatments on knotweed propagules. Specifically, the objective is to determine the temperature and duration combinations required to achieve complete mortality of Bohemian knotweed seeds and rhizomes. Bohemian knotweed, the most prolific and widely distributed of the three species (Grimsby and Kesseli 2010; Gaskin et al. 2014), is the focus of this study. Rhizomes, which account for most of the plant's establishment potential (Gowton et al. 2016), are a primary concern, but seeds are also included due to their emerging role in natural establishment, driven by the substantial seed production observed annually (Beerling et al. 1994; Bram and McNair 2004).

Methods

Bohemian knotweed rhizomes and seeds were collected on October 23, 2023, from a site near the municipal library in Mission, BC, Canada. Rhizomes were excavated and cut to 10 cm lengths before being sealed in plastic bags placed in a cooler for transport. Seeds were collected by severing dead seed heads, which were then stored in brown paper bags and later cold stratified.

Rhizomes were culled to exclude any that were obviously dead or excessively damaged. Samples lighter than 10 g were also removed. An average weight was calculated for the remaining rhizomes, and those that varied by the greatest degree were removed. To further limit the effect of third variables on treatment efficacy and analysis, samples were separated into four weight classes. Samples were then block randomized by weight class to assign treatment using formulas in Microsoft excel. Each treatment contained an even number from each weight class to ensure a weight distribution reflecting that of the overall population in each treatment.

Rhizomes were treated at three different temperatures for three different time periods. Temperatures of 100, 125 and 150°C over periods of 10, 20 and 60 minutes were used for this trial. Each treatment had nine replicates of four rhizomes for a total of 36 rhizomes per treatment. Each replicate of four rhizomes was fed through the oven separately in all cases. After treatment, rhizomes were planted in well-draining 4" pots with 600 ml of a 1:1 mixture of potting soil and sand. Rhizomes were left to grow for a period of 30 days and observed for signs of growth. As a control 36 untreated rhizomes were also planted before treatment (initial viability). After 30 days of growth, each rhizome was excavated and observed for growth. Presence of root or shoot material was determined as confirmation of survival. An ANOVA and Tukey test were conducted using R software, which looked to determine statistical significance of treatment as it related to mortality when compared to untreated samples.

Seed trials were similar to those of the rhizomes, but used time increments of 10, 20, 30, 40, 50, and 60 minutes, as more samples were available. Assignment of treatment was fully random, and seeds were placed in 15 mL centrifuge tubes filled with 10 mL of water, where they were allowed to grow over 30 days. Presence of a radicle was used as an indication of viability.

Results

Rhizomes had high initial viability at 97%. Viability by treatment can be seen in Fig. 1. Increases in treatment period and temperature resulted in a decrease in viability, with zero viability observed after 60 minutes at all temperature treatments, and at 20 minutes when treated at 150 degrees. All treatments, except treatment at 100 degrees Celsius for 10 minutes, had a significant effect when compared to controls.

Initial seed viability was 78%. Seed viability by treatment can be visualized in Fig. 2. Viability dropped with intensity of treatment, but there were some anomalous results – namely the 11.11% viability seen in treatments of 125 degrees Celsius for 60 minutes. There is also an unexpected 2.78% viability for samples treated at 125 degrees Celsius for 40 minutes. All treatments at 150 degrees Celsius resulted in seed mortality.

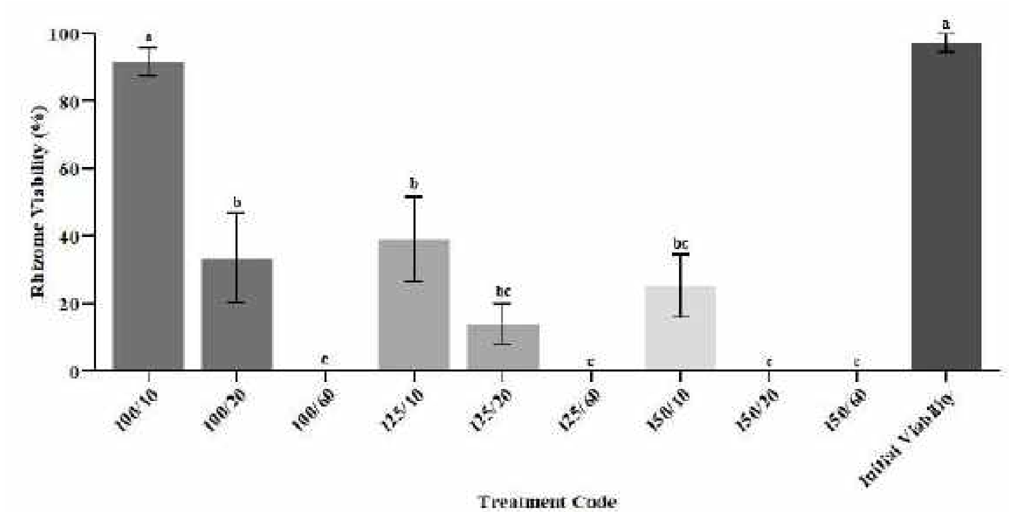

Fig.1: Viability of bohemian knotweed rhizomes based on thermal treatment with correlations. Treatment codes indicate temperature(°C)/time(minutes) except in case of Initial Viability (control), where no treatment took place. Columns are shaded based on temperature of treatment.

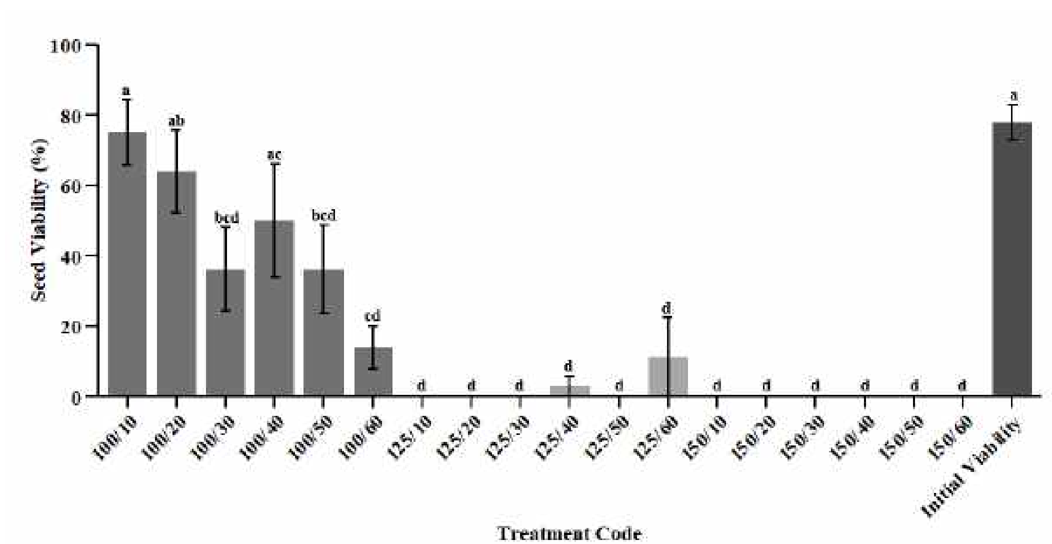

Fig.2: Viability of bohemian knotweed rhizomes based on thermal treatment with correlations. Treatment codes indicate temperature(°C)/time(minutes) except in case of Initial Viability (control), where no treatment took place. Columns are shaded based on temperature of treatment.

Discussion

Rhizome mortality under heat treatment exhibited a clear pattern of reduced viability with increasing temperature and application duration, suggesting that knotweed rhizome viability can be significantly diminished with relatively low energy input.

In contrast, results for seed viability under thermal treatment were less consistent. The expected decline in viability with increasing treatment intensity was not observed, with an unusual spike in viability at 125°C for 40 minutes. This anomaly is likely due to human or technical error, as all four surviving seeds came from the same experimental replicate, which showed 100% survival. Additionally, the inconsistency may stem from the lack of measures to ensure uniformity in the seed sample population, a step that was taken with rhizomes. Future trials could benefit from improved sample uniformity and increased sample sizes. Despite these challenges, initial seed viability fell within the 55–100% range reported in the literature (Forman and Kesseli 2003; Bram and McNair 2004), validating the novel viability assessment methodology used in this study, which also proved more cost-effective than conventional methods.

This research provides an initial understanding of the effects of thermal treatment on knotweed propagules but was limited by sampling location. Bohemian knotweed's high genetic diversity (Gaskin et al. 2014) suggests that the efficacy of thermal treatment may vary with location and seasonal factors. Additionally, knotweed propagules are often mixed with soil in practical applications, highlighting the need to study the impact of soil composition and moisture on treatment efficacy. Large rhizome and stem fragments could also limit treatment effectiveness.

Despite these limitations, results suggest that temperatures as low as 150°C, applied for as little as 60 minutes, can ensure the mortality of both seed and rhizome propagules. Although in-situ treatments using fire have been ineffective for killing vegetative propagules due to the plant's high water content (Child and Wade 2000), externally generated heat through incineration, composting, microwave radiation, or emerging technologies like thermal desorption may offer viable alternatives.

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Passive vs active restoration to improve soil health of old potato production circles in the Leipoldtville Sand Fynbos, South Africa

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Key words: brush packing; soil phosphorous; soil organic carbon; indigenous plants

Abstract

Potato production is the main land use in the endangered Leipoldtville Sand Fynbos vegetation type on the west coast of South Africa. Many fields have been abandoned and their restoration is important to conserve this vegetation type. These abandoned fields are subject to wind erosion and have high soil phosphorous levels due to fertilisation. We addressed the question "Does active restoration enhance soil health faster than natural processes?" We selected three sites, all in sandy soils with high soil phosphorous levels (35–63 mg/kg) compared to the surrounding natural vegetation (7–11 mg/kg). Cultivation had ended 5–7 years previously and sites were in different states of recovery. Seven treatments were applied, including planting of indigenous species, an initial rye mix consisting of cereal rye, lupins and serradella, and brush packing using branches from invasive trees packed in a single layer at a density of 50–80% soil cover, in various combinations, as well as a control. Soil samples were collected to determine changes in phosphorous levels using citric acid analysis, organic carbon using the Walkley-Black method, and microbial diversity using Biolog EcoPlates. Due to drought from 2017–2020 the initial rye mix established poorly and had little impact on the soil-P levels. Phosphorous levels decreased over time at two of the sites but increased significantly at Site 3, adjacent to active croplands. Organic carbon increased over time at Site 2 and Site 3. At Site 1, with the least natural plant cover, organic carbon only increased in the treatments that included brush packing. At all sites there was a significant increase in soil microbial diversity, but at Site 1 it was better in treatments with brush packing.

There was an improvement in overall soil health over time. Abandoned fields with the least natural cover benefited most from restoration actions.

Introduction

The Fynbos biome is recognized as one of the global hotspots of diversity. It ranks among the world's 25 most threatened biodiversity hotspots (Mittermeier et al. 2011). Vast expanses of this once-pristine habitat have succumbed to permanent agriculture, with crops, potatoes, and rooibos tea plantations replacing natural vegetation. The biome's transformation is further exacerbated by inappropriate fire management practices, livestock grazing, invasion by alien plant species, and overexploitation of natural resources (Mucina and Rutherford 2006).

Leipoldtville Sand Fynbos is an arid, endangered ecosystem with a mediterranean climate and acidic, sandy soils (Mucina and Rutherford 2006). Less than 45% of its natural vegetation remains, the rest is cultivated lands of which 27% is under pivot irrigation and used for potato production. As input costs rise and soil diseases proliferate, many of the fields are being abandoned and left to recover through natural succession, which is a very slow process in drylands. The abandoned fields are prone to wind erosion and years of fertilisation has led to high soil phosphorous levels compared to the surrounding natural vegetation. These high phosphorous levels inhibit the establishment of Fynbos species (Hawkins et al. 2010), since Fynbos soils are acidic and nutrient-poor, especially in terms of nitrogen and phosphorous levels (Richards et al. 1997). Therefore, some form of active restoration is necessary to ameliorate the soil condition, reduce wind erosion, and initiate the establishment of natural vegetation. We addressed the question "Does active restoration enhance soil health faster than natural processes?"

Methods

The study was done at three sites in the Leipoldtville Sand Fynbos on the west coast of South Africa. This winter rainfall area receives an average annual rainfall of 263 mm. All sites are characterized by deep sandy soils with high phosphorous levels (29–62 mg/kg) and low organic carbon levels (0.07–0.20%) compared to soil phosphorous levels in the adjacent natural vegetation that are below 10 mg/kg. Cultivation ended 5–7 years previously and sites were in different states of recovery.

The same experimental design and layout were implemented at all three sites, following a randomised block design with four replicates and seven treatments, which consisted of a control and a mix of the following treatments:

1) To combat the high phosphorous levels an initial rye mix (R), consisting of cereal rye, lupins and serradella, was planted in 2017 and 2018. Minimum soil disturbance was done with a tine implement to prepare the soil, and after sowing, the soil was rolled to ensure good seed-soil contact. Due to a drought in 2017 the planting was repeated in 2018. The plants were cut down and removed before seed set to remove the phosphates from the trial.

2) To combat wind erosion, brush packing (B) was done with branches from local invasive trees in 2020, which also provided organic matter. The branches were packed in a single layer at a density of 50–80% soil cover. Wind speed reached 11 m/s at Redelinghuys and Eland's Bay sites, where signs of wind erosion was the most visible.

3) Lastly cuttings (P) from three species indigenous to the area were made and planted in the plots to increase the species diversity on the trial.

Composite soil samples were collected at the start (June 2017) and end (October 2023) of the study to determine changes in phosphorous levels using citric acid analysis, changes in organic carbon using the Walkley-Black method (The Non-affiliated Soil Analysis Work Committee 1990), and changes in microbial diversity using Biolog EcoPlates (Lee et al. 2020).

Data was analysed using ANOVA, Fischer's Least Significant Difference test and Principal Component Analysis.

Results

The study area experienced a drought from 2017 until 2020. This resulted in the poor establishment of the initial rye mix and it had no significant impact on the soil phosphorous levels (plant-available phosphorous). However, the phosphorous levels decreased significantly over time at two of the sites ($p < 0.01$) but increased significantly at Eland's Bay ($p = 0.0056$) (Fig. 1a). There were no significant differences between the treatments for each site over time.

The soil organic carbon (SOC) increased significantly over time at the Eland's Bay and Sandberg sites ($p < 0.001$) (Fig. 1b), with no significant difference between the treatments at both sites. At Redelinghuys, with the least natural vegetation cover on the abandoned land and the worst establishment of planted cuttings, the organic carbon only increased significantly (LSD = 0.0702) in the Brush packing treatment (Fig. 1b).

At all three sites there was a significant increase over time in soil microbial diversity ($p < 0.001$), as seen on the first axis of the PCA, indicating an improvement in the overall soil health (Fig. 2).

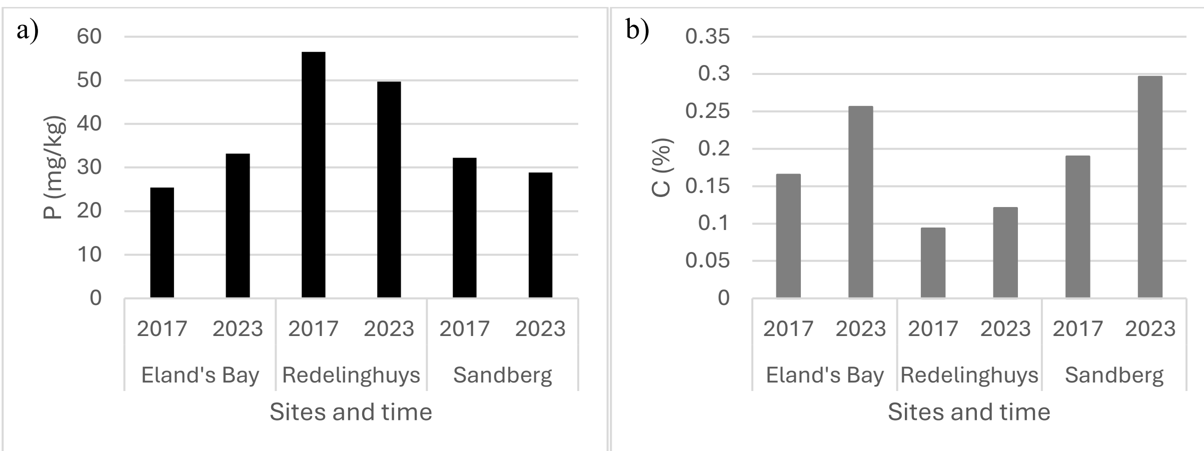

Fig. 1 Soil phosphorous levels (a) and organic carbon content (b) in 2017 and 2023 at Eland's Bay, Redelinghuys and Sandberg sites, South Africa.

Discussion

Hawkins et al. (2010) found that a cover crop mix of oats and lupins decreased the soil-P levels by 10–30% because of their fast growing rate. In the case of this study, the below average rainfall received in 2017 and 2018 resulted in no germination of the initial rye mix sown in 2017, and a poor growth rate of those plants that did establish in 2018. Therefore, the expected outcome was not achieved. According to Prasad and Chakraborty (2019), soil phosphorous is mostly lost through erosion and not leaching from the soil. At Sandberg soil-P was most probably removed from the soil by the plants established in each of the plots, as it had the best plant cover of all the study sites and no visible signs of wind erosion, with the maximum wind speed less than 9 $m.s^{-1}$. The wind at Redelinghuys and Eland's Bay sites reached a speed of up to 11 $m.s^{-1}$. At Redelinghuys, with visible signs of wind erosion, and the least plant cover, soil-P was lowered over time because of the wind erosion. At the Eland's Bay site, part of the trial area was covered by soil from an adjacent, actively used cropland caused by wind erosion.

This is most probably the reason for the increased soil-P over time. The other study sites did not have any active croplands in the surrounding area.

More plants established at Eland's Bay and Sandberg sites lead to an increase in the SOC in all the treatments over time supporting similar results reported by Qiu et al. (2018). At Redelinghuys the provisioning of branches on the soil assisted in the establishment of plants and an increase in SOC. The increase in SOC can lead to improved soil water retention and in dry areas, such as Leipoldtville Sand Fynbos, can result in improved vegetation growth (Li et al. 2024). This is likely to be beneficial during dry periods as the availability of soil water is a limiting factor in arid ecosystems (Qiu et al. 2018).

The improvement in the soil microbial diversity at all sites indicated an improvement in the soil health. Soil microbes are responsible for the decomposition of organic matter, nutrient transformation, plant health maintenance and the degradation of toxic compounds in the soil amongst others (Lee et al. 2020). This provides ecosystem services essential for humans, such as food production, climate regulation, and the provision of clean water (Adhikari & Hartemink 2016; Pulleman et al. 2012).

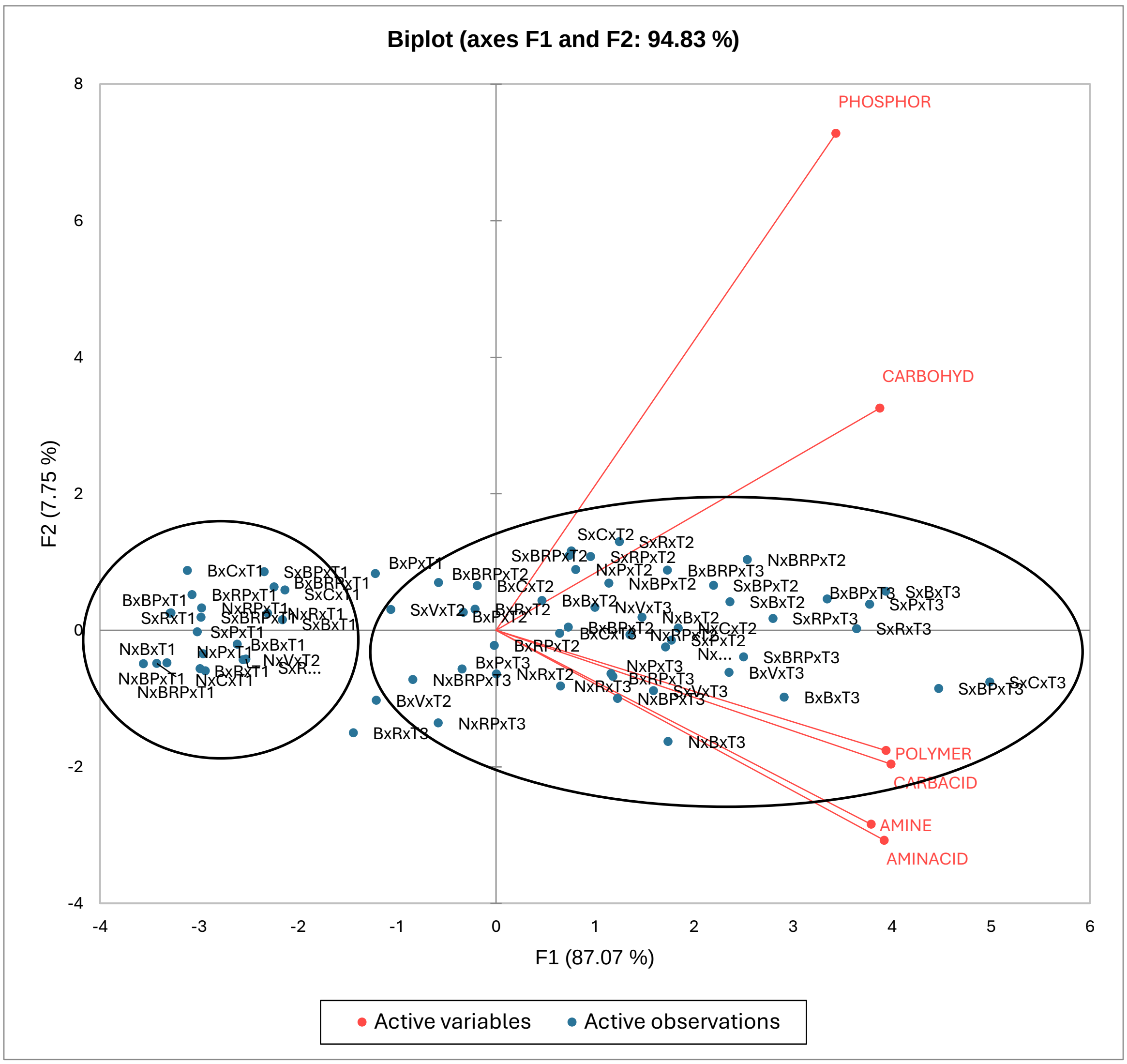

Fig. 2 Principal component analysis (PCA) of soil microbial diversity in 2017 (T1), 2021 (T2) and 2023 (T3) in the different treatments at Redelinghuys (B), Eland's Bay (N) and Sandberg (S). C = control; B = brush-packing; R = initial rye mix; P = planting indigenous species.

Conclusion/Implications

There was an improvement in overall soil health over time. Abandoned fields, such as the Redelinghuys site with the least natural cover benefited the most from the restoration actions.

Acknowledgements

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Passive vs active restoration to improve soil health of old potato production circles in the Leipoldtville Sand Fynbos, South Africa

Swanepoel, A[1]; Saayman, N[1]; Swart, R[2]; Rheeder, C[3]

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Key words: brush packing; soil phosphorous; soil organic carbon; indigenous plants

Abstract

Potato production is the main land use in the endangered Leipoldtville Sand Fynbos vegetation type on the west coast of South Africa. Many fields have been abandoned and their restoration is important to conserve this vegetation type. These abandoned fields are subject to wind erosion and have high soil phosphorous levels due to fertilisation. We addressed the question "Does active restoration enhance soil health faster than natural processes?" We selected three sites, all in sandy soils with high soil phosphorous levels (35–63 mg/kg) compared to the surrounding natural vegetation (7–11 mg/kg). Cultivation had ended 5–7 years previously and sites were in different states of recovery. Seven treatments were applied, including planting of indigenous species, an initial rye mix consisting of cereal rye, lupins and serradella, and brush packing using branches from invasive trees packed in a single layer at a density of 50–80% soil cover, in various combinations, as well as a control. Soil samples were collected to determine changes in phosphorous levels using citric acid analysis, organic carbon using the Walkley-Black method, and microbial diversity using Biolog EcoPlates. Due to drought from 2017–2020 the initial rye mix established poorly and had little impact on the soil-P levels. Phosphorous levels decreased over time at two of the sites but increased significantly at Site 3, adjacent to active croplands. Organic carbon increased over time at Site 2 and Site 3. At Site 1, with the least natural plant cover, organic carbon only increased in the treatments that included brush packing. At all sites there was a significant increase in soil microbial diversity, but at Site 1 it was better in treatments with brush packing.

There was an improvement in overall soil health over time. Abandoned fields with the least natural cover benefited most from restoration actions.

Introduction

The Fynbos biome is recognized as one of the global hotspots of diversity. It ranks among the world's 25 most threatened biodiversity hotspots (Mittermeier et al. 2011). Vast expanses of this once-pristine habitat have succumbed to permanent agriculture, with crops, potatoes, and rooibos tea plantations replacing natural vegetation. The biome's transformation is further exacerbated by inappropriate fire management practices, livestock grazing, invasion by alien plant species, and overexploitation of natural resources (Mucina and Rutherford 2006).

Leipoldtville Sand Fynbos is an arid, endangered ecosystem with a mediterranean climate and acidic, sandy soils (Mucina and Rutherford 2006). Less than 45% of its natural vegetation remains, the rest is cultivated lands of which 27% is under pivot irrigation and used for potato production. As input costs rise and soil diseases proliferate, many of the fields are being abandoned and left to recover through natural succession, which is a very slow process in drylands. The abandoned fields are prone to wind erosion and years of fertilisation has led to high soil phosphorous levels compared to the surrounding natural vegetation. These high phosphorous levels inhibit the establishment of Fynbos species (Hawkins et al. 2010), since Fynbos soils are acidic and nutrient-poor, especially in terms of nitrogen and phosphorous levels (Richards et al. 1997). Therefore, some form of active restoration is necessary to ameliorate the soil condition, reduce wind erosion, and initiate the establishment of natural vegetation.

We addressed the question "Does active restoration enhance soil health faster than natural processes?"

Methods

The study was done at three sites in the Leipoldtville Sand Fynbos on the west coast of South Africa. This winter rainfall area receives an average annual rainfall of 263 mm. All sites are characterized by deep sandy soils with high phosphorous levels (29–62 mg/kg) and low organic carbon levels (0.07–0.20%) compared to soil phosphorous levels in the adjacent natural vegetation that are below 10 mg/kg. Cultivation ended 5–7 years previously and sites were in different states of recovery.

The same experimental design and layout were implemented at all three sites, following a randomised block design with four replicates and seven treatments, which consisted of a control and a mix of the following treatments:

1) To combat the high phosphorous levels an initial rye mix (R), consisting of cereal rye, lupins and serradella, was planted in 2017 and 2018. Minimum soil disturbance was done with a tine implement to prepare the soil, and after sowing, the soil was rolled to ensure good seed-soil contact. Due to a drought in 2017 the planting was repeated in 2018. The plants were cut down and removed before seed set to remove the phosphates from the trial.

2) To combat wind erosion, brush packing (B) was done with branches from local invasive trees in 2020, which also provided organic matter. The branches were packed in a single layer at a density of 50–80% soil cover. Wind speed reached 11 m/s at Redelinghuys and Eland's Bay sites, where signs of wind erosion was the most visible.

3) Lastly cuttings (P) from three species indigenous to the area were made and planted in the plots to increase the species diversity on the trial.

Composite soil samples were collected at the start (June 2017) and end (October 2023) of the study to determine changes in phosphorous levels using citric acid analysis, changes in organic carbon using the Walkley-Black method (The Non-affiliated Soil Analysis Work Committee 1990), and changes in microbial diversity using Biolog EcoPlates (Lee et al. 2020).

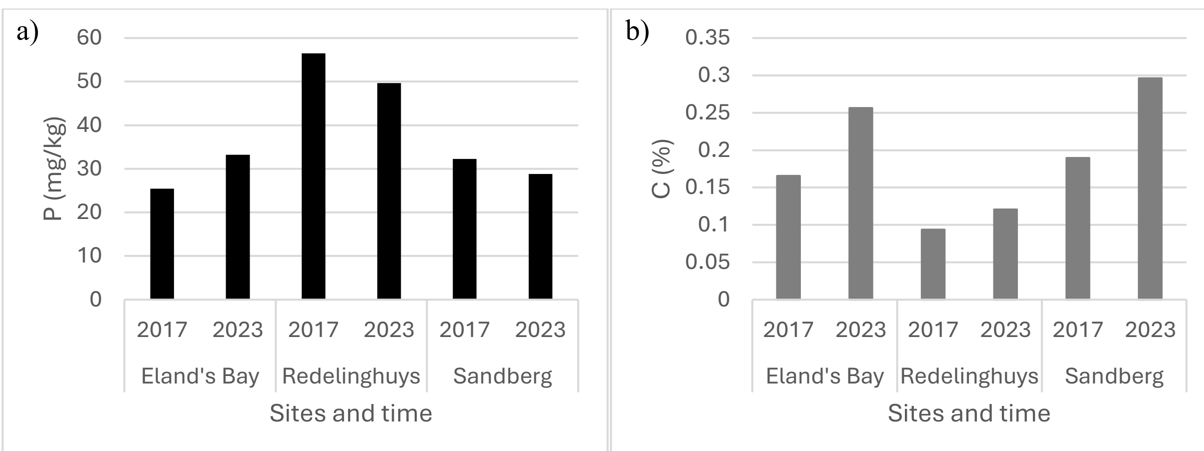
Data was analysed using ANOVA, Fischer's Least Significant Difference test and Principal Component Analysis.

Results

The study area experienced a drought from 2017 until 2020. This resulted in the poor establishment of the initial rye mix and it had no significant impact on the soil phosphorous levels (plant-available phosphorous). However, the phosphorous levels decreased significantly over time at two of the sites ($p < 0.01$) but increased significantly at Eland's Bay ($p = 0.0056$) (Fig. 1a). There were no significant differences between the treatments for each site over time.

The soil organic carbon (SOC) increased significantly over time at the Eland's Bay and Sandberg sites ($p < 0.001$) (Fig. 1b), with no significant difference between the treatments at both sites. At Redelinghuys, with the least natural vegetation cover on the abandoned land and the worst establishment of planted cuttings, the organic carbon only increased significantly (LSD = 0.0702) in the Brush packing treatment (Fig. 1b).

At all three sites there was a significant increase over time in soil microbial diversity ($p < 0.001$), as seen on the first axis of the PCA, indicating an improvement in the overall soil health (Fig. 2).



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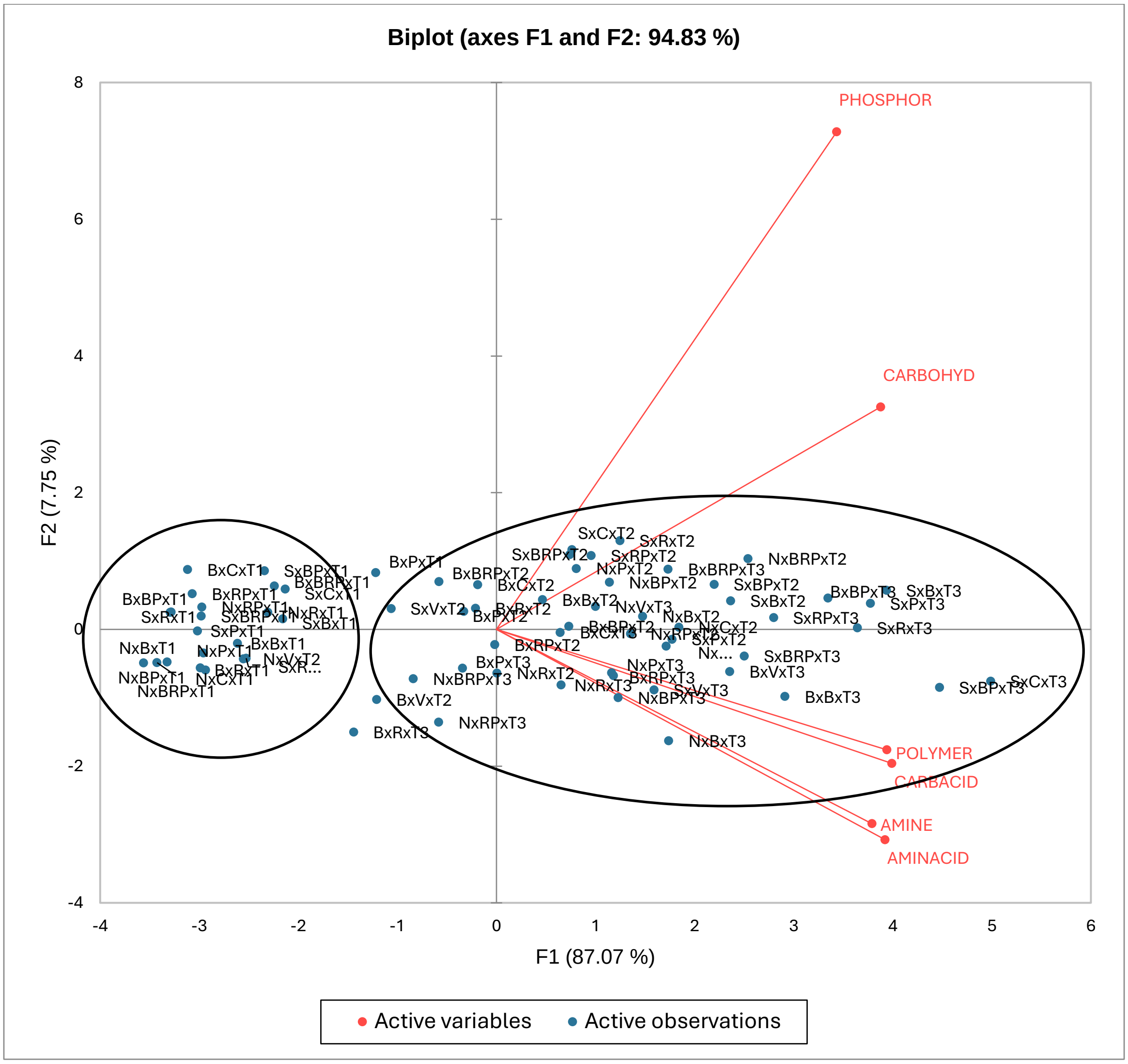

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Moderating soil surface temperature via restoration hollows and its implication for restoration strategies in arid rangelands

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Key words: rangeland restoration; soil temperature; micro-climate

Abstract
Arid regions worldwide, including the drier areas of the Western Cape of South Africa, often suffer from rangeland degradation resulting from poor management, mining activities or other anthropogenic sources of disturbance. Without active restoration intervention, these areas may take a considerable amount of time to recover. Digging hollows as a form of active restoration has been successfully applied to restore vegetation to denuded areas in arid regions around the world. However, the effect of these hollows on soil surface temperature has yet to be determined.

To determine the role of restoration hollows in providing suitable micro-climates for plant growth, soil surface temperature measurements were compared between bare ground and hollows during both summer and winter at three sites in the arid region of the Western Cape. Soil temperatures within the hollows were lower than that of bare ground during the warmest part of the day, and higher than bare ground during the coolest part of the day. Hollows have a moderating effect on soil surface temperature, which creates a more suitable micro-climate for seed germination. Restoration hollows may offer a cost-effective alternative to other restoration methods, such as brush packing and tilling. This research contributes to the broader understanding of land restoration strategies in arid environments, potentially reducing restoration costs and improving ecosystem resilience in the face of environmental challenges, including climate change.

Introduction
Much of the arid rangelands of the world is degraded and denuded of vegetation, often due to disturbances such as overgrazing and mining activities, amongst others (Carrick 2022). Rangelands cover over 70% of the land surface of South Africa and most of these are degraded to some extent (Carrick 2022). Degraded rangelands have reduced plant productivity and are prone to soil erosion (Snyman 2003).

Restoration of degraded rangelands improves productivity by re-establishing plant cover to denuded areas and improves their capacity support grazing animals (Snyman 1999). Restoration can be expensive, time consuming, labour intensive and often prone to failure due to adverse weather conditions or inadequate rainfall (Saayman et al. 2017). Brush packing, digging soil hollows, and other forms of soil treatments have been promoted by many restoration practitioners to provide suitable seed germination sites (Coetzee 2005; Bothma and Van Rooyen 2006; Carrick et al. 2022). Soil hollows create a more favourable environment for seedling germination and establishment (Milton and Coetzee 2022). Soil hollows can be dug by hand or with the use of a specialized “dyker plough” that operates on a cam wheel and digs hollows at set distances and depths (Snyman, 2003).

The rationale being that these hollows will capture runoff rainwater, organic matter and seeds, and in addition, brush packing within the hollows will provide protection to seedlings (Bothma and Van Rooyen 2006).

There is a significant difference in temperature and in diurnal temperature fluctuations between bare ground, restored vegetation and intact vegetation, with bare ground reaching higher temperatures and temperature fluctuations (Drezner 2007; Hamberg et al. 2020). Snyman (2003) found that the soil temperature on bare ground in the grassland biome could reach temperatures as high as 65 °C. Large temperature fluctuations on bare ground are detrimental to seedling germination (Milton and Dean 1990; Saayman and Botha 2010). Nurse plants provide seeds with protection against severe temperature fluctuations (Esler et al. 2006). Brush packing is typically used in restoration of bare areas to simulate nurse plants (Ren et al. 2008).

The aim of this paper is to determine if the creation of hollows in bare patches may provide a moderating effect to soil temperature which creates a suitable microclimate for seeds to germinate and for seedlings to survive.

Methods

The trial was conducted at three sites in the Western Cape province of South Africa: the Worcester Veld Reserve, the Wolwekraal Nature Reserve at Prince Albert and at the Nortier Research Farm near Lambert’s Bay. All three sites have a Mediterranean climate. The Worcester and Prince Albert sites both have shallow, poorly developed soils with Mispah and Glenrosa soil forms prevailing. These soils are generally shallow and rocky with a high clay content. The soils of Nortier Research Farm consist of fine aeolian (regic) sands of the Namib soil form (Western Cape Department of Agriculture 2024).

January is the warmest month of the year for the Prince Albert site, with an average temperature of 22.2°C, while February is the warmest month for the Worcester and Nortier sites with average temperatures of 22.3°C and 19.7 °C respectively (Western Cape Department of Agriculture 2024). July is the coldest month for all three sites, with average temperatures of 10.8°C, 11°C and 12.9 °C for Prince Albert, Worcester and Nortier respectively (Western Cape Department of Agriculture 2024).

A row-column treatment design with two treatments and 20 replicates was followed at each study site. The two treatments are hollows dug and a control - an area of cleared ground adjacent to each hollow. At each study site the trial consisted of 20 hollows, placed 10 meters apart. The hollows were dug in a grid pattern of 5 columns and 4 rows. Each hollow is one meter in diameter with a concave bottom, 20 cm deep at the centre. The hollows were dug by hand and the removed soil was used to build a berm on the downslope side of the hollow, to retain runoff water (Coetzee 2005).

An Infrared thermometer was used to measure the soil surface temperatures within the centre of each hollow and in the centre of the control. These measurements were made at dawn and at 14:00, on one day during summer and winter. The timing of the measurements was intended to capture the temperature during the coldest and warmest time of day. Measurements were only taken on days with little or no cloud cover or strong wind.

Data were analysed separately by time and were subjected to analysis of variance (ANOVA) using the General Linear Models Procedure (PROC GLM) of SAS software (Version 9.4; SAS Institute Inc, Cary, USA). The Shapiro–Wilk test on the standardized residuals from the model verified normality (Shapiro and Wilk, 1965). Levene's test verified homogeneity of treatment variances (Levene, 1960). Fisher's Least Significant Difference (LSD) was calculated at the 5% significance level to compare interaction means (site*treatments, site*season, treatment*season, site*treatment*season) and main effects, treatment, site and season means (Ott and Longnecker, 2010). Box and whisker plots for temperature for site*treatment*season were constructed using XLSTAT (Addinsoft,2024).

Results

Temperatures within hollows were significantly higher at dawn compared to bare ground in each site (Figure1). Afternoon temperatures were lower within hollows compared to bare ground, though not all were significantly different. The winter afternoon temperatures at the Worcester site were the exception, with temperatures within the hollows being significantly higher than the control (Figure 2). It should be noted that there was a gentle wind present during this part of the data collection. The temperature difference between hollows and bare ground for each site, time and season is displayed in table1.

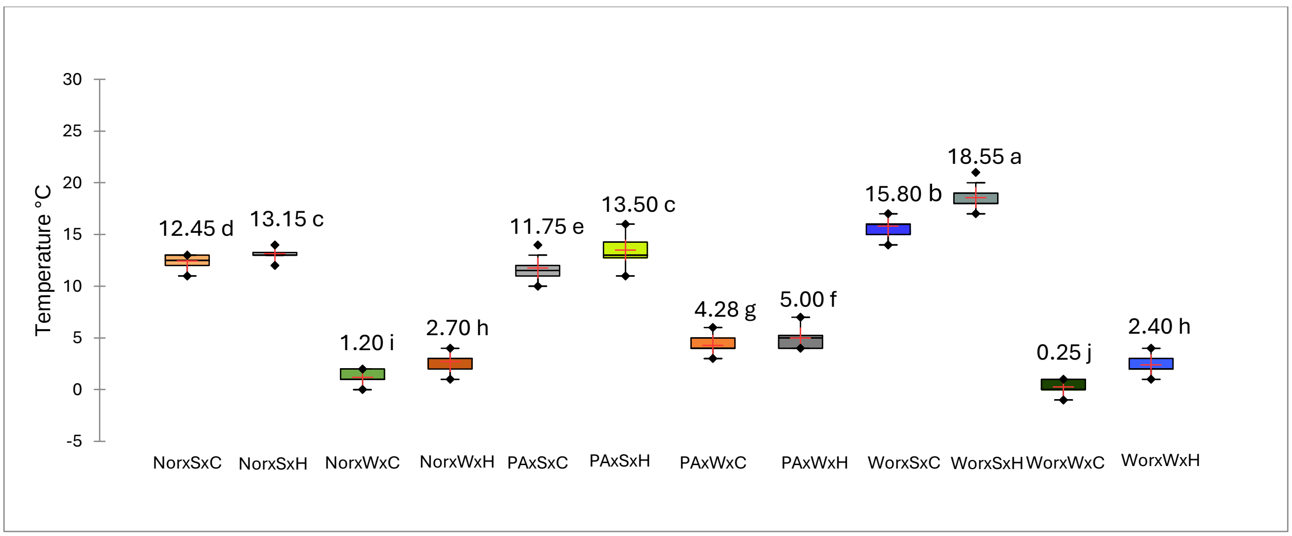

Figure 1. Soil surface temperatures within hollows and controls taken at dawn for three sites during summer and winter. Mean values with significant differences ($p<0.05$) are displayed with a different adjacent letter. Nor = Nortier, PA = Prince Albert, Wor = Worcester, S = Summer, W = Winter, C = Control, H = Hollow.

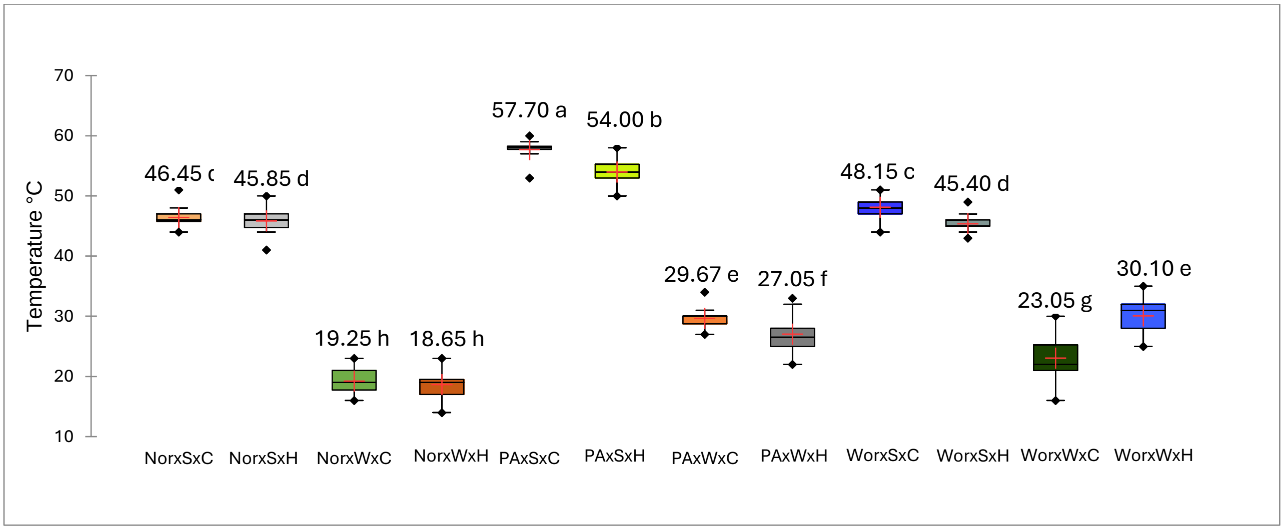

Figure 2. Soil surface temperatures within hollows and controls taken at 14:00 for three sites during summer and winter. Mean values with significant differences ($p<0.05$) are displayed with a different adjacent letter. Nor = Nortier, PA = Prince Albert, Wor = Worcester, S = Summer, W = Winter, C = Control, H = Hollow.

Table1: Effect of hollows on soil surface temperature compared to bare ground in °C. *=significantly different, $p<0.05$; ns= not significantly different.

	Worcester	Prince Albert	Nortier
Summer-Morning	+2,75*	+1,75*	+0,7 ns
Winter-Morning	+2,15*	+0,72 ns	+1,5*
Summer-Afternoon	-2,75*	-3,7*	-0,6 ns
Winter-Afternoon	+7,05*	-2,62*	-0,6 ns

Discussion

The soil surface temperature within the hollows were warmer during the coldest time of day, and cooler during the hottest time of day. This insulating effect protects seeds and seedlings from temperature extremes and contributes to creating the more stable micro-climate that seeds require to germinate and for seedlings to establish (Esler et al. 2006; Milton and Coetzee 2022).

Wind caused rapid soil surface temperature fluctuations, which impeded accurate measurements. These temperature fluctuations were especially evident at the Nortier site, which is adjacent to the coast and is particularly windy. It is likely that some of the temperature measurements taken during even slightly windy conditions, could have been affected by wind-chill (Ashcroft and Gollan 2013). Severe windy conditions may also decrease the efficacy of hollows, a problem that could be addressed by trapping air within the hollows with brush packing. Differences in soil composition and moisture content may also influence soil surface temperature in hollows (Ashcroft and Gollan 2013). Despite these confounding factors, it is clear that soil hollows provide a moderating effect on soil surface temperature.

Conclusions and Implications

Restoration hollows create a more favourable micro-climate for seed germination than bare ground. These hollows offer a simple way to improve the survival rate of seedlings and to allow revegetation of denuded arid rangelands.

Acknowledgements
This work was financially supported by the Western Cape Department of Agriculture. The Wolwekraal Nature Reserve is acknowledged for providing one of the study sites and labour to construct the hollows.

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Ranch economic aspects of Lesser Prairie Chicken habitat conservation efforts in central USA rangelands

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Key words: ranch economics; lesser prairie chicken; conservation practices

Abstract

The lesser prairie chicken has been listed as a threatened and endangered species by the U.S. Fish and Wildlife Service in distinct population segments. Approximately 95% of the species' habitat is in private land ownership. Conservation efforts focus on these lands, with funding potentially supplied through the Natural Resources Conservation Service (NRCS) Environmental Quality Incentives Program (EQIP). Under EQIP, practice payments are made to landowners to implement planned conservation practices. This project estimates the economic impact of implementing lesser prairie chicken conservation practices on small and large representative ranches in 4 Major Land Resource Areas (MLRA).

Economic models were developed in the General Algebraic Modelling System (GAMS) as recursive linear programs and run for 20 years. Random precipitation patterns and cattle price sets were used. Baseline models were first developed to balance forage with the average herd size. Models evaluated practices on all or half the rangeland area, with the ranch paying 100, 25, or 0% of the conservation cost and then compared to baseline models. The baseline models were based on a small and a large representative ranch for each MLRA with no conservation practices or payments. Results show that restoring lesser prairie chicken habitat on private rangeland may or may not be profitable, depending on ranch size, area treated, forage response, cattle prices, and how much of the conservation practice cost is paid by the rancher.

For all analysis scenarios and cattle prices, small and large ranches have higher household income (HI) when they pay 0% of the cost, regardless of treatment area. Small and large ranches show a decrease in HI when the ranch pays 25% of the conservation cost. These results may not be applicable to every ranch, so an individual ranch analysis should be conducted before participation in LPC conservation. Ranchers should also determine if profit, household income, or some combination is most important. The basic framework used in this study can guide individual ranch analysis.

Introduction

The US Fish and Wildlife Service has listed two Distinct Population Segments (DPS) of Lesser Prairie Chickens (LPC) under the Endangered Species Act. The Northern DPS is identified as threatened status and the Southern DPS is designated for endangered status. Elmore et al. (n.d.) noted that the current threats to the LPC include, but are not limited to, tree invasion and planting, long-term fire suppression, and improper cattle grazing management. Cattle grazing can reduce the height and density of grasses and allow for shrubs to become too dense (Van Pelt et al. 2013).

Approximately 95% of the land area of the species is in private land ownership. Conservation is thus focused on these lands with funding potentially supplied through Natural Resources Conservation Service (NRCS) conservation programs, most notably through the Environmental Quality Incentives Program (EQIP). Under EQIP, practice payments are made to landowners to implement planned conservation practices. The NRCS, through the Working Lands for Wildlife program, has taken the lead in encouraging private landowners to implement LPC conservation practices since 2010 with the Lesser Prairie Chicken Initiative (NRCS 2023a). Voluntary participation in the Working Lands for Wildlife can have significant long-term benefits to the landowner through protections for incidental take under the Endangered Species Act (NRCS 2023b).

Removing trees is a primary goal to improving habitat for LPC. Using prescribed fire is often described as the most efficient method, but it is not always an acceptable practice. In cases where it is not desired, using herbicides followed by skeleton removal mechanically is the option. Alternatively, prescribed grazing can be used to create habitat heterogeneity if properly applied.

This project seeks to understand the economic impact on small and large ranches in four Major Land Resource Areas (MLRA) covering most of the LPC habitat. As shown in Figure 1, we are focused on the southern portions of MLRAs 72 and 73 in Kansas, the northern portion MLRA 77D in New Mexico, and the eastern portion of MLRA 77E in Texas.

Methods

LPC conservation practices are derived from the Van Pelt et al. (2013) publication by the Western Association of Fish and Wildlife Agencies. LPC habitat occurs in the southern Great Plains, with a dry temperate climate that has a mean annual temperatures ranging from 45°F to 79°F. The annual precipitation in this area ranges from 10 to 30 inches.. Potential lesser prairie-chicken habitat was reduced by 56% from a potential of 43,258 km2 to the current 18,908 km2 in ~115 years (Portillo-Quintero et al. 2022). The MLRAs that were chosen correlate with the four vegetation types defined by Van Pelt et al. (2013) and each has different representative ranches and sizes and different practices that would be most likely. Ranch models were developed for each MLRA based on a small and large size. A baseline model used a representative ranch with no LPC conservation practices.

Counties in each MLRA were selected based on the algorithm used in Maczko et al. (2022). A rangeland county is defined as having more than 25% rangeland vegetation and fewer than 200 people per square mile. Only counties with more than 50% of their land area within an MLRA were included. The 2017 Census of Agriculture (NASS 2019) beef cattle and operation numbers were used to estimate a small and large size operation. Each counties numbers were weighted by the percentage of rangeland vegetation for a weighted average. Small ranches were considered to have 50-199 beef cows and large had greater than 200 beef cows.

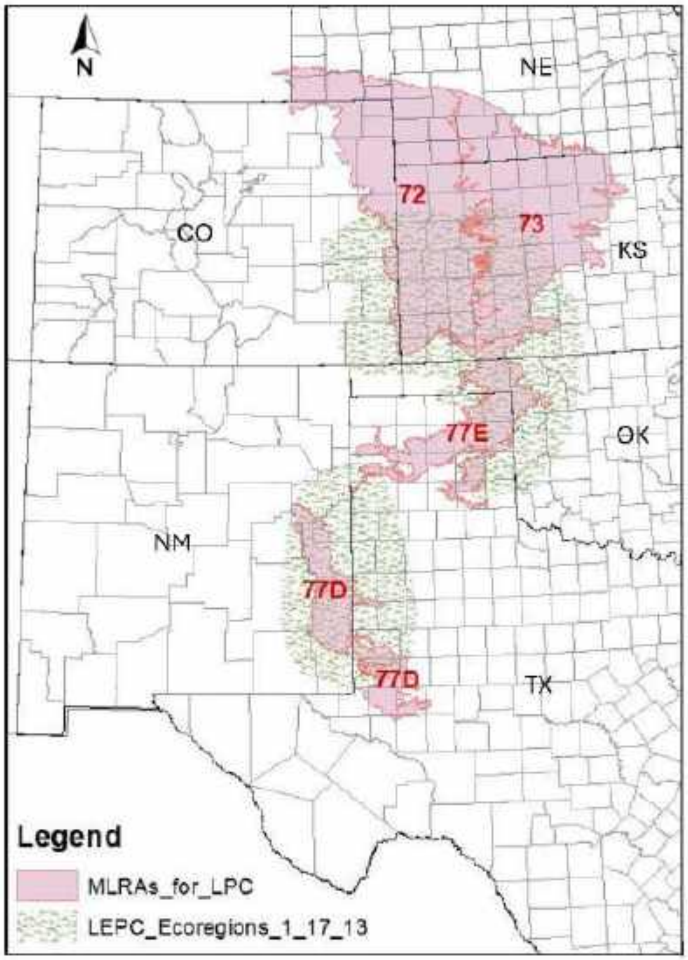

Fig 1a. Major Land Resource Areas 72, 73, 77D and 77E with Lesser Prairie Chicken habitat.

Fig 1b. Historic Lesser Prairie Chicken range (blue) and current habitat (green). Map by BirdLife International.

Ranch models for each MLRA are based on representative enterprise budgets published for each region. MLRA 72 and 73 were based on Dhuyvetter et al. (2014). MLRA 77D was based on NMSU (2019a, 2019b). MLRA 77E was based on Amosson (2017). Values were indexed to 2019 using index values from NASS following the procedure by Rimbey and Torell (2011). These enterprise budgets fed into the ranch models described below. The ranch models seek to maximize the present value of net ranch income as shown in Equation 1.

$$I=\sum_{t=1}^{20}\left[(L_t P_{lt}+H_t P_h-FC_t-AC_t-LC_t-LPC_t)(1+r)^{-t}\right] \quad [1]$$

Where I = Net Ranch Income

Lt = Livestock sales in year t

Plt = Price of livestock in year t

Ht = Hay sales in year t

Ph = Price of hay

FCt = Forage cost in year t

ACt = Animal cost in year t

LCt = Loan cost in year t

LPCt = Lesser prairie chicken conservation cost in year t

r = Discount rate

The model is solved subject to a variety of constraints with the most important being to balance the forage sources with the herd size in each season of the year.

$$\sum_{s=1}^{n} LC_s \, AU_c \, S_n = \sum_{s=1}^{n} \left(NR_{st} \, PPT_t + RES_{st} + FEED_{st} \right) \quad [2]$$

Where: LCs = Livestock class numbers in each season

AUc = Animal unit equivalents for livestock class

Sn = Season

NRst = Native rangeland production in season s and year t

PPTt = Precipitation index in year t

RESst = Crop residue production in season s and year t

FEEDst = Hay fed in season s and year t

What we feel is more important to a ranch family is Net Household Income (Equation 3) which is defined as,

$$HI = L_t P_{lt} + H_t P_h - FC_t - AC_t - LC_t - LPC_t + O - FAM - FIX_t \quad [3]$$

Where O = Off Ranch Income

FAM = Family living expenses

FIXt = Fixed costs in year t

Off ranch income is set at the level defined by ERS (2022; 2023a; 2023b) and ERS NASS (2022).

Results by MLRA

MLRA 72

When all rangeland areas are treated on both large and small ranches, net ranch income (NRI) and household income (HI)nly increase when NRCS pays for 100% of conservation practices regardless of cattle prices. In all other cases, the ranch would see declines. In the case of treating half the rangeland area, large ranches would see increases in NRI and HI when the ranch pays 25 or 0% of the conservation practices. Small ranches would see increases when they pay 0% of the conservation practices, except for a slight increase in HI at high prices. Brood cow numbers increase the most at low cattle prices and decline at higher prices.

MLRA 73

When all rangeland areas are treated, large ranches generally gain both NRI and HI when the ranch pays 25 or 0% of the conservation practice costs, except for NRI at low cattle prices. Small ranches generally see a decline in NRI and an increase in HI when they pay 25 or 0% of the conservation practices. When treating half of the rangeland area, large and small ranches have the same responses, but at higher amounts. Brood cow numbers increase the most at low cattle prices and decline at higher prices.

MLRA 77D

When all rangeland areas are treated, large ranches show increases in NRI and HI when the ranch pays 25 or 0% of the conservation practices. Small ranches also show an increase in NRI at high prices and HI at medium and high prices when they pay 100% of the conservation costs. Brood cow numbers increase the most at low cattle prices and decline at higher prices.

MLRA 77E

When all rangeland areas are treated, large ranches show increases in NRI and HI when the ranch pays 100, 25, or 0% of the conservation practices. Small ranches also show an increase in NRI and HI except when they pay 100% of the conservation cost at low cattle prices. When half of the rangeland area is treated, large ranches show a decrease in NRI and HI when they pay 100% of the conservation practice costs. Small ranches show an increase in NRI and HI at all levels of them paying the conservation practice costs. Brood cow numbers increase about the same number regardless of cattle prices.]

Discussion

We examined the economic impacts of lesser prairie chicken habitat improvement on small and large ranches in four Major Land Resource Areas using NRCS conservation practice scenarios. All of the scenarios show that with some level of financial assistance ranchers can implement LPC conservation practices without experiencing lasting negative impacts to their ranch or personal household incomes. However, without assistance, it is unreasonable to expect ranchers to implement conservation at the personal cost it would require. Based on the scenarios of removing trees from half or all the rangelands and implementing prescribed grazing with reduced utilization, results show varying responses across ranch sizes and MLRAs.

Conclusions and Implications

Consideration of the economic impacts of implementing conservation and management practices to LPC habitat on ranches in the 4 MLRAs addressed by this research shows that both removal of trees and grazing heterogeneously are key techniques to use (Van Pelt et al. 2013). Trees can be removed using herbicides followed by mechanical removal of the skeletons, chaining, or prescribed burning. In all cases, follow up treatment is necessary to remove trees missed in the initial treatment and to prevent reestablishment. Grazing at a light utilization rate can be used to create heterogeneous habitat that the LPC prefer at different life stages.

Specifically, our research focused on elucidation of economic impacts associated with implementing these practices on small and large ranches, using NRCS conservation scenarios. Modelling shows that restoring lesser prairie chicken habitat on private ranches may or may not be profitable for the rancher or the ranch household, depending on the size of the ranch, how much area needs to be treated, the forage response to removing trees, cattle prices, and how much of the conservation practices need to be paid by the rancher.

It is important to note that we considered representative ranches in each MLRA based on enterprise budgets for each state, rather than individual ranches in a given region. Because individual ranches vary greatly, results may not be directly applicable to every ranch. It is important for private lands and public lands ranchers to conduct an individual ranch analysis before participating in LPC conservation if profit or household income is important for the operator. The basic framework used in this study can guide such individual analyses.

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Impact of flooding on rangeland condition in low-gradient multi-channel river systems of the Flinders River Catchment

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Key words: Rangeland condition, Floods, Flinders River catchment, Multi-channel systems

Abstract
Across northern Australia's rangelands, riverine flooding has long-lasting impacts on landscape health, function, and productivity. This PhD project aims to improve understanding of the factors influencing the impact of flooding on rangeland condition in low-gradient, multi-channel river systems. The project focuses on the Flinders River catchment, north-west Queensland, Australia. Using on-ground and remote sensing data, the project will: (i) develop a hydrologically conditioned high-resolution digital elevation model (DEM) for enhanced flood modelling; (ii) simulate flood events using hydrodynamic modelling; (iii) determine the impact of flooding on rangeland condition; and (iv) identify the key factors influencing post-flood rangeland condition recovery. The research will provide valuable new insights into flood impact and recovery to inform land management, flood mitigation, and conservation practices, supporting long-term rangeland health and resilience.

Introduction
Australia's northern rangelands cover over 1.2 million square kilometres, including parts of Western Australia, Northern Territory, and Queensland (Russell-Smith and Sangha 2018). These rangelands provide multiple critical ecosystem services, including food production, cultural and recreational values, habitat for wildlife, water and nutrient cycling, and carbon sequestration and storage (Brown and MacLeod 2017). In northern Australia, as is the case globally, the health and function of rangelands are under increasing pressure from the combined effects of climate change and extreme climate events, invasive species, altered fire regimes, land use conversion and poor grazing land management (McKeon et al. 2004; Boone et al. 2018).

The frequency and intensity of floods has increased globally due to climate change, deforestation, poor land management, population growth, and overgrazing (Power and Callaghan 2016; Huda et al. 2022). This trend is projected to worsen, resulting in escalating flood losses and economic impacts (Taguchi et al. 2022). In northern Australia, climate change is expected to intensify floods and prolong droughts (Ghofrani et al. 2016; State of Queensland 2019a; IPCC 2023). The impacts of floods on rangeland condition in northern Australia, however, are not well quantified, and the interplay between flooding and other factors influencing rangeland recovery remains poorly understood.

Flooding in northern Australia's rangelands is a recurring hazard with significant social, economic and environmental implications (Nafari et al. 2016; McLean 2022). The 2019 Flinders River flood, for example, inundated approximately 13 million hectares (Figure 1). The flood event, coupled with an extreme wind chill event, resulted in the death of over 450,000 head of cattle, caused widespread infrastructure damage, and had long-lasting impacts on community well-being (Phelps 2019).

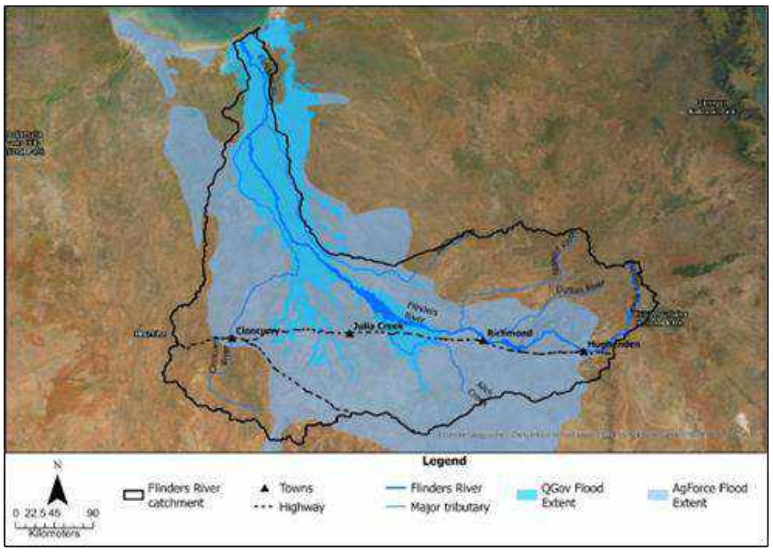

Figure 1. Inundation extent of the flood zone as mapped by the State of Queensland (2019b)and AgForce Queensland (2019).

The flood event also had severe impacts on the health and functioning of the region's sensitive natural assets (Figure 2), including widespread soil erosion, native vegetation and pasture die-back, as well as reduced water quality and availability (Hall, 2019).

Figure 2. (A) Dead Mitchell grass tussocks in a heavily washed area; (B) pedestalling of Mitchell Grass tussocks; and (C) silt deposition.

In low-gradient, multichannel systems such as the Flinders River catchment, intricate drainage networks, channel morphology and floodplain topography influence water and sediment distribution during flood events (Sockness and Gran 2021; Jacobson et al. 2022; Dawson and Lewin 2023; Shukla et al. 2024).To fully understand the flood impacts in these rangeland ecosystems, reliable flood mapping and modelling is essential. Although recent advances in satellite technology offer opportunities for developing high-resolution elevation models to improve flood modelling, gaps in coverage due to dense vegetation and clouds, and lack of sufficient details in elevation remain the main challenges for accurate flood extent mapping, especially in data-scarce low-gradient multichannel systems (Jarihani et al. 2015; Peramuna et al. 2023; Cohen et al. 2024).

This PhD project seeks to address the identified knowledge and information gaps and provide stakeholders and policymakers with the necessary information to inform decisions on effective flood management strategies, supporting land recovery and resilience in the Flinders River catchment and rangeland systems more broadly.

Methods

This study will collect data from primary sources, including on-ground elevation measurements and land condition assessments, as well as secondary sources such as Digital Elevation Models (DEMs), satellite images, and climate and hydrology information. To enhance flood mapping and modelling in the Flinders River catchment (Figure 3), the conventional 30-m DEM will be optimised by integrating higher resolution DEMs with on-ground Real-Time Kinematic GPS measurements. The optimised DEM will be utilised alongside satellite imagery to analyse flood characteristics and simulate flood events using advanced hydrological software (e.g., SWAT, HEC-RAS) integrated with Geographic Information Systems. These flood models will serve as inputs for assessing the impact of flooding on rangeland condition through ground cover change analysis before and after flood events. This assessment leverages on-ground land condition evaluations and satellite imagery and employs spatial regression models to reveal the dynamics of ecosystem resilience and recovery following flooding events.

Figure 3: The Flinders River Catchment

Result and Discussion

The project is in early stages of development and as yet, no results have been obtained.

The proposed research will enhance fundamental scientific understanding of the impact of flooding on rangeland systems in low-gradient multichannel catchments. The detailed assessment of flood impacts on land condition in the Flinders River catchment will provide valuable insights into landscape resilience and the factors that affect recovery of rangeland condition after extreme floods. Detailed information on floods and how they affect rangeland condition will enable better prediction and help mitigate the destructive outcomes of future flood events. The project will also enhance the accuracy of flood modelling and prediction tools by capturing the complexities of flooding in low-gradient multi-channel systems. In general, the outcomes of this research will provide stakeholders and decision-makers with the necessary information and data to make well-informed decisions about land management strategies in a way that will promote both flood mitigation and rangeland conservation across the Flinders catchment and beyond.

Expected outputs

The expected outputs of the research are:

- A hydrologically conditioned high-resolution DEM for enhanced flood modelling in low-gradient multichannel systems.
- Comprehensive flood maps and models for the Flinders River catchment.
- Detailed assessment reports on the impact of flooding on rangeland condition.
- Insights into the key factors influencing post-flood recovery of rangelands in the Flinders River catchment.

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Plant community composition changes following Twolined spittlebug (P*rosapia bicincta*) infestations in Hawaii rangelands

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Key words: Rangeland plant pests, pest management

Abstract

Twolined spittlebug (TLSB), *Prosapia bicincta* (Hemiptera: Cercopidae) was first detected in 2016 in the South Kona district of Hawai´i Island where it had damaged over 2,000 acres of rangeland. In 2017, four locations were selected for monthly monitoring of TLSB activity, population dynamics, and changes in plant community composition. Two monitoring sites were at the center of the infestation while the other two were located outside the northern and southern boundaries to estimate the rate of spread. At each location a series of 100-m long transects were established along elevational gradients between 500 and 1,850 m. Along each transect, ten 0.25-m^2 quadrats were placed every 10 m on alternating sides of the transect. In each quadrat, data were collected on vegetative cover and height, plant species composition, live and dead grass cover (%), nymph and adult abundance, and nymph-plant associations. The surveys revealed that between 2017-2023, TLSB expanded its range to over 72,183 ha, primarily in pastures of Hawai´i's most important forage grasses, Kikuyu (*Pennisetum clandestinum*) and pangola (*Digitaria eriantha*). TLSB was detected between ~500-1,700 m in elevation and activity was highest during the wet season (Apr-Oct). Mean TLSB densities (126 nymphs/m^2) in pastures located between 1,000-1,300 m in elevation were significantly higher than in pastures between 500-999 m (64 nymphs/m^2) and >1,300 m (20 nymphs/m^2). Pastures with the highest TLSB densities experienced the greatest decrease in mean grass cover (30%) and greatest increase in mean forb (76%), bare ground (39%), and shrub (7%) cover. Landscape-level changes were observed in rangelands damaged by TLSB as shown by the loss of forage grass cover and subsequent replacement by invasive weeds including Pamakani (*Eupatorium adenophorum*), wild blackberry (*Rubus* spp.), fireweed (*Senecio madagascariensis*), and Hilograss (*Paspalum conjugatum*). The establishment and spread of TLSB has devastating impacts on the ecosystem services Hawaii rangelands provide.

Introduction

Twolined spittlebug (TLSB), *Prosapia bicincta* (Say), is a pasture and turfgrass pest native to southeastern United States (Shortman et al. 2002, Thompson and Carvalho 2016). Twolined spittlebug negatively impacts rangelands by feeding on important forage grasses (Byers and Wells 1966, Shortman et al. 2002). In 2016, TLSB was detected in the South Kona district of Hawai´i Island (Wilson et al. 2023). Between 2017 and 2020 the pest rapidly expanded its range at rate of over 14,000 ha per year (Wilson et al. 2023) and by the end of 2021 occupied over 72,183 ha across the South Kona district.

The Hawai´i beef industry is economically, culturally, and ecologically important to the state. Over 142,000 head of beef animals are managed across nearly 300,000 acres of rangelands (20% of Hawai´i's land mass) that are managed by over 1,300 ranches. The value of Hawai´i-raised beef cattle is estimated to be more than $48 million annually (USDA-NASS 2022). Over 60% of the beef cattle in the state are raised on the island of Hawai´i where the TLSB currently poses the most significant threat.

High density TLSB infestations often result in nearly 100% die back of key pasture grasses including Kikuyu (*Pennisetum clandestinum*) and pangola (*Digitaria eriantha*) grasses. The loss of these important livestock forages provides entry for the establishment of low-quality forage, weeds, and invasive plants, including Pamakani (*Eupatorium adenophorum*), wild blackberry (*Rubus spp.*), fireweed (*Senecio madagascariensis*), and Hilo grass (*Paspalum conjugatum*). Twolined Spittlebug's rapid rate of spread and apparent preference for Kikuyu and pangola grass creates the potential for the pest to spread throughout the islands and cause irreparable harm to large areas of valuable rangelands. Consequently, this pest threatens the economic sustainability of the Hawai´i livestock industry, reduces the ecosystem services derived from these landscapes, and ultimately harms Hawai´i communities through decreased agricultural revenue and reduced food security.

Methods

In 2017, four separate locations were selected for long-term, monthly monitoring of TLSB activity and population dynamics, and changes in plant community composition. Two the monitoring sites were at the center of the initial infestation while the other two sites were located outside of the northern and southern boundaries of the known distribution of the pest to estimate the rate of spread. At each location, a series of transects were established along elevational gradients between 500 and 1850 m. A total of 17 transects were established across the four sample sites. Along each transect ten sample points were systematically established every 10 m alternating between the left and right side of the transect line. A 0.25 m^2 ring was used at each sample point to record vegetative cover by species, percent live and dead grass by species, vegetation height by functional group (grass, forb, shrub), and a count of TLSB nymphs and adults. Along each transect, one adult sweep net sample was collected. All data were collected across all transects and sites monthly. Generalized linear mixed models (GLMM) were used to determine if season and elevation influenced TLSB nymph and adult abundance while accounting for random effects (location and year). For each GLMM, season and elevation were fixed effects grouped categorically by wet (April – October) or dry (November – March) season, and low (500-999 m), mid (1,000 – 1,300 m), or high (> 1,300 m) elevation. Tukey's pairwise comparisons were conducted to evaluate seasonal and elevational trends. Plant community data were quantified by mean percent cover by functional group (grass, forb, and shrub) or bare ground for each transect. Changes in percent cover by functional group or bare ground were assessed over the study period. A Wilcoxon-Mann-Whitney test was used to compare changes in mean grass cover and determine if grass cover varied significantly between years for each elevational category.

Results

Twolined Spittlebug Population Distribution

The monthly surveys revealed that the TLSB expanded its range from approximately 28,102 ha in 2017 to over 72,034 ha by 2021 (Fig. 1).

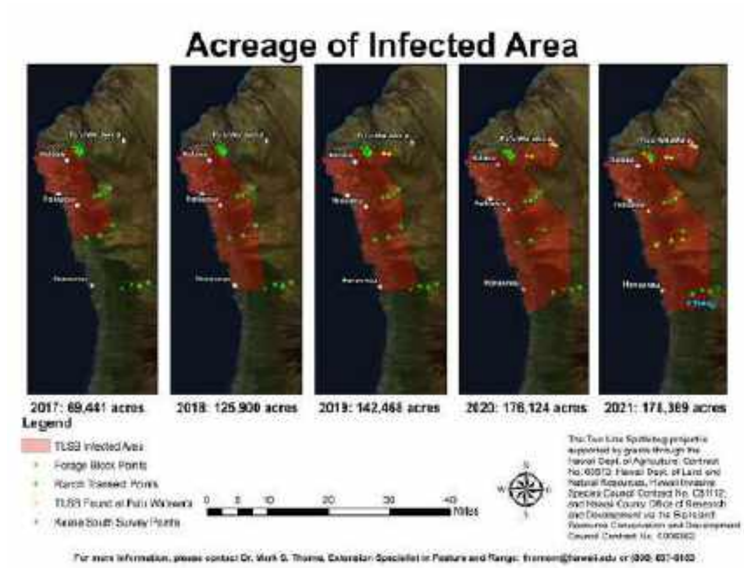

Fig. 1. Twolined Spittlebug population distribution between 2017 and 2021 within the South Kona District of the island of Hawai´i.

Results showed that season and elevation were good predictors of nymph (X^2 = 138.9, df =1, P≤0.001) and adult (X^2 = 148.79, df=1, P≤ 0.001) abundance. Mean nymph and adult abundance was significantly (P<0.0001) higher in the wet season compared to dry season months across all sites and years. Nymph abundance coincided with the wet season (April – October) with little activity between November and March (dry season). Of all nymphs sampled 95% were collected in the wet season and 5% during the dry season. Adult activity also coincided with the wet season, but peak abundance was highest between May and November and lowest from December through April. Of all the adults sampled, 94% were collected in the wet season and 6% in the dry season.

Elevation had a significant effect on the timing and abundance of both nymph and adult population dynamics (Fig. 2). The highest abundance of nymphs and adults were detected at the mid elevation (1,000 – 1,300 m), followed by the low elevation (500 – 999 m) sites. The high elevation (> 1,300 m) category had significantly lower nymph and adult abundance than the mid and low elevation categories.

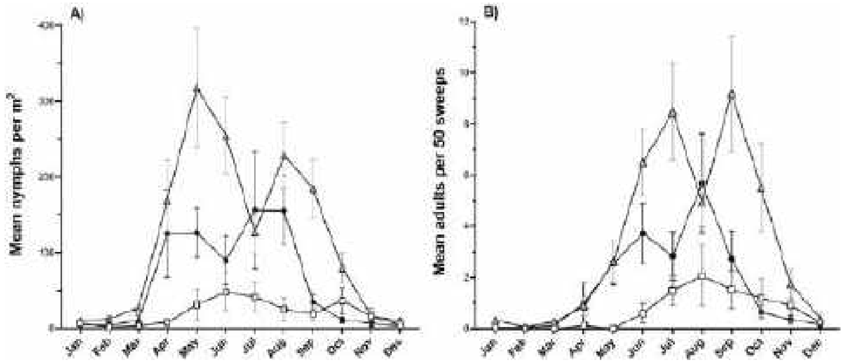

Fig. 2. Seasonal variation of Twolined Spittlebug A) nymph and B) adult abundance (mean ± SEM) by elevation. Low elevation = 500-999 m (black circles), mid elevation = 1,000-1,300 m (grey triangles), and high elevation > 1,300 m (white squares).

Plant Community Composition

Twolined Spittlebug nymphs were detected on 32 different plants. Grasses accounted for 72% of the associations, while legumes (16%), sedges (6%), and forbs (6%) made up the remainder. Mean grass cover decreased significantly over the study period at the low (73% vs 57%; W=1749, P-0.0004) and mid (68% vs. 47%, W=3852, P<0.0001) elevations, but did not vary significantly at the high elevation (89% vs 90%; W=1243, P=0.975). As grass cover decreased, forb cover and bare ground increased, while shrub cover remained constant (Fig. 3).

Discussion and Implications

The nymph and adult abundance patterns observed in our study follow closely with the lifecycle of the Twolined spittlebug in its home range. In Florida, the TLSB lifecycle from egg to egg averaged 76 days which included 19 days for egg hatch, 50 days for nymph development to adult, and 7 days until the adult female begins laying eggs (Fagan and Kuitert 1969). Under optimal conditions the entire lifecycle of duration, plus time needed for the next generation of nymphs to hatch is about 95 days. The distinct abundance peaks and synchronous activity indicate two generations of TLSB per year in the Kailua-Kona pastures. The rapid and synchronous outbreak of nymphs with the arrival of the wet season suggest that TLSB eggs enter diapause prior to the dry season followed by a period of postdiapause quiescence (Pires et al. 2000, Sujii et al. 2001). At this stage of postdapause quiescence, eggs can respond under humid conditions and stimulate immediate eclosion, resulting in abrupt synchronous first population peak (Pires et al. 2000, Sujii et al. 2001. Peck 2002).

Precipitation varies widely across the island of Hawaii and this variability becomes more extreme with drought conditions (Luo et al. 2024). The temporal differences in abundance patterns of TLSB observed in this study were likely influenced by the year-to-year variation in rainfall and the onset of drought conditions late in 2020. Likewise, the spatial variation in TLSB abundance was likely influenced by the variability in microclimates that occur over short distances due to the abrupt elevation changes across the Kona rangelands. Moreover, drought effects did not manifest evenly across the Kona rangelands, so differences in plant community responses across sites may have contributed to variation in habitat suitability for TLSB over time, impacting their distribution and abundance.

The changes in groundcover reported in this study suggest that TLSB infestations have caused widespread and long-term damage to Kona rangelands dominated by Kikuyu and pangola grasses, ultimately resulting in landscape transformation through invasion and establishment of invasive weeds and low-quality forage grasses (Wilson et al. 2023). Damage caused by the invasion of TLSB in Hawai´i will necessitate a shift in the conventional rangeland management practices. Management of TLSB in Hawai´i rangelands will need to be developed based on site-specific information due to variation in elevation, climate conditions, and plant communities across the island of Hawai´i.

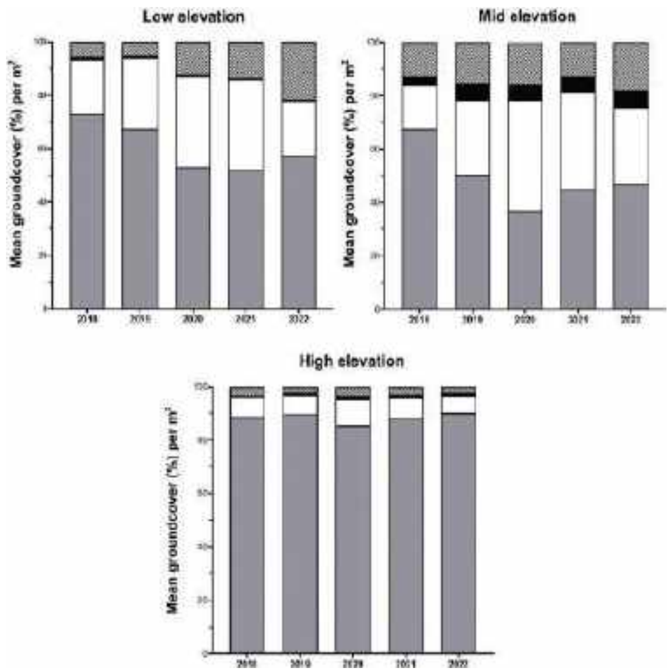

Fig. 3. Annual variation in proportion of mean groundcover in low (500-999 m), mid (1,000-1,300 m), and high (> 1,300 m) elevations groups over the study period across all four sample sites in the North and South Kona districts on the island of Hawai´i. From top to bottom of the bars, grass cover shown in dark grey, forb cover in white, shrub cover in black, and bare ground in light grey strips.

Acknowledgements

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Ecology and management of bush encroachment – a paradigm shift

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Key words: animal performance; rangeland ecology; rangeland management; woody plant encroachment

Abstract

Tree and shrub densities have increased by approximately 30-50% in many areas of southern Africa, which increase the amount of bare soil surfaces and consequently declines in soil functions, which hinders the recovery of herbaceous plants. Additionally, encroaching woody plants such as *Vachellia species*, *Seriphium plumosum* and *Senegalia caffra* may alter ecosystem services such as forage production for livestock; and thereby increase associated costs of livestock management. The expansion of woody plants in communal and commercial systems is attributed to local and global driver including but not limited to overgrazing, elevated atmospheric CO_2, erratic rainfall. In an attempt to understand the underlying causes of woody plant encroachment, and develop management interventions the following objectives were explored the 1) effect of season, burning, slope position, and their interaction on *Seriphium plumosum* L. crude protein, neutral detergent fibre, total phenolics and condensed tannins concentrations, 2) optimal tree density that will maximize forage production, 3) the use of woody encroaching species as a measure of control of endoparasites in cattle, and 4) use of encroaching woody species as fodder and their effect on animal performance, methane emission and meat quality. Crude protein concentration was higher during the wet season in post-fire treatment sites than in no fire treatment sites, which were also higher than CP concentrations during dry season at no fire treatment sites and post-fire treatment sites. The results showed that mechanical- and chemical -control, as well as fire application influences the structure and functioning of savannas by creating gaps that promote grass production. *Senegalia caffra* resulted in nearly 100 % mortality of internal parasites in cattle after just 2 hours of application. Lastly, the encroaching woody plants showed the potential for use as fodder for livestock without adversely affecting animal performance, improve carcass characteristics and reduce methane emission.

Introduction

Woody plant encroachment has increased by approximately 30-50% in many areas of southern Africa, which hinders the recovery of herbaceous plants (Kraaij and Ward 2006). Given the widespread spread of woody plants into grasslands and savannas in southern Africa and worldwide (Archer et al. 2017), there is a considerable decline in the agricultural potential of rangelands (Börner et al. 2007). For instance, the increasing rate and extent of *Vachellia karroo*, *Senegalia caffra* and *Seriphium plumosum* in South Africa will compromise ecosystem services such as forage production to support a large population of grazers, with negative impacts on the pastoral economy (Pule 2018). In contrast, tannin-rich plants such as *Vachellia and Senegalia* species do not only aid in the reduction of enteric methane emissions in cattle (Piñeiro-Vázquez *et al*., 2015) but they are also beneficial to herbivore' health and well-being by minimizing parasitism in ruminants (Mbatha et al. 2002). The expansion of woody plants in communal and commercial systems is attributed to local and global driver including but not limited to overgrazing, elevated atmospheric CO_2, erratic rainfall. In an attempt to understand the underlying causes of woody plant encroachment, and develop management interventions the following objectives were explored the 1) effect of season and burning and their interaction on *Seriphium plumosum* L. forage quality; 2) optimal tree density that will maximize forage production, 3) the use of woody encroaching species as a measure of control of endoparasites in cattle, and 4) use of encroaching woody species as fodder and their effect on animal performance, methane emission and meat quality.

Methods

The studies were conducted in 1) Bronkhorstspruit (25.76907°S, 28.67918°E), Gauteng Province, South Africa; 2) & 3) Roodeplaat experimental ranch of the Agricultural Research Council (25º 56'S, 28º 35'E) in Gauteng Province, South Africa; and 4) Agricultural Research Council - Animal Production farm (25° 53'S, 28° 11'E), Gauteng province, South Africa. Objective one: a combination of *S. plumosum*'s fine leaves and twigs from previously burned and unburned (n = 116) areas were sampled from randomly selected plants during the wet (n = 58) and dry (n = 58) seasons, respectively. The 58 samples were from burned (n = 29) and unburned (n = 29) treatment areas. *Seriphium plumosum* samples were collected in (2015) wet/growing season on previously burned areas, while on unburnt areas, samples were from previous (2014) wet/growing season. The minimum distance between sampled *S. plumosum* plants at each sampling site was approximately 10 m. Objective two: a tree-thinning study was conducted in two savanna sites that differ in soil texture and woody species. Trees were thinned to the approximate equivalents of 0% (control-no removal), 10, 20, 50, 75 and 100% (complete removal of trees), followed by herbicide application on half of the stumps for each plot. Tree stumps were treated with herbicide within 15 min after felling during the growing season (Teague and Killilea, 1990; Burch and Zedaker 2003). Objective 3: grass biomass was assessed using five randomly placed 50 cm × 50 cm quadrats in each plot, with all of the grass samples within the quadrats harvested regardless of species. Objective 3: seedlings (< 1m) and adult trees (> 1.5m) of seven woody encroaching species (namely *Vachellia nilotica*, *Vachellia tortilis*, *Senegalia caffra*, *Ziziphus mucronata*, *Vachellia karroo*, *Searsia lancea and Euclea crispa*) were sampled in addition to *Opuntia ficus-indicathat* that was used as a control. Leaf-based ethanol extract: a 20% ethanol solution was prepared in order to extract the dried-ground plant material by adding 1500 µl of ethanol 96% to 0.1 g of ground leaves from each encroacher species (i.e. *V. nilotica*, *V. tortilis*, *S. caffra*, *Z. mucronata*, *V. karroo*, *S. lancea and E. crispa*) into an eppendorf tube (McIntire, 2005-2008). Objective 4: edible *S. plumosum* (i.e. leaves and twigs) were harvested using a tractor slasher and sun-dried for three days before bailing. *Seriphium plumosum* forage material was used for chemical analysis (i.e. dry matter, crude protein, neutral detergent fibre, metabolizable energy, acid detergent fibre and condensed tannin and feed formulation. Twenty-eight Nguni steers aged 22 months with a mean body weight of 300 ± 10kg were randomly assigned to one of four treatment diets containing *S. plumosum* meal levels at 0, 10, 20 or 30 % as replacements for Lucerne hay.

Results

Seriphium plumosum forage quality

There was a significant interaction effect of season x fire on NDF and CP ($P < 0.05$), but not on CTs and TPs concentrations ($P > 0.05$). The interaction effects of season x fire on *S. plumosum* crude protein (Fig. 1) and neutral detergent fibre. The effect of dry season × fire (5.34 % g−1 DW ± 0.18 SE), as well as dry season × no fire (5.09 % g−1 DW ± 0.18), on CP percentage were insignificantly different. However, the wet season post-burning had significantly higher CP (7.33% g−1 DW ± 0.31) than the wet season on unburned treatment (6.08% g−1 DW ± 0.20; Fig. 2a).

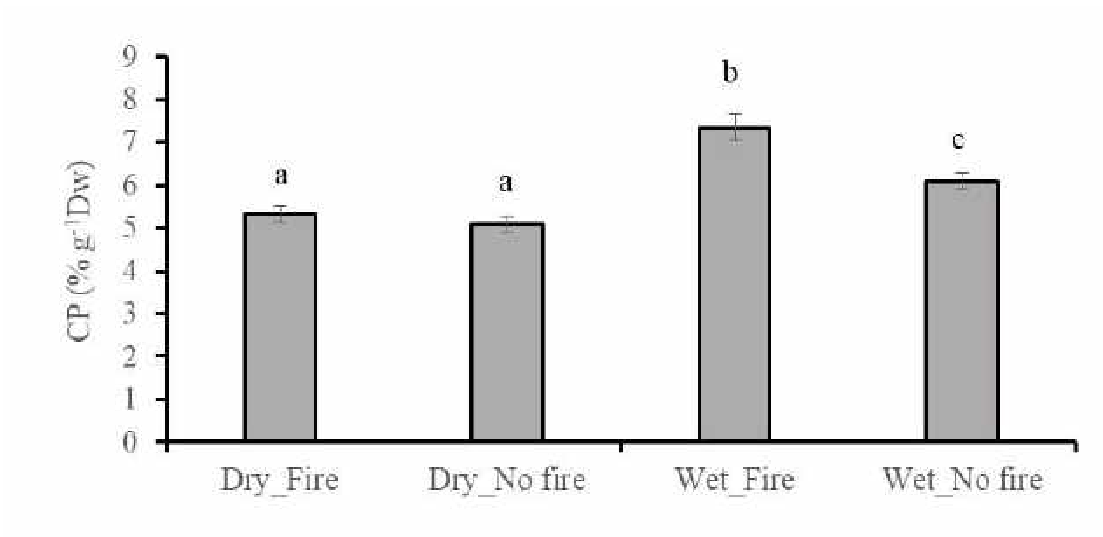

Fig. 1. *Seriphium plumosum* mean crude protein (CP) concentrations during the dry season in burned (fire) and unburned (no fire) areas and during the wet season in burned (fire) and unburned (no fire) areas.

Tree thinning on biomass production

The study revealed that the control plots (0 %) had a higher recorded grass biomass than at 75% and 100% (complete removal) removal treatments. In site 1, the control plots (0 %) had a higher recorded grass biomass than at 75% and 100% (complete removal) removal treatments. At site 2, tree removal significantly increased grass-biomass at the end of the first and second growing seasons i.e. grass biomass increased in the plots totally cleared of trees in the first growing season at site. Grass biomass increased in the plots totally cleared of trees in the first growing season at site 2. Towards the end of the second growing-season, grass biomass was greater than the previous season across all treatments, with substantial increases at 50%, 75% and 100% removal.

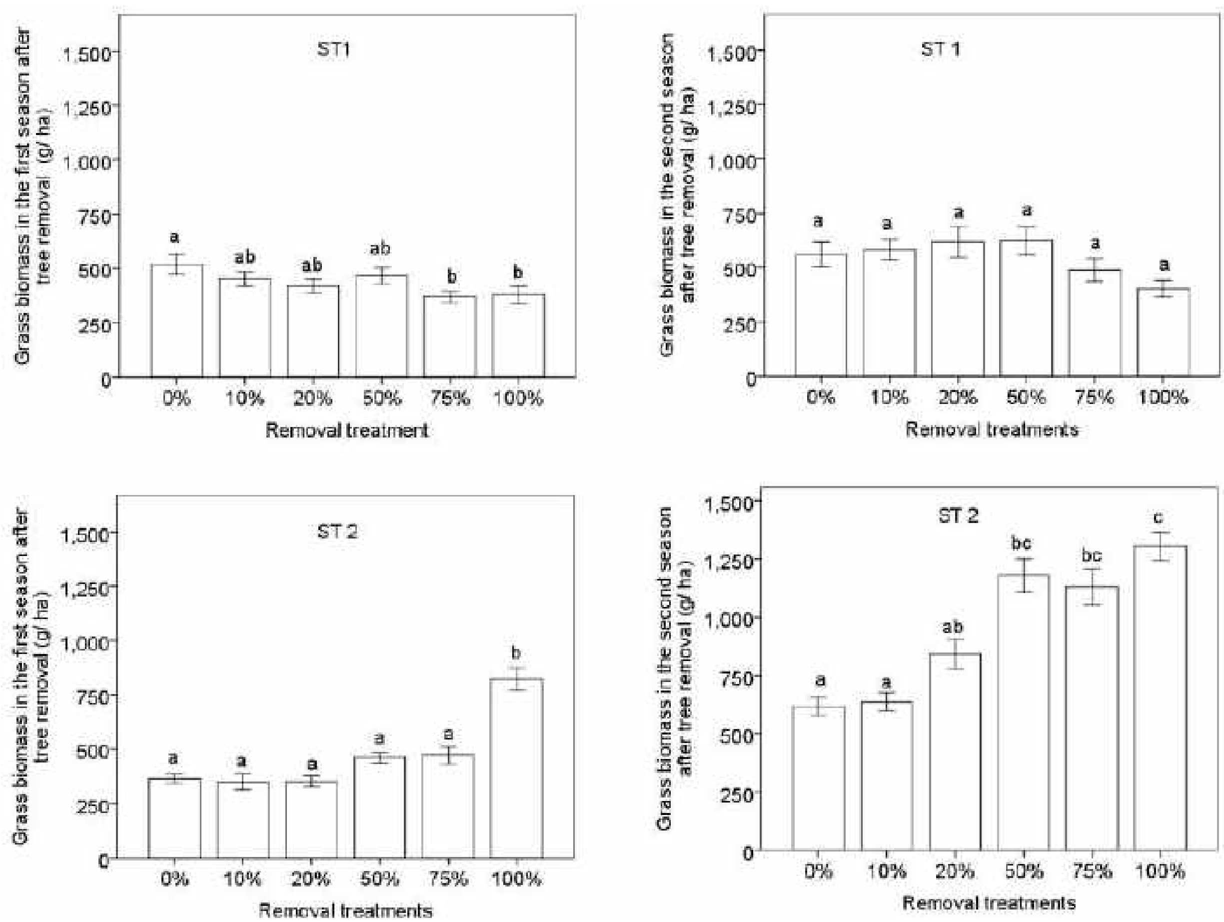

Fig. 2. Grass biomass production after tree removal in study sites 1 (ST1) and 2 (ST2). Treatments range from 0% = no removal (control) to 100 % removal = complete tree removal.

Encroaching woody plants: implications for internal parasites

Opuntia ficus-indica yielded the highest inhibition at 43.88% after 4 hours of application followed by *Vachellia karroo* at 42.26%. At species evaluated except for *Vachellia tortilis* parasitic larvae mortality was noted after 1 hour averaging 52.40% mortality at four hours. *Senegalia caffra* resulted in nearly 100 % mortality after just 2 hours of application.

Encroaching woody plants as fodder for ruminants

Seriphium plumosum meal inclusion in the diets at 0, 10, 20 or 30% did not affect live weight, feed conversion ratio and body condition score values of Nguni steers. Notably, Nguni steers fed a diet with 30 % of *S. plumusom* meal had lower significantly lower (P<0.05) CH_4 emission values than those fed diets having 10 or 20 % of *S. plumosum* meal. No significant difference was observed (*P* > 0.05) on tenderness, warmer blazer shear force, cooking loss %, beef aroma and bloody flavour of Nguni steers fed varying levels of *S. plumosum* meal.

Implications

The study has demonstrated that strategic use of fire may contribute to improve *S. plumosum* CP concentrations, especially in the wet season. This may result in improved preference and intake of *S. plumosum* by browser, thus contributing to control its encroachment on semi-arid grassland communities and livestock production. Additionally, encroaching woody plants can be used as fodder for livestock without adversely affecting animal performance, improve carcass characteristics and reduce methane emission. While tree removal may increase standing grass biomass in multi-tree-species systems on healthy soils, it may not be effective in monospecific stands especially on eroded clay soils. Thus the recovery of key ecosystem services such as an increased forage production may not be realised, regardless of investment in woody species control.

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The Migration Characteristics of *cfp* Fluorescent Labeled Rhizobium in *Dolichos lablab L.* Plants and Rocky Desert Surface Soil

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Key words: *Dolichos lablab* L.; Fluorescent labeled rhizobium; Migration; distribution

Abstract

In this study, cyan fluorescent protein (*cfp*) labeled endophytic rhizobia of *Dolichos lablab* L. was used as the test strains which had strong nitrogen-fixing ability, low fluorescence loss rate, and good genetic stability. Through methods such as reinoculation and spot application of bacterial suspension in rocky desert mountain areas, we investigated the quantity and distribution of fluorescently labeled rhizobia in *Dolichos lablab* L. plants at different growth stages, as well as the migration characteristics of these bacteria on the surface of rocky desertified soil in the absence of hosts. The results indicate that in terms of spatial distribution, the fluorescently labeled rhizobia concentrated in the roots primarily. Specifically, during the vegetative stage, they are mainly present in the taproot, while from the budding stage to the pod-setting stage, they are predominantly found in the lateral roots. In terms of temporal dynamics, the highest count during the vegetative stage and the lowest during the budding stage. The number of labeled bacteria in the aboveground part of the plant was only 39.93% of that in the root, mainly distributed in the stem tip, flower bud and pod. During the development from flower buds to pods, the quantity of labeled bacteria shows a trend of increase-decrease-increase, with the lowest count observed inside the flowers. The surface soil of rocky desertification provides a suitable microenvironment for the survival of fluorescently labeled rhizobia. These labeled rhizobia can colonize the surface soil of rocky desertification and migrate across the soil surface over time. They can migrate from the central point O in vertical, oblique, and horizontal directions, but their distribution at various sampling points is discontinuous and unstable.

Introduction

Dolichos lablab L. is a high-quality leguminous green manure crop. It can establish a symbiotic relationship with soil bacteria-rhizobia-allowing the plant to grow in nitrogen-deficient soil conditions (Zhang et al. 2020). Rocky desertification is a significant driver of ecological degradation. Studies have demonstrated that rhizobia associated with leguminous crops can enhance the physical and chemical properties of rocky desertified soils, reduce soil pH, and significantly increase the levels of organic matter and essential nutrients, such as nitrogen, phosphorus, and potassium. These findings highlight the potential of rhizobia to improve soil quality and contribute to ecological restoration (Du et al., 2025). Therefore, introducing rhizobia into rocky desertification soils, even in the absence of leguminous crops, can improve soil properties, provide a source of nitrogen, and enhance overall soil health.

In this experiment, fluorescently labeled rhizobia of *Dolichos lablab* L. were introduced into *Dolichos lablab* L. plants and surface soils of rocky desertification areas. The study investigated the quantity and distribution of the labeled bacteria in different plant parts and at various growth stages of *Dolichos lablab* L., analyzed their movement within the plants, and examined their colonization ability and distribution characteristics in rocky desertified soils without a host plant. This research provides a theoretical foundation for the production of seeds pre-inoculated with rhizobia and offers valuable insights into improving soil conditions in the absence of leguminous crops.

Methods

Test Seeds: The experimental seeds used were *Dolichos lablab* L. of the "Rungao" variety, with a purity of over 90%.

Test Strain: The experimental strain was a genetically stable rhizobium strain (Y-1) capable of producing cyan fluorescence.

Preparation of Bacterial Suspension: After activation, strain Y-1 was inoculated into YMA liquid medium and cultured at 28°C with shaking at 120 r/min until the optical density (OD_{600nm}) reached 0.5-0.8. The culture was then centrifuged at 4000 r/min for 10 minutes to remove the supernatant, leaving the bacterial cells. The cells were resuspended in an equal volume of sterile water and dispersed to prepare the bacterial suspension.

Seed Treatment and Sowing: *Dolichos lablab* L. seeds were placed in a sterilized Erlenmeyer flask and soaked in 5% povidone-iodine solution for 5 minutes, followed by rinsing with sterile water 5-6 times. The seeds were then soaked in the bacterial suspension for 2 hours. Using the hole-sowing method, seeds were planted in plots with a spacing of 40 cm between holes and 45 cm between rows, with one seed per hole.

Bacterial Suspension Application: Every 30 days, 30 ml of the bacterial suspension was applied to each plant. Watering was adjusted as needed to maintain adequate soil moisture.

Plant Sampling: At various growth stages of *Dolichos lablab* L. (130 days [vegetative stage], 216 days [squaring stage], 226 days [Florescence], and 235 days [pod stage]), three plants were randomly selected at each stage. The selected plants, including their roots, were carefully uprooted, washed, and air-dried to remove surface moisture. Using sterile scissors, the plants were divided into different parts: root, stem, leaves, stem tip, and stage-specific parts, such as flower buds (squaring stage), flowers (Florescence), and pods (pod stage). Each plant tissue sample was surface-sterilized, ground, diluted, and plated following Zhang (2012). Colony counts were recorded for each sample, with each part tested in triplicate.

Soil Sampling in Rocky Desertification Areas: A rocky desertification site with no vegetation was selected for soil sampling. The site was located in Wudang District, Guiyang City, Guizhou Procince. Sampling points were established in three directions: horizontal (H), vertical (V), and diagonal (D), with five points along each direction. Adjacent points in each direction were spaced 30 cm apart (Fig. 1). The central point (O) was treated with 100 mL of bacterial suspension. Soil samples were collected from each sampling point on the 7th, 14th, and 21st days following bacterial application. For each sample, 1 g of soil was placed in a sterile Erlenmeyer flask, mixed with 100 mL of sterile water to prepare a soil suspension. The suspension was diluted, plated, cultured, and colony counts were recorded following Zhang (2012).

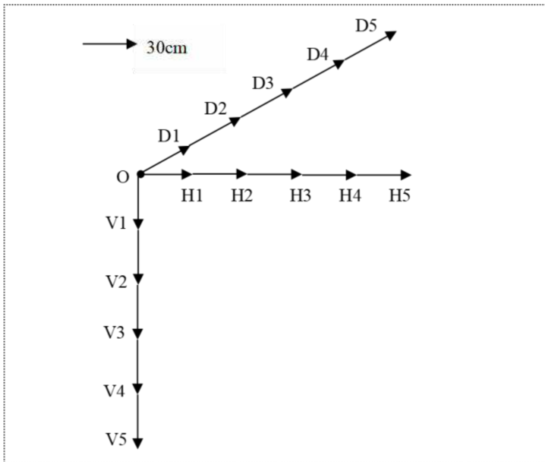

Fig.1 The distribution map of rocky deseritification mountain bacteria solution.

Results

[Quantity and distribution of labeled bacteria in different parts of Dolichos lablab L. plant at different growth stages]

Table 1 highlights the variation in the distribution of labeled bacteria across different parts of the root system and growth stages. During the vegetative stage, the quantity of labeled bacteria in the tap root was 14.58 times, 42.98 times, and 39.68 times higher than that in the squaring stage, florescence, and pod stages, respectively. Lateral roots exhibited the highest bacterial counts during the squaring stage, while the labeled bacteria in hair roots showed a gradual increase as the plant grew. In terms of timing, the root had the highest bacterial counts during the vegetative stage, with the lowest counts observed during the squaring stage. Within the vegetative stage, labeled bacteria were detected in the lower stem, lower leaves, and stem tip, with the highest concentration in the stem tip - 201.17% and 534.29% higher than in the lower stem and lower leaves, respectively. However, the distribution of bacteria in stems and leaves was discontinuous across different growth stages. During the reproductive growth phase, labeled bacteria were detected in all reproductive organs of *Dolichos lablab* L., with the highest counts observed in flower buds. The bacterial counts in flower buds were 5.59 times, 10.71 times, and 1.25 times higher than those in floral primordia, flowers, and pods, respectively.

Table 1 The number of labeled bacteria in each site of *Dolichos lablab* L. plants during different growth stage

Plant parts	The number of labeled bacteria (cfu·g^{-1}·FW)			
	Vegetative stage	Squaring stage	Florescence	Pod stage
Tap roots	71297	4577	1621	1752
Lateral roots	3563	4860	1101	701
Hair roots	6667	10230	18994	24276
Down Stem	7407	91	-	10886
Down leaves	3517	-	-	-
Stem tip	22308	-	-	-
Floral primordia	1341	-	-	-
Flower bud	-	7500	-	-
Flower	-	-	700	-
Pod	-	-	-	6000

Note: "-" means no labeled rhizobia. The same as below.

The quantity and distribution of labeled bacteria at different sampling points in surface soil of the karst mountainous area over time

Table 2 The number of labeled rhizobia at each point at different sampling times

Sampling point	The number of labeled bacteria at different sampling time (cfu·g^{-1}·FW)		
	Day 7	Day 14	Day 21
O	6971	1967	-
H1	-	31527	-
H2	-	-	-
H3	-	-	1196
H4	-	-	50
H5	-	-	3162
D1	-	-	+
D2	-	19927	149
D3	-	75	325
D4	-	+	5645
D5	-	667	1166
V1	2379	575	+
V2	-	-	27634
V3	-	-	9481
V4	-	7409	535
V5	-	-	50

Table 2 reveals that the quantity of labeled bacteria at the central point (O) gradually decreases as the inoculation time increases. Horizontal direction: On the 7th day, no labeled bacteria were detected at any sampling points. By the 14th day, labeled bacteria were detected only at H1, while on the 21st day, they were detected only at H3. This indicates that labeled bacteria migrate horizontally over time and distance. Vertical direction: On the 7th day, labeled bacteria were detected only at V1. By the 14th day, they were detected at V1 and V4. By the 21st day, labeled bacteria were detected at all points except V1. Diagonal direction: On the 7th day, no labeled bacteria were detected at any point. By the 14th day, labeled bacteria were detected at D2, X3, and D5. By the 21st day, labeled bacteria were detected at all points except D1.

In conclusion, labeled bacteria can effectively colonize surface soils and demonstrate tracer effects, providing valuable insights into their distribution characteristics in rocky desertification environments.

Discussion

Most labeled bacteria were primarily distributed in the plant's root, consistent with previous studies, which have shown that while endophytic bacteria can move within plants, they exhibit a preference for specific parts (Zhang 2012; Zhang et al. 2020). Labeled bacteria within the root can migrate to the above-ground parts of the plant, but their distribution is discontinuous. For instance, bacteria have been observed moving from roots to stems and leaves in tobacco, rice, and clover plants. The variation in microenvironments across different plant parts results in endophytic bacteria occupying distinct ecological niches within various organs and tissues (Chi 2006; Gyaneshwar et al. 2001; Zhang et al. 2020). During the development from flower buds to blooms, the number of labeled bacteria in flowers decreased, likely because the nutritional environment during development failed to induce bacterial chemotaxis. Endophytic bacteria can move and adhere to root surface through chemotaxis or by chance, facilitated by root exudates. After mutual recognition and penetration of the root surface, they can colonize the host plant (Artur et al. 2019). When inoculated onto rocky desertified surfaces, the distribution of labeled bacteria in different directions was discontinuous. However, their widespread presence at greater distances from the inoculation point demonstrates that bacteria can migrate to deeper soil layers and spread through capillary water. Additionally, even in the absence of a host, labeled bacteria can colonize rocky desertified soils as independent entities. This suggests that rocky desertified soil provides a microenvironment conducive to bacterial survival and colonization.

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The effects of different restoration measures on plant diversity and carbon sequestration in pastoral ecosystem

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Key words: pasture, ecological restoration, diversity, fencing, farmyard manure, mechanical drilling

Abstract:
Pature management measures such as fencing, the application of farmyard manure, and mechanical drilling have been implemented to address pasture degradation. This study explored the response patterns of grassland vegetation communities and soil nutrients under different restoration methods and compared the effects of these interventions.

The experiment was conducted in 2023 on degraded pasture in Chenbalhu Banner, Hulunbeier City, Inner Mongolia Autonomous Region. Four treatments were applied: control (CK), fencing (WF), farmyard manure (NJF), and mechanical drilling combined with farmyard manure (DNJF). In August of the same year, plant and soil surveys were conducted to evaluate the short-term restoration effects on plant community characteristics, biodiversity, and soil carbon and nitrogen content.

The results showed that WF, NJF, and DNJF significantly increased vegetation cover, density, and above ground biomass compared to CK, with notable improvements in community height and aboveg round biomass ($P < 0.05$). These treatments effectively enhanced plant diversity in degraded pastures, with WF having the most pronounced impact.

Analyzing plant functional groups revealed that perennial grasses exhibited the highest summed dominance ratio under WF, reaching 80.57%. All restoration methods promoted the growth of perennial grasses and increased the summed dominance ratio of C4 plants, thereby improving the light-use efficiency of the plant community. DNJF showed the greatest improvement in soil organic carbon and total nitrogen content

compared to WF and NJF. Correlation analysis indicated that DNJF strengthened the positive relationship between vegetation communities and soil nutrients.

In summary, the three restoration methods—fencing, farmyard manure application, and mechanical drilling combined with farmyard manure—had significant effects on degraded pastures. Fencing notably enhanced plant diversity, farmyard manure significantly boosted grassland productivity, and mechanical drilling effectively improved soil fertility. Among the methods, mechanical drilling combined with farmyard manure proved to be the most effective for the sustainable management of degraded pastures in Hulunbeier.

Introduction

Overgrazing is a key driver of grassland degradation, characterized by imbalances in grassland ecosystem structure and a diminished ability for self-regulation (Li B, 1997). This degradation is evident in reduced vegetation biomass, alteration in species composition, in increased soil compaction, higher sand content, and lower organic matter levels (Deng Y et al. 2021).

These changes adversely affect grassland productivity, leading to decreased outputs of agricultural products like livestock and herbs, while also compromising ecological functions such as air purification, water retention, soil conservation, and biodiversity protection (Zhang F, et al 2022).To mitigate pasture degradation, researchers have explored various restoration treatments, including no-tillage replanting, rational grazing, artificial grassland establishment, fencing, plowing, and fertilization, evaluating their effectiveness, advantages, and limitations (Gu C, et al. 2022, Yu S,,et al. 2019, Sun X, 2024). Each restoration method has specific applications, benefits, and constraints. Based on the characteristics of the study area, this research focuses on three treatments: fencing, farmyard manure application, and mechanical drilling combined with farmyard manure.

Given the negative impacts of pasture degradation on both productivity and ecology, as well as the economic challenges of restoring extensive grassland areas, identifying cost-effective restoration strategies is crucial. This study examines degraded pastures in Chenbaerhu Banner, Hulunbuir City, Inner Mongolia Autonomous Region, using three treatments: fencing, farmyard manure, and mechanical drilling combined with farmyard manure. The study comprehensively analyzes the responses of vegetation characteristics, soil nutrients, and the interaction between vegetation and soil to these treatments, providing a scientific basis for optimizing ecological pasture restoration.

Methods

1.1 Study area

The study area is located in Wuzhuer Gacha, West Wuzhuer Sumu, Chenbaerhu Banner, Hulunbuir City, Inner Mongolia Autonomous Region, China (latitude 48°48′–50°12′N, longitude 118°22′–121°02′E). The research site is situated within a family pasture that has experienced severe degradation due to year-round grazing. This has led to low vegetation, reduced coverage, and a decline in high-quality forage species such as *Leymus chinensis*, along with decreased plant diversity.

1.2 Field sampling and sample collection

The experiment, initiated in May 2023, was conducted on a flat land plot with four treatments: control (CK), fencing (WF), farmyard manure (NJF), and mechanical drilling combined with farmyard manure (DNJF) .Four transects were established, corresponding to the four treatments, each covering an area of 50 m × 600 m. A 10 m isolation zone was maintained between the transects to prevent cross-contamination. Farmyard manure consisted primarily of sheep and cow manure. Specialized soil drilling machinery was used for the mechanical drilling treatment, designed to drill and loosen the grassland soil. The drilling parameters included a depth of 10 cm, a hole diameter of 5 cm, and a width of 7 cm.

Vegetation surveys were conducted using sampling methods during the plant growth period in August 2023. For each sample plot, the species present, their height, coverage, and density were recorded. Following plant sampling, soil samples were collected using a soil drill at two depth layers: 0–15 cm and 15–30 cm. soil bulk density, soil organic carbon, and total nitrogen content are analyzed. The biodiversity of the sample plots was calculated using the following indices and Plant functional groups were classified based on life forms, water ecological types, and photosynthetic pathways. To quantify the dominance of functional groups within the community, the Summed Dominance Ratio (SDR4) was used as a comprehensive indicator. Data were analyzed using Excel 2021 and SPSS 22.

Results

2.1 Plant Community Characteristics and Species Diversity Under Different Restoration Treatments

2.1.1 Impact of Different Restoration Treatments on Community Characteristics

The plant community height and aboveground biomass were significantly higher under the WF, NJF, and DNJF treatments as compared to the CK treatment ($P < 0.05$). After applying WF, NJF, and DNJF, community height increased by 57.98%, 50.23%, and 57.83%, respectively, compared to CK. The increase in aboveground biomass was most pronounced under NJF, with a growth rate of 110.6% higher than that observed under WF and DNJF (Figure 1d).

There were also significant differences in the effect of the restoration treatments on the dominant species *Leymus chinensis*. Under NJF treatment, the height, density, and aboveground biomass of *Leymus chinensis* were significantly better than those under the other treatments ($P < 0.05$). In contrast, the density, coverage, and above-ground biomass of *Leymus chinensis* were lower under the WF treatment than under the other restoration methods.

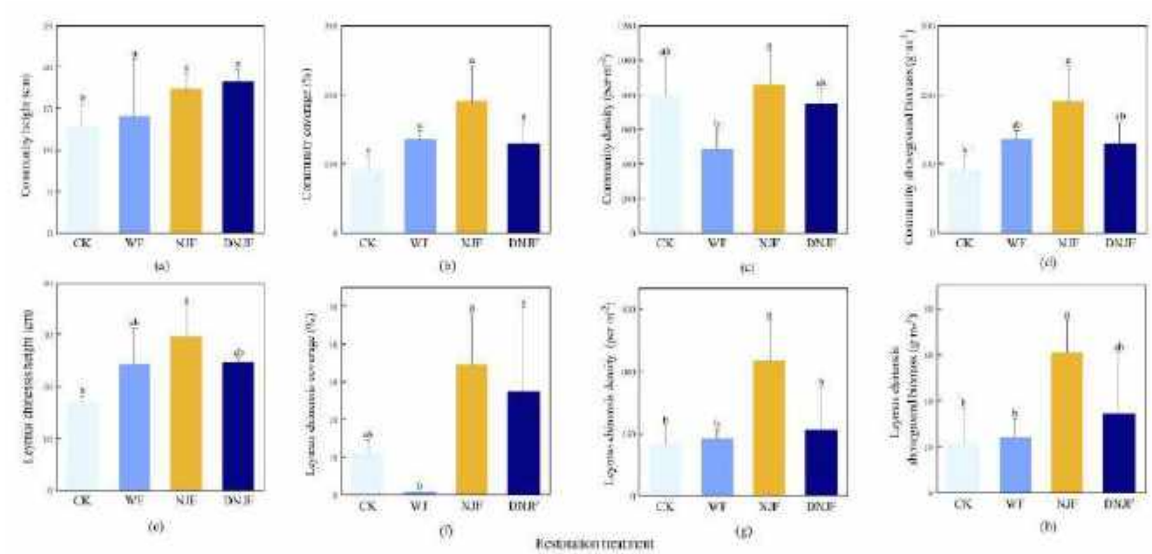

Figure 1 Effects of different restoration treatments on plant community characteristics

2.1.2 Impact of Different Remediation Treatments on the Alpha Diversity of Community Species

The Margalef richness index was significantly higher under the WF treatment than under the other treatments (P < 0.05) (Figure 2). The Pielou evenness index was highest under the CK treatment, followed by the DNJF and NJF treatments. The lowest Pielou evenness index was observed under the WF treatment. This suggests that, although species richness increased under WF, the uniformity of species distribution decreased.

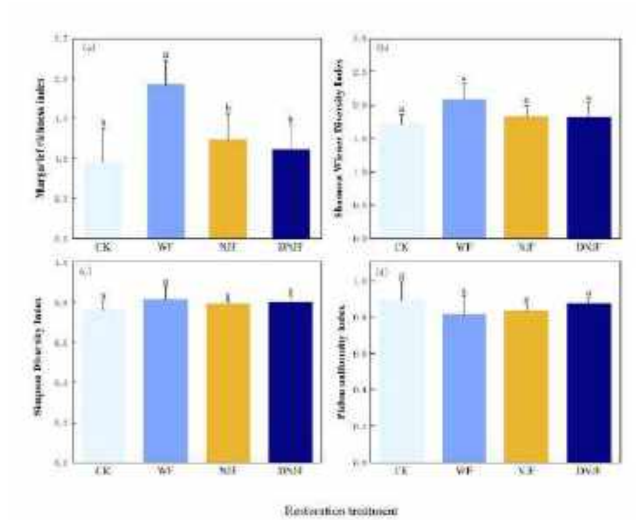

Figure 2 The impact of different restoration treatments on plants diversity

2.2 Impact of Different Restoration Treatments on the Summed Dominance Ratio of Plant Functional Groups

2.2.1 Summed Dominance Ratio of Community Life Form Functional Groups

The summed dominance of perennial forbs under WF treatment was significantly higher than that of CK, with an increase of 100.03%. Additionally, all three restoration treatments (WF, NJF, and DNJF) significantly reduced the ratio of sedges (P < 0.05). Specifically, the sedge ratio decreased by 38.59%, 24.14%, and 28.92%, respectively, as compared to CK. The ratio of annual grasses under NJF and DNJF treatments was significantly higher than CK, with increases of 216.63% and 284.32%, respectively (Figure 3a)..

2.2.2 Summed Dominance Ratio of Raunkiaer's Life Form Functional Groups

The summed dominance ratio of geophyte plants under WF treatment was the highest among the Raunkiaer life form functional groups (Figure 3b). In contrast, among the other three treatments, geophyte plants had the highest ratio under CK and NJF treatments. The summed dominance of geophyte plants in CK and NJF was significantly higher than in WF (P < 0.05), which was 1.74 times and 1.79 times greater, respectively.

2.2.3 Summed Dominance Ratio of Community Water Ecological Type Functional Groups

When categorizing plants based on their adaptability to water conditions (Figure 3c), xerophyte plants dominated the grazing plant communities. The summed dominance ratio of xerophyte plants under WF treatment was significantly lower than under CK and DNJF (P < 0.05), with reductions of 25.73% and 21.94%, respectively.

2.2.4 Summed Dominance Ratio of Community Photosynthetic Pathway Functional Groups

C3 plants dominated the plant communities under all treatments. However, the summed dominance ratio of C4 plants was higher after NJF treatment compared to the other treatments, with a significant increase of 1.47 times over WF ($P < 0.05$) (Figure 3d).

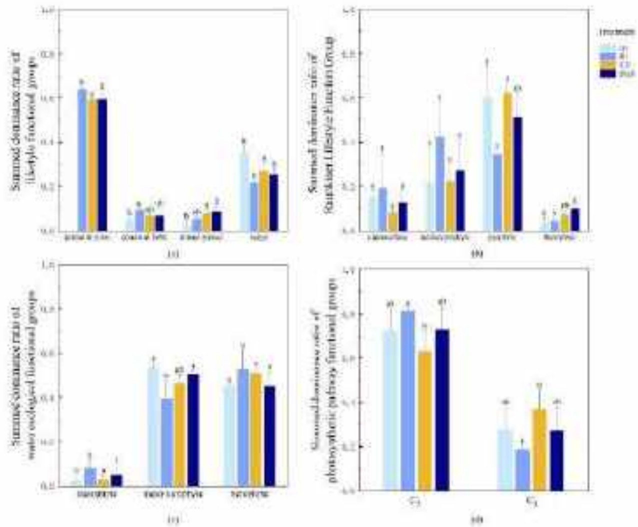

Figure 3 The impact of different restoration treatments on the comprehensive advantage ratio of plant functional groups

2.3 Impact of Different Remediation Treatments on Soil Carbon and Nitrogen Nutrients

The DNJF treatment had a significant effect on increasing soil organic carbon content in the top 0-15 cm soil layer ($P < 0.05$), with a 29.64% increase compared to CK (Figure 4a). The WF and NJF treatments increased organic carbon content by 26.19% and 23.32%, respectively, compared to CK. Among these, DNJF showed the most significant increase in organic carbon content. In the 15-30 cm soil layer, all three remediation treatments increased soil organic carbon content as compared to CK; with WF, NJF, and DNJF increased by 18.14%, 22.56%, and 20.53%, respectively. All three remediation treatments had a positive effect on increasing the total nitrogen content in the soil for both the 0-15 cm and 15-30 cm layers (Figure 4b). In the 0-15 cm soil layer, WF, NJF, and DNJF increased total nitrogen content by 8.46%, 14.97%, and 26.03%, respectively, compared to CK. In the 15-30 cm soil layer, the NJF and DNJF treatments increased total nitrogen content by 4.06% and 42.89%, respectively, compared to CK.

2.4 Impact of Different Remediation Treatments on the Correlation Between Plant and Soil Nutrients

Aboveground biomass, litter dry weight, community height, community coverage, species richness, the Margalef richness index, Shannon-Wiener index, and Simpson index were all negatively correlated with soil nutrients in both the 0-15 cm and 15-30 cm soil layers of CK treatment(Figure 5).

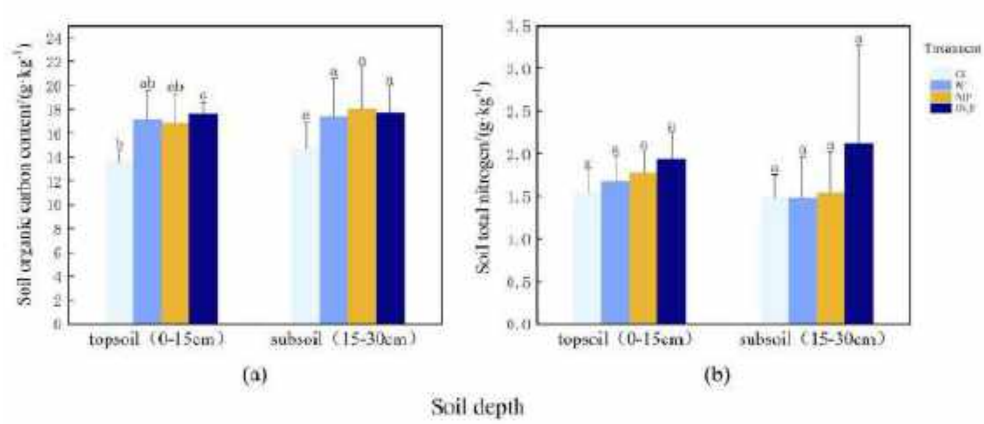

Figure 4 Effects of different remediation treatments on soil carbon and nitrogen nutrient content

Compared to CK, after the WF treatment, the correlation between vegetation indices and soil nutrients generally showed a downward trend, except for litter dry weight, community coverage, and community density. After the NJF treatment, there was a positive correlation between aboveground biomass, community height, and total nitrogen content in the 0-15 cm soil layer. Finally, following the DNJF treatment, the correlation between the Margalef richness index, Shannon-Wiener index, Simpson index, and soil nutrients became positive. Notably, compared to other remediation treatments, the positive correlation between plants and soil nutrients was strengthened under DNJF treatment.

Figure 5 Correlation between Plant Community Characteristics and Soil Nutrients under Different Restoration Treatments in pasture

Discussion

All three restoration treatments promoted the growth of key vegetation indicators, such as aboveground biomass, but their specific effects on plant communities varied. Grassland fencing, a common method for protecting and managing grasslands, restricts human activities and livestock grazing. This approach can enhance the ecological status of grasslands, boosting productivity and biodiversity (Diao Z et al. 2011, Liu T, Yang J, Yang J,et al. 2019). Our results showed that fencing significantly increased aboveground biomass and had the most pronounced effect on vegetation diversity compared to other treatments. From a community composition perspective, fencing increased the proportion of perennial grasses. However, the improvement in the growth of the dominant species, *Leymus chinensis*, was not significant. Liu Hongmei's study Hongmei L et al. 2022) indicated that under fenced conditions, the germination rate of *Leymus chinensis* seeds is lower due to the absence of livestock trampling, which may affect seedling establishment. The higher proportion of drought-tolerant plants under fencing, as compared to other treatments, aligns with findings by Yin Guomei *et al.* (2014) in Hulunbuir. The plant community in fenced areas seems more suitable for arid and semi-arid environments, but it does not restore *Leymus chinensis* to a dominant position. This suggests that further research is needed to determine optimal fencing periods for effective grassland restoration.

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THEME 5. MANAGING RISK – CLIMATE AND OTHER SYSTEM SHOCKS AND TRENDS

Climate change impacts and ecological resilience

South African mesic grasslands are resistant to drought but not warming

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Key words: mesic; climate change; species richness, ecosystem services

Abstract

Current climate change models predict increases in temperature, reduced frost and more variable rainfall with increased frequency of extreme weather events such as flooding and drought. Southern Africa is expected to experience more frequent drought, and the grassland biome expected to be significantly affected by this. A possible reduction in area of between 30 and 50% is predicted. Given the importance of the grassland biome from both an intrinsic and economic perspective this reduction could have serious economic and food security consequences. For these reasons, it is critical to increase our understanding of ecosystem processes under drought-stress and warming. In winter 2019 a rainfall exclusion and warming trial was established in a good condition mesic grassland in KwaZulu-Natal, South Africa. Rainout shelters reduced the incoming precipitation by 53% and open-topped chambers increased daytime air temperature by 2°C. Species abundance data was collected annually. Rainfall manipulation had a marginal effect on species composition, however warming resulted in reduced abundance of several common forbs and the loss of numerous forb and grass species, also reducing species richness. Simpson's diversity was unaffected. These reductions in species richness reduce the ability of the grassland to recover from climatic perturbations and thus rainfall reduction coupled with warming presents a significant threat to grassland ecosystem services.

Introduction

In South Africa, the grassland biome is the second most diverse, after the fynbos biome, and contains many rare and threatened species (Rutherford & Westfall 1994). However, almost 60% of the grassland biome has been modified through development and crop production (Low and Rebelo 1998) and less than 3% is conserved (SANBI 2013). The remainder is used for livestock production, predominantly cattle and sheep (SANBI 2013). After modification and degradation, the second major threat to grasslands is climate change (SANBI 2013). Current climate change models predict increases in temperature, reduced frost and more variable rainfall with increased frequency of extreme weather events such as flooding and drought (IPCC, 2022). Data gathered since 1950 has shown increased CO_2, temperatures, and frequency of extreme climatic events (IPCC 2012). Southern Africa is one of the regions expected to experience more frequent, long-lasting drought and heat waves (Trisos et al. 2022 in IPCC, 2022). This will significantly affect the grassland biome, possibly reducing the area by between 30 and 50% (Mucina and Rutherford 2006). Given the importance of the grassland biome from both an ecological and economic perspective this reduction could have serious economic and food security consequences (Kapuka & Hlásny 2021, Miranda et al. 2009). For these reasons, it is critical to increase our understanding of ecosystem processes under warming and drought-stress.

Methods

The trial was established using the Drought-Net Research Coordination Network standard protocols (Smith et al. 2024), where clear plastic roof sheeting was used to impose a statistically extreme, 1-in-100 year drought. Nine plots (5 x 3.5 m, with six 1 m^2 subplots) were arranged in a split-plot, randomised block design in a section of good-condition natural veld at the Ukulinga Research Farm, University of KwaZulu-Natal (30°24′ S, 29°24′ E). The farm has summer rainfall with a mean annual precipitation of 838 mm and a mean annual temperature of 18 °C (Ward et al. 2020). The plots were established in 2019, with the 2019/2020 growing season being the first treatment year. Rainfall manipulation took place at the whole plot level and warming at the subplot level. The rainfall manipulation treatments were drought (53% reduction), ambient and run-on (diversion of intercepted rainfall from drought). Warming was applied on a single subplot using hexagonal open-topped warming chambers made from 2 mm thick clear polycarbonate sheeting (Mu et al. 2017), resulting in an average daytime temperature increase of ~2 °C. Species composition was surveyed at the beginning of the growing season (early December) and at the peak of the growing season (late March). Maximum abundance per species was used for data analysis. In dedicated destructive sampling subplots (for rainfall manipulation only), biomass was harvested after the last rains (late April/early May) and separated into functional groups. Data analysis was conducted in R statistical software (version 4.2.0) and R studio (version 2024.9.1.394) using packages *vegan* (Oksanen et al. 2024) and *dplyr* (Wickham et al. 2023) and plots created using *ggplot* (Wickham et al. 2016) and *ggrepel* (Slowikowski 2024.). Changes in species composition between the first (2020) and the fifth (2024) treatment years were assessed using PERMANOVA and visualised using a partial canonical correspondence analysis. Data were log transformed to reduce the influence of rare species. When PERMANOVA revealed significant effects, a SIMPER analysis was conducted to identify the species contributing to the differences. Differences in species richness and Simpson's diversity were assessed using repeated measures ANOVA.

Results

After five years of treatment application PERMANOVA revealed significant effects of year and warming on species composition (Figure 1 a&b). There was a marginal effect of moisture level ($p = 0.051$) but no significant treatment interactions. SIMPER analyses ($p > 0.05$) indicated that the differences between 2020 and 2024 were driven by decreases in the abundance of two grass species (one palatable and one acceptable), which were replaced by increases in two palatable grass species. Warming resulted in two to three-fold reductions in abundance of three common forb species and an eight-fold reduction in abundance of one acceptable grass species. In addition, five grass and fifteen forb species occurring in low abundance were lost due to warming.

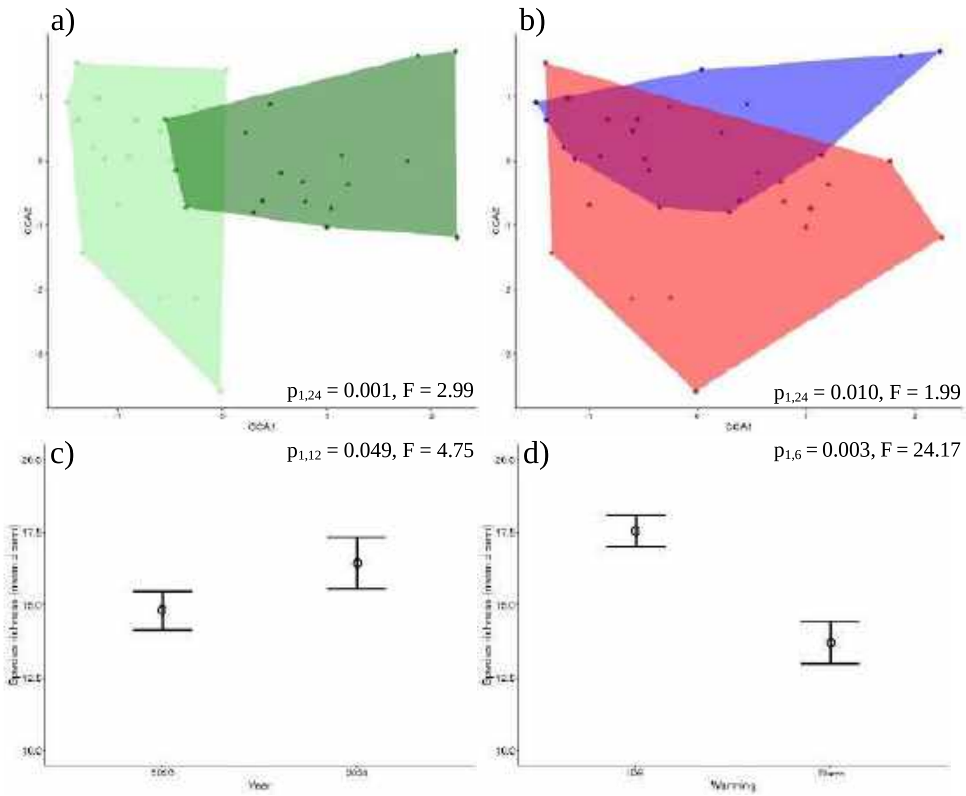

Figure 1: Partial Canonical Correspondence Analysis (pCCA) biplots showing the relationship between species composition (a) Year (2020 in light green and 2024 in dark green), (b) Warming (IDE/unwarmed in blue and warmed in red) after accounting for spatial effects using blocking. Eigenvalues of the axes (CCA1 and CCA2) are 0.218 and 0.171, explaining 18.48% and 14.51% of the constrained variation, respectively. The analysis was conducted after a significant PERMANOVA. The effect of (c) Year and (d) Warming on mean (± SE) species richness after a repeated measures ANOVA revealed significant effects.

Simpson's diversity showed no significant effects. Species richness was also significantly affected by year and warming. Overall species richness increased from 2020 to 2024, while warming reduced species richness compared to ambient conditions (Figure 1 c&d).

Discussion

The distribution of the grassland biome is strongly driven by climate, occurring across a rainfall range of 400 – 2000 mm (Department of Environmental Affairs 2015, Mucina and Rutherford 2006). Mesic grasslands are currently predicted to become 10 – 15% drier (Department of Environmental Affairs 2015). This level of rainfall reduction has been found to significantly reduce grassland productivity and diversity (Miranda et al. 2009), however, the duration of drought has a greater impact on the ecosystem than the intensity (Sala et al. 2015). Single-year drought studies tend to produce more variable responses than multi-year studies (Griffin-Nolan et al. 2018, Petrie et al. 2018) but in general, drought reduces productivity (Balachowski and Volaire 2018) through altered species composition and tuft morphology, and reduction in basal cover. Over the last 14 years, annual rainfall in the study site was observed to fluctuate by over 250 mm above and below the long-term annual mean of 838 mm (unpublished data). The lack of response observed over five years of rainfall reduction is likely due to the adaption of these mesic grasslands to regular rainfall fluctuations, however, with extended exposure to drought the vegetation is expected to lose this resilience (Midgely et al 2011).

The reduction in species richness observed after five years of warming to 2° C above ambient supports the predictions made by SAEON (2015). Since species richness is expected to influence the capacity of the vegetation to withstand and recover from perturbations like droughts (Van Ruijven & Berendse 2010) the combination of warming and long-term exposure to drought puts these grasslands at risk of degradation and woody invasion through reduced fire frequency and intensity. By contrast, diversity was unaffected, likely because the dominant species were unresponsive to the treatments.

Although South African mesic grasslands have been resilient to five years of extreme drought, they have suffered significant degradation through species loss because of warming. Extended exposure to drought, particularly given the marginal significance observed after five years of rainfall reduction, coupled with warming is expected to cause future vegetation degradation. This will result in the loss of numerous ecosystem services which are likely to have economic and food security consequences. This response observed in mesic grasslands, near the centre of the biome's rainfall range, is concerning and highlights the need for research closer to the limits of the rainfall range as these areas are likely to exhibit more rapid and extreme responses.

Acknowledgements
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Temperature change in central Australia: episodic warming

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Key words: Temperature, episode, breakpoint, change plot, vegetative cover, central Australia

Abstract

From 1871 to 2024, central Australia experienced distinct warmer and cooler episodes, delineated by breakpoints in mean monthly maximum temperatures (maxima). Early episodes trended cooler; some warmer; later episodes trended warmer. Cooler and warmer components of the maxima both trended warmer in recent years. A system constant of 2.57^{o}C (the difference in episode averages between warmer and cooler components of maxima) was found across the 109 sets of records examined. Changes in Alice Springs maxima from 2001 to 2024 were strongly related to changes in certain oceanic climatic indicators and rainfall. Changes in arid South Australian vegetative cover were related to changes in maxima and changes in rainfall. Monthly changes in components of its vegetative cover were associated with changes in a complex of maxima, rainfall, and different ocean indicators.

Introduction and Methods: *Expecting the average, knowing the unexpected*

Each day, each month, each year, we expect the temperature to be average, despite its continuing rise and fall, while wanting to know whether it will be, is, and has been hotter or colder than we expected. This difference to the average ("*the unexpected*") is as important to us as the average. When Alice Springs maxima are plotted by month, the difference to the average surges up and down (Fig. 2), different to the structured if ragged maxima (Fig. 1). (Figs. 1 to 5 use Alice Springs Post Office 1887-1953; Fig 6 shows Alice Springs Airport 1941-2024)

When you add these differences together in sequence, you form the Change Plot (Fig. 3), showing how maxima have changed over time, once you've allowed for temperature increase or decrease. A Change Plot depicts what you didn't expect, and have not known, including episode duration and the large difference between each and all warmer and cooler episodes (Fig. 1.4).

In any change plot, all measures in an incline were above average, and below average in any decline, but not increasing nor decreasing significantly within each episode. The peaks and troughs are the sharp breakpoints between warmer and cooler episodes.

Change plots were used to visualise and analyse the interrelationships of maxima, rainfall, vegetation, and oceanic climatic indicators. Regression analysis, ttest, tabulation and chi test were statistical methods employed (Stata: www.stata.com). Alice Springs maxima and the vegetative cover of arid South Australia are used as examples for central Australia.

Monthly temperature and rainfall data were downloaded from Australian Bureau of Meteorology (BOM: www.bom.gov.au/climate/data). Ocean indicators were from BOM and National Oceanographic and Atmospheric Administration (https://www.ncei.noaa.gov/cdo-web/). Vegetative cover data were from Rangelands and Pasture Productivity (https://map.geo-:rapp.org).

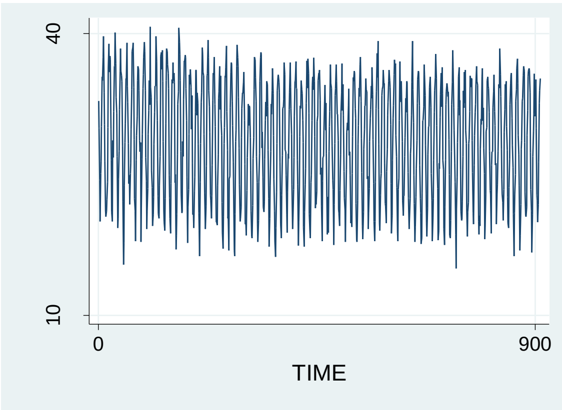

Fig. 1 Monthly maxima

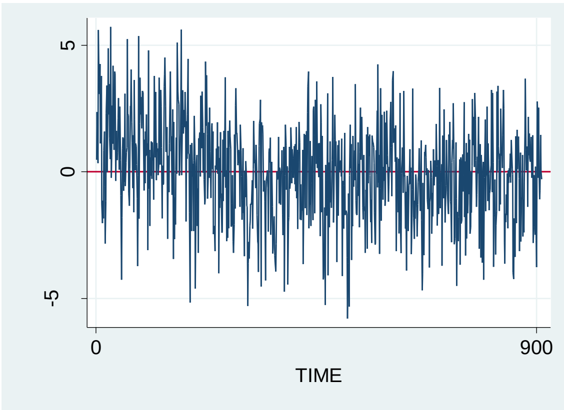

Fig. 2 Difference to monthly average

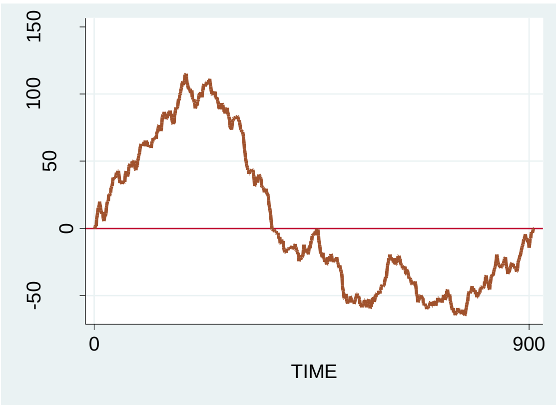

Fig. 3 Change Plot

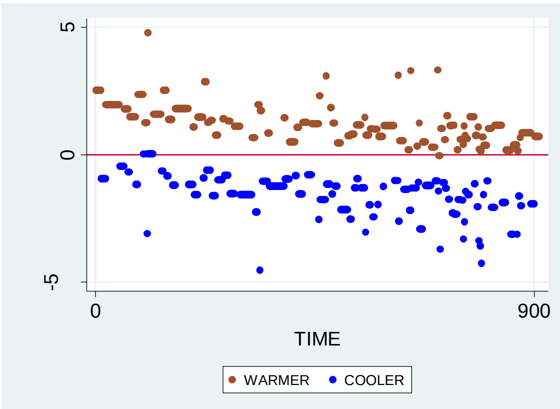

Fig. 4 Episode Mean Difference to Average

Results:

Seeing temperature change

The numerous short episodes that can be seen in the change plots of Alice Springs Post Office (159 between 1878-1953 – Fig. 3) and Airport (343 between 1941-2024) can be grouped into 28 longer episodes (Fig. 5). These episodes have two features:

- Large episodic oscillations between cooler and warmer episodes
- A distinct fall then rise

The duration of longer oscillations can vary from less than 1 year to decades.

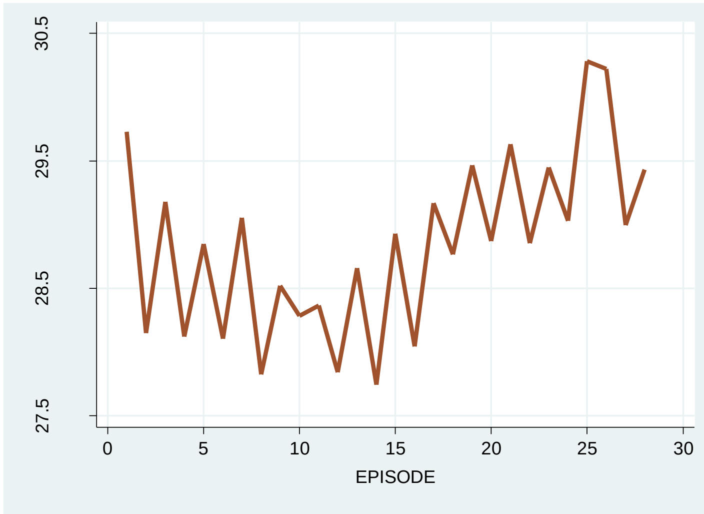

Fig. 5. Longer cooler and warmer episode maxima for Alice Springs 1878 to 2024

These oscillations in maxima were found in all 109 central Australian records examined, together spanning 1871 to 2024. See locations in Appendix.

Warmer and cooler episodes of the maxima oscillate about a constant

Parsing the change plot of monthly maxima for Alice Springs (1941 to 2024) found 172 warmer and 171 cooler episodes. Each mean episode difference to the average is plotted in Fig. 6. The warmer episode means averaged 30.45 ºC lasting 3.1 months; the cooler episode means averaged 27.10 ºC and 2.6 months, compared with general mean of maxima: 28.92ºC.

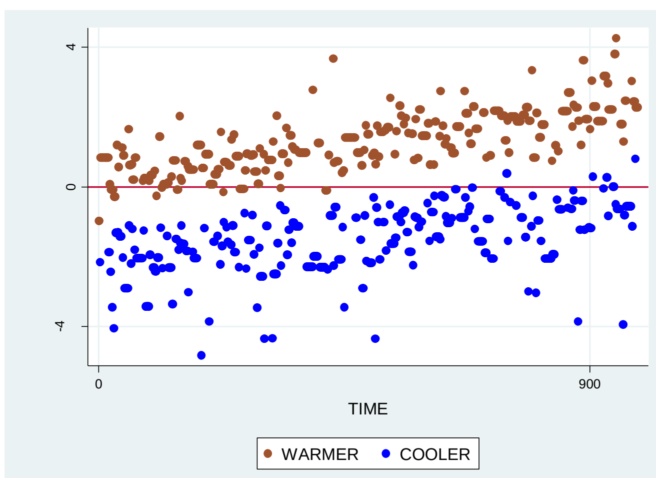

Fig. 6. Episode mean difference to average monthly maxima: Alice Springs 1941 to 2024

The trend in warmer and cooler maxima averaged 0.0128 ºC per warmer episode and 0.0098 ºC for cooler episodes. The maxima had a lower trend of 0.0012 ºC. The decadal change for warmer episodes was 0.266 ºC; 0.198 ºC for cooler episodes, and 0.234 ºC for all maxima. Over the 83 years, the mean episode difference between warmer and cooler episodes of the maxima averaged +2.81 ºC, larger than the total change in maxima (+1.93 ºC). The total change in maxima for Alice Springs 1878-1953 (see Fig. 4) was a cooling of -1.44 ºC.

Falls in maxima were common in records beginning before 1940 (21 of 32 sites) across central Australia. Rises in maxima were observed in all records beginning from 1940. Decadal trend averaged +0.032ºC for records commencing before 1940, and +0.310 ºC for later sets of records.

For 109 sets of records from 1871 to 2024, the difference between the warmer and cooler shorter episode means centred around a constant: +2.57 ºC (95% CI: 2.53 to 2.61). The varying durations of shorter episodes determined the timing of the larger oscillations, together with varying maxima. The average durations of shorter episodes at any site varied from 2.2 to 5.7 months, with a mean of 3.63.

The oceans influenced maxima

Changes in and over surrounding oceans were related to changes in maxima. For monthly maxima of 4 Alice Springs area sites (Airport, Jervois, Kulgera, Grape Farm) from 2001 to 2024, change in amplitude of the MJO (Δ_MJOAmpl) accounted for 43% of changes in maxima on regression analysis. Including changes in SOI, AO and IOD explained 75% of maxima changes; adding changes in rain raised explanatory power to 90% for changes in monthly maxima:

Δ_maxima ~= +2.25 Δ_MJOAmpl – 0.052 Δ_SOI + 0.67 Δ_AO - 0.95 Δ_IOD -0.048 Δ_rain - 3.393977

*[*Abbreviations*: Δ_parameter: change in a parameter; SOI: Southern Oscillation Index; AO: Antarctic Oscillation; IOD: Indian Ocean Dipole; MJO: Madden-Julian Oscillation - Ampl Amplitude; Phase-Phase; RMM1 -RM1; RMM2 -RM1]*

Maximum temperature changes influenced vegetative cover

Monthly changes in vegetative cover (2001 to 2024) were related to the warmer and cooler episodes when considered with changes in rainfall across central Australia. In one example, the relationships for arid South Australia (see Appendix) were stronger for %green cover and %bare ground than for %non-green cover on regression analysis.

- Δ_Green ~= +1.20*Δ_max +0.38 *Δ_rain +19.1 (R^2 - 0.67)
- Δ_Non-Green ~= +2.80*Δ_max +0.32*Δ_rain +51.7 (R^2 - 0.39)
- Δ_Bare Ground ~= -4.00*Δ_max - 0.75*Δ_rain - 75.5 (R^2 - 0.52)

Maxima and rainfall were for 6 sites (Oodnadatta, Moomba, Woomera, Marree, Yunta, Ceduna).

Maxima, rainfall and the oceans influenced vegetative cover

Changes in vegetative cover of arid South Australia were related to changes in oceanic climatic indicators combined with changes in maxima and rainfall on regression analysis:

- Δ_Green: Δ_[maxima, rain. amplitude of MJO, SOI] (R^2 - 0.85)
- Δ_Non-Green: Δ_[maxima, rain, SOI, IOD] (R^2 - 0.60)
- Δ_Bare Ground: Δ_[maxima, rain, SOI, AO, {Phase, RM2 of MJO}] (R^2 - 0.76)

- Δ_Total Cover: Δ_[maxima, rain, SOI, AO, {Phase, RM2 of MJO}] (R^2 - 0.76)

Discussion, Conclusions and Implications

This study found central Australian maximum temperatures from 1871 to 2024 had structured variability in a binary (warmer/cooler) system with breakpoints delineating episodes. This system may be determined by or interact with oceanic and continental influences, as well as rainfall, from analysis of 2001 to 2024 records. Changes in vegetative cover may be a part of this systemic interaction. The Madden-Julian Oscillation was found to be important in maxima changes, and vegetative cover change.

Changes in maxima were important in vegetative cover changes. Intuitively, the observed large jumps in maxima between cooler and warmer episodes are likely to be important for vegetation. The marked increases over time in both cooler and warmer components of the maxima across central Australia are concerning due to the anticipated manifold effects of global warming, and the likelihood of episodic, extended, widespread large increases in maxima; correlated reduction in rainfall; and consequent widespread falls in vegetative cover.

The widespread cooling from early 1900s may reflect the severe loss of vegetation and soil with the rabbit invasion of eastern Australia and overstocking of its rangeland areas (Barnard 1962, Rolls, 1984; Lunney 1994), with subsequent buildup of airborne particulates, as with "*global dimming*". It is also possible that the limited evidence of warming from the early 1870s to 1890s may reflect the cessation of indigenous burning practices to manage vegetative cover, thereby reducing airborne particulates, as their populations and culture were affected by Europeans from late 1700s and first part of 1800s onwards (Gammage 2012).

Using change plots to visualise and analyse empirically and statistically the dynamics and interrelationships of vegetation, climate and other phenomena opened new ways to understand and quantify Australian rangelands. Change plots remove the cyclic elements of temperature and vegetation that obscure underlying linear change and discontinuities.

Episodicity and episode duration can be included as climate characteristics (Foley 1957, Curran 2023).

The episode mean [*warmer-cooler*] difference is a system constant, in the same sense that each location has a characteristic average rainfall, and differences between wetter and drier episodes centre on constants (Curran 2023), despite varying considerably around that constant from year to year, by month-of-year, and within each day.

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Wealth creation, income distribution, and adaptation among Sahelian (agro)pastoralists in a shock-prone environment

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Abstract
Sahelian (agro)pastoralists face significant undervaluation of their livelihoods. A 2017-2021 comparative study across six Sahelian countries, involving 3,070 households initially and 2,216 later, examined income trends and coping strategies. Household incomes stabilized at around 2 million FCFA annually from 2017 to 2020, with notable disparities across countries. Burkina Faso, Mali, Mauritania, and Senegal saw income growth, while Chad experienced a decline. Livestock sales and reliance on subsistence farming influenced these differences. Despite challenges, livestock sales remained crucial, though declining in some areas. Adaptive strategies like destocking and mobility were employed, but limited capacity hindered stronger responses.

Introduction
In developing countries with large livestock sectors, the challenge is to promote efficient production systems that meet rising demand while minimizing environmental and health impacts and improving smallholder farmers' well-being. Pathways for growth include genetic improvements, better nutrition, disease control, environmental risk management, and infrastructure development. However, each country's livestock sector is shaped by its unique context. A critical issue for policymakers is the lack of reliable, up-to-date data (Alary et al., 2011; Wane et al., 2009a, 2009b, 2018, 2020, 2024). Incomplete data and improper economic modeling can hinder effective policymaking and overlook indirect contributions like draft power and manure (Pica-Ciamarra et al., 2014; Kebebe, 2019).

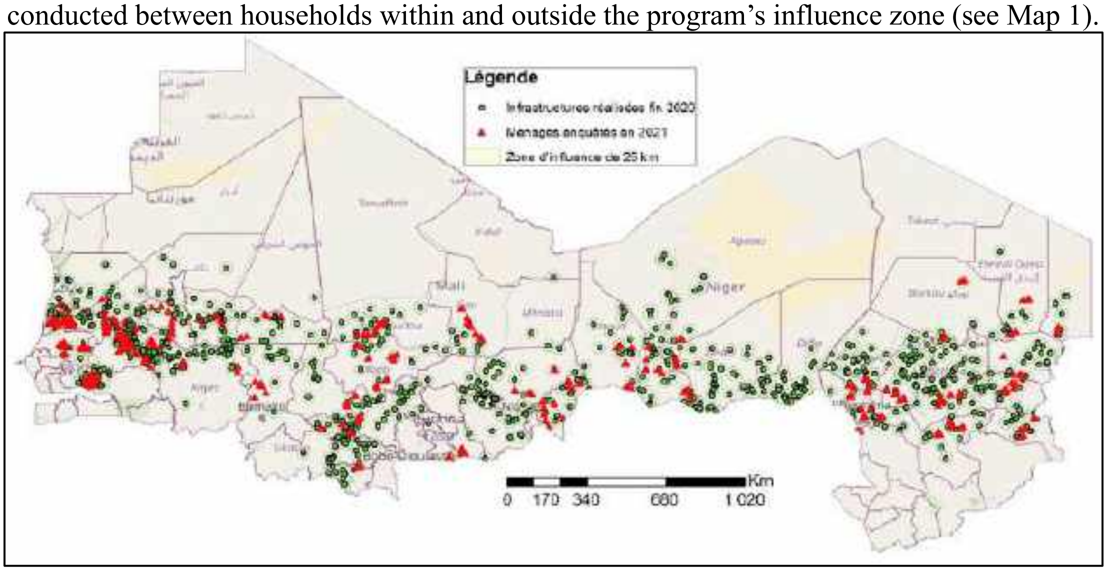
Method
This study examines household income dynamics within Sahelian agro-pastoral communities, utilizing data from two survey periods (2016-2017 and 2020-2021) to enable both aggregated and disaggregated comparative analysis. The primary focus is on the evolution of income inequality, framed within Sustainable Development Goal (SDG) No. 10, which aims to reduce economic disparities. In addition, the study develops an approach to assess the multifaceted shocks experienced by pastoral households and the priority strategies they adopt to address threats to their income, assets, food security (including both production and

purchasing capacity), food stocks, and livestock holdings. The analysis draws on 3,070 agro-pastoral households surveyed in 2016-2017 and 2,352 households in 2020-2021 across six Sahelian countries.

Table 1. Strategic Selection of Study Sample Sizes

	Survey sample 2016-2017	Survey sample 2020-2021
Mauritania	527	353
Senegal	948	359
Mali	579	360
Burkina Faso	513	404
Chad	503	359
Total (without Niger)	**3 070**	**1 835**
Niger	NC	517
Total (including Niger)	**n.a.**	**2 352**

This study analyzes income evolution by revisiting a sample of 350 households from a 2016-2017 survey in 2020-2021. During this period, the PRAPS1 program significantly invested in infrastructure (boreholes, vaccination parks, livestock markets, production routes, dairy units, etc.) and economic services (Support for agro-pastoral organizations, capacity building, etc.). A comparative analysis was conducted between households within and outside the program's influence zone (see Map 1).



Map 1 – Location of Surveyed Households in PRAPS Countries in 2021 marked with red triangles, and infrastructural investments marked with green circles.

Results and discussions

Impact of Multidimensional Shocks on Sahelian Agro-Pastoral Households: Income, Assets, and Livelihoods

Between the two survey periods, 27% of households in six Sahelian countries reported climate-related, 36% health-related, 26% economic, 8% security-related, and 3% social shocks. Analysis of shocks over the past three years reveals varied impacts on daily life. Climate shocks primarily involved droughts (71% of households), particularly in Mauritania (92%) and Burkina Faso (89%), with flooding reported in Chad (51%) and Mali (49%). Health shocks, notably animal diseases, affected 50% of households, with significant global disparities. The COVID-19 pandemic also had severe economic and health consequences. Economic shocks included rising food and livestock feed prices, while security shocks involved livestock theft and bushfires. Social shocks included reduced financial transfers (remittances from migrants across and outside Africa), notably in Mali and Niger.

Adaptation Strategies and Coping Mechanisms of Sahelian Agropastoral Households in Response to Multidimensional Shocks

Sahelian (agro)pastoralists have employed various strategies to safeguard their livelihoods amid multifaceted shocks. Key adaptive strategies include destocking (22%) and mobility (14%). However, a concerning 15% of households reported no response, reflecting limited coping options.

Table 2. Prioritized Strategies of Sahelian Households in Response to Multifaceted Shocks

Description	First priority	Secondary priority	Tertiary priority	Description	First priority	Secondary priority	Tertiary priority
Community Support	0%	1%	2%	Seasonal Migration	2%	2%	2%
NGO Assistance	2%	2%	2%	Permanent Migration	0%	0%	0%
Government Aid	2%	2%	2%	Long-Term Migration	1%	1%	1%
Help from Relatives	4%	6%	8%	Family Labor	7%	7%	6%
Alternative Income Activities	1%	2%	3%	Wage Labor	3%	4%	3%
Placing children with other families	0%	0%	0%	Mobility Strategies	14%	5%	4%
Destocking	22%	15%	10%	No Response/No Strategy	16%	17%	27%
Borrowing/Loans	5%	8%	8%	Meal Reduction	3%	3%	2%
Market Garden Fencing	2%	2%	2%	Reduced Food Portions	2%	3%	3%
Fodder Storage Enclosures	1%	1%	1%	Use of Food Substitutes	3%	3%	2%
Savings Strategies	4%	7%	4%	Selling Non-Productive Assets	1%	1%	1%
Adoption of Resilient Species	1%	1%	1%	Selling Productive Assets	0%	1%	1%
Additional Employment	2%	3%	2%	Selling Food Reserves	2%	2%	1%

The COVID-19 pandemic further exacerbated challenges by restricting mobility and market access, causing a decline in destocking (from 15% to 10%) and an increase in inaction (from 16% to 27%). Borrowing also rose from 5% to 8%. These trends indicate a weakening of adaptive capacity, emphasizing the need for targeted interventions to strengthen resilience. Country-specific responses varied, with notable increases in inaction and reliance on external support.

Adapting Livelihoods: Income Generation in the Context of Multidimensional Shocks

In the context of multifaceted shocks, Sahelian (agro)pastoralists primarily generate income from livestock, with subsistence consumption playing a pivotal role in securing their livelihoods. Between 2017 and 2020, total income, including livestock sales, crop sales, foraging, transfers, and subsistence, remained stable at around 1.9 million FCFA annually per household. Income increased by 0.6% when including Niger and by

6% excluding Niger, although regional disparities persist. In countries like Burkina Faso, Mali, Mauritania, and Senegal, income grew (9%, 14%, 7%, and 13%, respectively), while Chad saw a 13% decline.

Table 3. Summary of income indicators and their variations over time

Country	Overall income 2016	Overall income 2021	Variation 2016-2021
Burkina Faso	1,501,293	1,647,793	10%
Mali	1,614,328	1,842,295	14%
Mauritania	1,438,813	1,533,146	7%
Senegal	2,864,303	3,248,213	13%
Chad	2,205,349	1,926,351	-13%
Niger	n.a.	1,426,062	n.a.
The Sahel	1,924,817	1,937,310	1%

Country	Crop income 2016	Crop income 2021	Variation 2016-2021
Burkina Faso	303,035	267,139	-12%
Mali	251,218	99,519	-60%
Mauritania	40,135	10,295	-74%
Senegal	125,894	297,042	136%
Chad	271,206	261,821	-3%
Niger	n.a.	975	n.a.

Country	Cash income 2016	Cash income 2021	Variation 2016-2021
Burkina Faso	1,138,591	1,409,818	24%
Mali	1,062,248	1,185,257	12%
Mauritania	617,846	1,156,604	87%
Senegal	1,892,967	1,919,769	1%
Chad	1,586,784	1,169,372	-26%
Niger	n.a.	711,731	n.a.

Country	Live-animal sales 2016	Live-animal sales 2021	Variation 2016-2021
Burkina Faso	505,863	1,409,818	179%
Mali	626,415	621,991	-1%
Mauritania	554,050	1,055,607	91%
Senegal	1,560,989	1,402,389	-10%
Chad	963,868	599,821	-38%
Niger	n.a.	379,051	n.a.

Country	Self-consumption 2016	Self-consumption 2021	Variation 2016-2021
Burkina Faso	362,701	215,541	-41%
Mali	552,080	657,037	19%
Mauritania	820,967	376,542	-54%
Senegal	971,336	1,328,444	37%
Chad	618,566	756,979	22%
Niger	n.a.	714,331	n.a.

Country	Dairy income 2016	Dairy income 2021	Variation 2016-2021
Burkina Faso	329,693	93,083	-72%
Mali	184,615	463,748	151%
Mauritania	23,660	90,703	283%
Senegal	206,084	220,338	7%
Chad	351,709	307,730	-13%
Niger	n.a.	331,705	n.a.

Country	Livestock income 2016	Livestock income 2021	Variation 2016-2021
Burkina Faso	835,556	1,142,679	37%
Mali	811,029	1,085,739	34%
Mauritania	577,710	1,146,310	98%
Senegal	1,767,074	1,622,727	-8%
Chad	1,315,578	907,551	-31%
Niger	n.a.	710 756	n.a.

The Role of Self-Consumption and Collective Investments in Reducing Income Inequality in Sahelian Agro-Pastoral Systems

Economic contributions of agro-pastoral households remain threatened by high levels of inequality despite slight reductions between survey periods. These inequalities stem from unequal access to productive resources. Little et al. (2001) and Wane et al. (2020) highlighted that high inequality in Sahelian pastoral and agropastoral systems is linked to limited access to economic resources such as infrastructure and land. A major challenge is addressing these disparities, measured through Gini monetary and total income indices. Between 2017 and 2020, PRAPS zone countries showed high-income inequality (Gini indices between 0.47 and 0.71) in the (agro)pastoral areas. However, Gini indices for monetary income generally decreased, reflecting improved economic conditions, especially in Mauritania (-25%). Total income inequality, including subsistence, also declined across all countries. In Niger, while income inequality remained high, areas influenced by PRAPS programs showed slightly less disparity. A key takeaway is that self-consumption (the equivalent income value of consuming what the agropastoralists produce themselves) significantly reduces income inequality, especially during disruptions like COVID-19. High inequality often reflects unequal access to productive resources and poses a source of instability. Reducing inequality aligns with targeted investments in agropastoral economies, reinforcing the value of PRAPS initiatives.

Conclusion

The analysis of income among Sahelian agropastoral households, though partial due to the lack of data for Niger in 2016, reveals significant trends. Between 2017 and 2020, total household income remained relatively stable at around 2 million FCFA. However, disparities were observed: incomes rose in Burkina Faso, Mali, Mauritania, and Senegal, while a decline occurred in Chad. Subsistence consumption played a crucial role in reducing income inequalities. Regarding shocks, 27% of households reported climate-related, 36% health-related, and 26% economic shocks, with varied coping strategies. Security-related shocks were less reported, likely due to inaccessible regions for investments and surveys. The COVID-19 pandemic worsened uncertainty, emphasizing the need for regular surveys and targeted aid programs.

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Climate change projections and their impact on grassland systems: a longitudinal study in central Spain

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Key words: Grassland, Mediterranean, Sustainable management

Abstract
Grassland systems are one of the most important ice-free ecosystems on Earth. They are important suppliers of ecosystem services such as carbon sequestration, biodiversity support, or pollination. However, in the last decades, there has been evidence of climate change linked to higher temperatures and reduced precipitation. In this study, we provide insight into the long-term dynamics of grassland systems that could help guide sustainable management. Grasslands in Spain are commonly located in the northern regions but also extend inland, where herbaceous and shrubby vegetation have adapted to thrive despite water scarcity conditions. Our study targets the region of Madrid, at the heart of the Iberian Peninsula, where grasslands cover almost 41% of territory. With reference to the Sixth Assessment Report from the Intergovernmental Panel on Climate Change, we established a 5×5 km grid to assess the proportion of grassland coverage. We employed proximity to a soil pit and a minimum grassland coverage of 40% within each grid cell as selection criteria. We gathered daily historical climate data on temperature and precipitation from 1950 to 2014 and future projections from 2015 to 2100. The future projections were SSP-4.5 and SSP-8.5 scenarios based on Shared Socioeconomic Pathways. First, we used MODIS data (2000–2024) to identify grassland coverage anomalies. Then, we applied the SIMPAST model, which required climate data, hydrological balance, solar radiation, and an initial seed count. Vegetation species were identified from September to May 2024–2025.

Introduction
Grasslands provide essential ecosystem services such as forage production, carbon sequestration, and biodiversity maintenance. They support extensive livestock systems and contribute to ecological stability. Additionally, they act as carbon sinks, regulate the hydrological cycle, and serve as habitats for diverse

plant and animal species (Bengtsson et al. 2019). Shaped by climate and human activity, Madrid's grasslands host a mix of herbaceous and woody species, creating ecologically valuable landscapes with notable differences between the north and south. However, their dynamics are highly sensitive to climatic, edaphic, and hydrological factors, as well as human management practices, making them vulnerable to climate change (Zhao et al. 2020). Projected climate trends for the Iberian Peninsula suggest rising temperatures, intensified heatwaves, and decreasing precipitation, leading to more frequent droughts and extreme weather events (Sanz-Elorza et al. 2003). These changes threaten water availability and ecosystem resilience, particularly in grasslands dependent on seasonal rainfall and soil moisture retention (Joyce et al. 2016). Such climatic shifts pose a major challenge to pasture productivity, a key resource for livestock. Reduced biomass and declining forage quality may jeopardize traditional grazing systems, increasing production costs and undermining economic sustainability, especially in extensive livestock farms that rely on natural pastures (Carozzi et al. 2022). Understanding the dynamics of herbaceous biomass under different climatic scenarios is crucial for developing sustainable adaptation and management strategies. The present study addresses this issue through an integrated approach that combines modeling based on climatic, edaphic, and hydrological data with fieldwork for the empirical characterization of herbaceous biomass. We selected three study areas representative of different environmental conditions within the Mediterranean environment at Central Iberian Peninsula: Buitrago del Lozoya (northern zone 975 m of altitude, influenced by a mountain climate), Colmenar Viejo (central zone 883 m, in the transition between *dehesa* (open forest pasture) and grassland systems), and Tielmes (southern zone 585 m, with a drier climate and greater agricultural pressure).

The study has the following main objectives: 1) Analyze the evolution of herbaceous biomass in relation to climatic and soil conditions. 2) Develop a predictive model to estimate pasture productivity under different climate change scenarios. 3) Provide information for livestock management and the conservation of herbaceous ecosystems.

Through this multidimensional approach, we aim to contribute to the design of climate change adaptation strategies and the optimization of pasture management, promoting the sustainability of agricultural systems and the conservation of ecosystem services associated with these ecosystems. Additionally, the results may be useful for the formulation of environmental management policies and informed decision-making in territorial planning and biodiversity conservation.

Methods

The study was conducted in three regions within the Community of Madrid, Spain, each selected for their distinct climatic and edaphic characteristics (Figure 1). These sites represent a gradient of environmental conditions, from humid mountain areas to semi-arid agricultural landscapes, allowing for an assessment of pasture biomass response to climate regimes. 1) Buitrago del Lozoya (North): A mountainous area with cooler temperatures, higher rainfall, and deeper soils that enhance drought resilience. 2) Colmenar Viejo (Central): A transitional zone with moderate precipitation and high sensitivity to drought, where land use and grazing influence pasture productivity. 3) Tielmes (South): The driest and warmest site, with shallow soils and low water retention, making it highly vulnerable to climate change impacts.

A process-based biomass simulation model, based on the SIMPAST framework (Etienne et al. 2008), was used to estimate pasture productivity under different climate scenarios. The model integrates climatic and edaphic variables to dynamically assess biomass production over a hydrological year. Climatic inputs include daily precipitation, maximum, minimum, and mean temperatures, as well as solar radiation and potential evapotranspiration, derived from six IPCC AR6 models (IPCC,2023) under four SSP scenarios

(SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5) for 2021–2100, with historical data from 1975–2021 (Kriegler et al., 2014; Riahi et al., 2017). Edaphic factors such as soil water retention, field capacity, wilting point, and effective soil depth were incorporated to evaluate moisture availability and its influence on pasture dynamics.

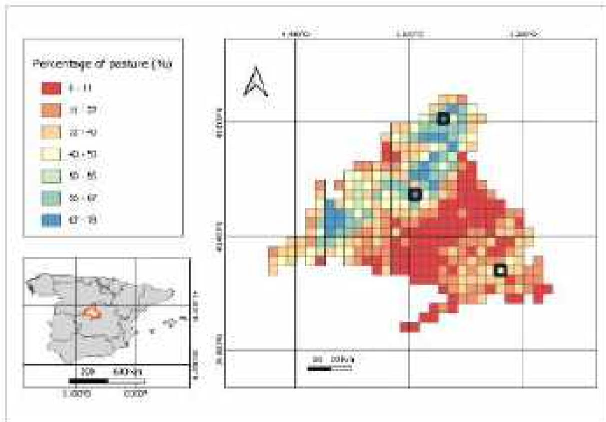

Figure 1. Geographic distribution of pasture percentage per pixel within the study area in the region of Madrid, Spain, derived from SIGPAC data and analyzed using QGIS (black circle).

The model calculates net primary productivity (NPP) and incorporates the leaf area index (LAI) as an indicator of vegetation cover. The hydrological balance is simulated by analyzing interactions between precipitation and soil moisture retention capacity, allowing for the assessment of biomass dynamics under historical and future climate conditions.

Results

Projected climate trends for the Madrid area (Spain) show a significant increase in annual mean temperature across all four SSP scenarios (Figure 2). By 2100, the highest-emission scenario (SSP5-8.5) suggests temperature increases exceeding 4 °C, while even the most optimistic scenario (SSP1-2.6) predicts warming above historical averages. These changes will likely intensify heatwaves and reduce seasonal thermal variability, impacting vegetation cycles and water availability.

Pasture biomass projections reveal strong spatial and temporal variability (Figure 3). The northern region (Buitrago del Lozoya) maintains relatively stable biomass levels due to higher precipitation and deeper soil. The central region (Colmenar Viejo) exhibits greater sensitivity to precipitation fluctuations, with biomass reductions during drought years. In contrast, the southern region (Tielmes) experiences the sharpest decline in biomass availability, highlighting its vulnerability to prolonged dry conditions and rising temperatures.

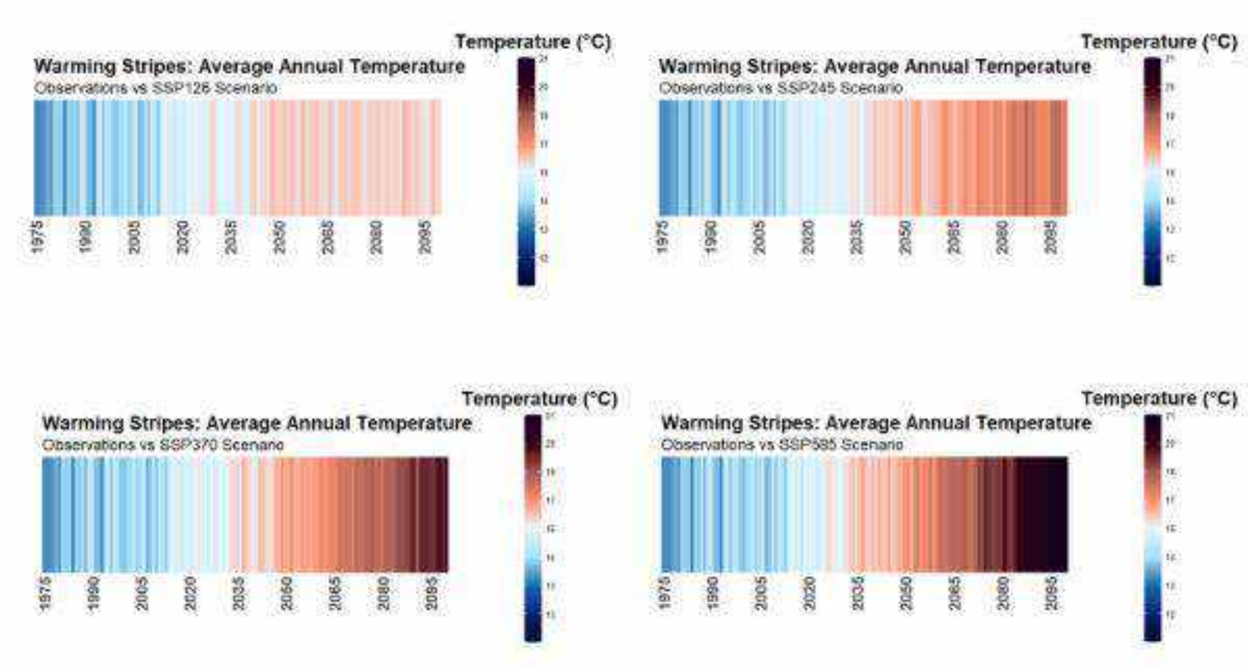

Figure 2. Annual mean temperature trends from 1975 to 2100 across the four SSP scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5) in the region of Madrid, Spain (Central Iberian Peninsula).

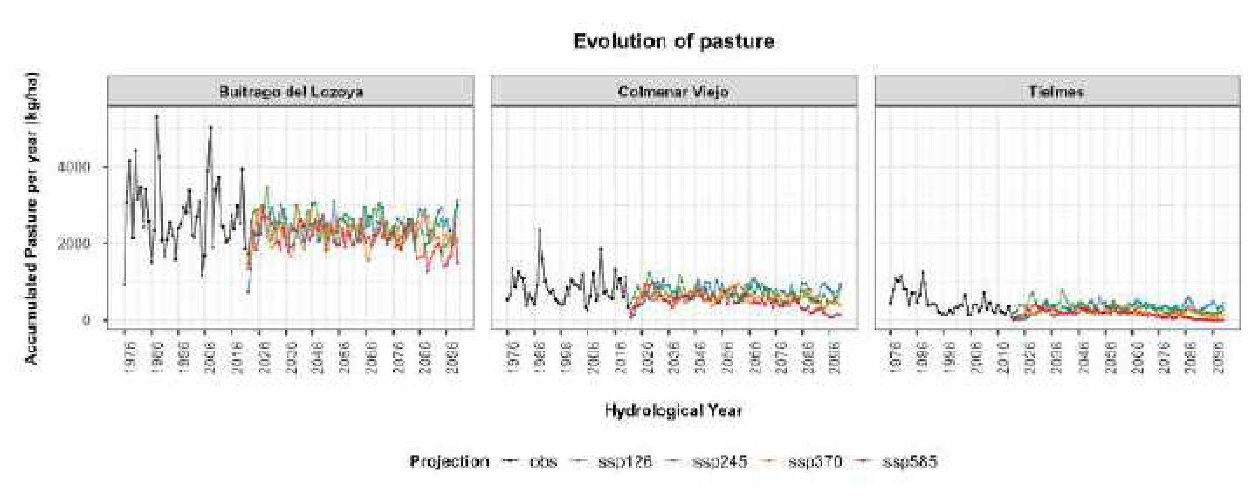

Figure 3. Temporal changes in simulated pasture biomass (dry matter) across the selected grids, showing interannual variability influenced by climate projections (Obs: observed climate; ssp126: SSP1-2.6, ssp245: SSP2-4.5, ssp370: SSP3-7.0, and ssp585 SSP5-8.5 scenarios).

Our results indicate that climate change will significantly affect pasture productivity, particularly in water-limited environments. While higher-altitude areas like Buitrago del Lozoya (North) may retain relatively stable biomass, warmer and drier regions such as Tielmes (South) will likely face severe reductions in forage availability. These findings align with previous studies on Mediterranean grasslands, where increasing aridity reduces primary productivity and alters species composition (Oesterheld et al. 1999; Peñuelas et al. 2007; Wang et al. 2022). This project highlights the importance of land management practices in mitigating productivity loss. Strategies such as adaptive grazing, improved soil conservation, and drought-resistant forage species may help sustain livestock systems under changing climatic conditions.

Conclusions and Implications

This study highlights the potential impacts of climate change on pasture productivity in the Madrid area of Central Spain, emphasizing regional differences in vulnerability. Northern grasslands may remain productive, while central and southern areas could experience substantial biomass reductions, affecting livestock sustainability. These findings underscore the need for adaptive management strategies to mitigate productivity losses and ensure the long-term viability of extensive livestock systems, key for economy and ecosystems. Future steps will include field validation through biomass sampling and species inventories, analysis of extreme events and integration of land management practices into the model as well as stakeholder engagement with local farmers and other land managers.

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Enhancing adaptive capacity to climate-related risks

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How are global megatrends likely to provide opportunities and challenges for Northern Australian rangelands?

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Key words: global megatrends; northern beef industry; cattle industry; Australia

Abstract

Over half of Australia's beef cattle are managed in extensive rangeland systems in the north and are vulnerable to climate challenges, infrastructure and labour limitations, and disruptions to trade. In this paper we consider research and industry viewpoints to explore opportunities for the northern Australian beef industry to ensure a sustainable, productive and profitable future. Our analysis is framed by the following megatrends; (1) adaptation to a **warmer and more variable climate** to protect livelihoods, infrastructure, and quality of life, (2) the **technology revolution and expansion** into northern Australia, providing new solutions to old problems, (3) **geopolitical shifts**, which change trade dynamics, disrupt supply chains, and offer alternative domestic and international markets, (4) the push for **more efficient resource use, with reduced impacts** on animals and the environment driven by changing consumer and market expectations, and (5) changing **regional demographics and human capital constraints**, which limit operational efficiency and social capital. While all megatrends will create some universal magnitude of effect, the unique landscapes and agricultural systems of the northern Australian rangeland system require a tailored, place-based assessment.

Introduction

Northern Australian rangelands encompass the tropical savannas, woodlands, shrublands and grasslands of the Northern Territory, Queensland, and Western Australia. Land use is dominated by cattle production based on unmodified native pastures, with other areas used for conservation, mining, defence, and as designated Indigenous Protected Areas. Livestock production in this region is typified by extensive pastoral properties used for cattle breeding operations and managed by a mix of family-owned and corporate enterprises. Production is orientated towards live-export, with cattle often transported long distances to one of four northern ports, before being shipped to Indonesia, Vietnam and other international destinations. The harshness of the landscape and unreliability of seasonal rainfall on a marginal feedbase is reflected by low livestock growth rates, sub-par reproductive efficiency and high mortality in both breeding stock and calves (McCosker et al, 2023). Complex land tenure rights, a sparse population that limits investment and expansion of infrastructure and historically poor phone and internet connectivity have all contributed to slow development. However, recent advances in technology and shifting overseas markets have the potential to be transformative. In this paper, we explore the influence of global megatrends, and the unique challenges and opportunities they present for northern Australian beef production systems going forward.

Adaptation to a warmer and more variable climate

The climate of northern Australia is characterised by distinct wet (October and April) and dry (May and September) seasons, though total annual rainfall is highly variable between years. There is high certainty that average temperatures and extreme heat events will increase into the future (CSIRO and Bureau of Meteorology, 2015), impacting the productivity and welfare of both livestock and people. Northern Australian cattle production systems are already adapted to hot conditions, with the region currently dominated by tropically-adapted *Bos indicus* breeds and their crosses. However, this region may also experience an increase in the frequency and/or intensity of extreme events such as heatwaves, cyclones, floods and bushfires (CSIRO and Bureau of Meteorology, 2015). These events affect the northern beef industry via impacts on livestock (reduced feed intake, mortalities), landscapes (soil erosion, damage to pastures) and infrastructure (loss of roads, fences, buildings), in turn impacting supply chains and rural communities. In addition, changing climates may be accompanied by biosecurity challenges, with changes in the range of endemic pests and diseases combined with new incursions.

While producers already make tactical decisions such as adjusting herd sizes to cope with harsh conditions and seasonal variability, extreme events are harder to prepare for because they are difficult to predict at local scales (temporally and spatially). There is also often very little that producers can do in advance to mitigate the impacts of these events in such extensive systems. Advice from local and state government agencies focuses on pre-emptively moving livestock out of high-risk areas, but the effectiveness of such approaches relies on having sufficient warning, human resources and capital to move animals, and the existence of safe refuge areas.

The technology revolution and expansion into northern Australia

With such expansive rangeland properties, remote resource monitoring and animal management are almost essential for any measurable improvement in operations and productivity. The commercialisation of connectivity options has borne a strong focus on cloud-supported robotics, the Internet of Things (IoT) and sensors, artificial intelligence (AI) and drone capability as well as renewable energy options for operations such as solar-powered bore pumps. For example, remote monitoring of water resources, feed biomass, and land condition combined with in-field animal weight sensors and monitoring of diet quality via eDNA can support decisions on stocking rates and paddock allocations, which could in turn be facilitated by virtual fencing and the use of drones for mustering. The adoption of such technologies can potentially help to improve animal welfare and productivity and reduce landscape degradation, whilst concurrently reducing human labour resource requirements. As the use of this technology increases, there will likely be changes in animal management protocols, for example the incorporation of drones allowing cattle to be mustered at night when there is a lesser risk of acute heat stress.

At the animal level, IoT and sensors, including water intake sensors, GPS and accelerometer tags and collars for behaviour monitoring provide an opportunity for remote data collection as well as decision-making and treatment at the individual animal level. Machine learning and AI are being used extensively on the developmental phase of product creation, for example as a mechanism to refine algorithms and eliminate arduous video annotation for animal behaviour and health monitoring and is also critical for the proceeding data aggregation step (Tedeschi et al. 2021).

While all purposeful technology can support the goal of informed decision-making, the accumulating breadth of technology options is also creating a clear signal that thoughtful yet simplified data analytics is also needed so that it is understandable, useful and real-time for informed decision-making that is appropriate for current conditions. Commercialised systems that master integration of data types are a necessity given the diverse sensor monitoring for non-confined, extensive rangelands. Development of predictive technologies to support management decision-making will rely on data accrual; however, historical data availability is a limiting factor and data ownership and privacy continue to be challenges.

Geopolitical shifts

As an export dependent nation, global trends provide opportunities and challenges for northern Australian beef. Climate challenges, political tension and conflicts influence price volatility and supply chains. However, an estimated increase in beef consumption over the next decade (in Australia and key live export markets Indonesia and Vietnam; ANZ Group Holdings Limited; MLA 2024) provides confidence in beef export demand. High Australian cattle prices and public animal welfare concerns lead to frequent disruptions in live trade (a cornerstone market for northern beef supply chains) in addition to the risk of trade disruption if Australia loses its disease-free status from lumpy skin disease or foot and mouth. Domestic efforts to improve access to premium market supply chains (EU, Japan) are challenging due limited potential to diversify land use across the pastoral zone both due to inherent land productivity and to restrictive (and inconsistent) State legislated lease terms. A dominant live export market, limited opportunity to diversify the feedbase and sparse road and rail infrastructure, impacted by seasonal cyclones and floods all contribute to a vulnerable northern beef supply chain. Yet half of the Australian beef herd is produced under these conditions. Where land productivity and legislation align pivot irrigation or dryland cropping as well as vertically integrated cattle businesses that move cattle to more fertile regions provided opportunities for diversified trade and access to higher value markets.

The focus of premium markets on sustainability has resulted in declining EU per capita beef consumption and an 8% shrinkage of the EU beef herd (European Union, 2021). Australia's response to welfare breaches has resulted in a 'clean, green beef' ethos underpinned by the Exporter Supply Chain Assurance System (ESCAS) (Windsor 2021). This leadership has encouraged Vietnam to set equivalent welfare standards providing opportunities for trade expansion. Megatrends affecting Brazilian supply chains indicate welfare compliance will be mandatory by 2040 (Malafaia et al. 2021). Australia's commitment to welfare, and the relative sustainability of northern beef production provide opportunities to capitalise on these markets where integrated supply chains allow for feedbase improvement.

As de-globalisation looms, the low tariffs negotiated through Australia's 1980s-2020s Free Trade Agreements (FTAs) are met by similar FTAs negotiated with other nations, increasing competition in export markets. At home, global volatility in key import markets imposes price volatility and supply chain instability on imported minerals (phosphorus and nitrogen from the Middle East, China and Russia). Development of domestic green ammonia plants and circular economy initiatives may provide cost-savings, food security and a sustainability advantage for Australian livestock producers. Potentially northern Australian producers can capitalise on broader megatrends influencing affluent Asians; digitisation of shopping, tailored personal experiences and Gen Z and Alpha as the largest consumer demographic. Could northern beef supply chains capitalise on a direct, personal shopping experience, emerging welfare-based priorities and build brand based relationships in the secure beef markets of Asia?

More efficient resource use, with reduced impacts on animals and the environment

Arguably, as long as grazing is managed to limit its negative impact on the landscape, beef produced in the northern Australian rangelands has the opportunity to be among the most sustainable in the world.

Therefore, northern Australian producers are perfectly placed to capitalise on consumer preference for beef certified for sustainability credentials. To achieve this, measurement and monitoring of biodiversity, natural capital and other sustainability metrics needs to occur, and the marketing of the products needs to be clear and tailored to the market preferences. Whether consumers are willing to pay for sustainable practices or simply demand them as standard is yet to be seen. Furthermore, existing nature-based markets enable producers to gain financially from not only potential price differentiation for sustainable practices, but also directly from implementing practices that reduce carbon emissions/sequester carbon (carbon markets) or improve/protect biodiversity (e.g. Nature Repair market). The northern rangelands are extremely well placed to enter these markets due to large property areas (e.g. average property size in NT in 2010 was >2700 km^2) and naturally high biodiversity due to limited land clearing. Additionally, projects using the Australian Government's savanna burning methodology have been able to earn significant carbon credits, mainly on the Indigenous estate (Edwards et al. 2021), and it is possible that the pastoral industry could also benefit from such schemes in the future.

Improving production efficiency of northern beef systems is also likely to be a focus into the future- particularly regarding identifying and removing non-performing animals, improving the quality of the feedbase and using the land for multiple purposes (e.g. solar farming and beef production using agrivoltaics). As long as stocking rates are maintained or reduced, improved efficiency also has the co-benefits of reduced methane intensity and less impact on the pasture. While the outlook holds promise, improving resource efficiency in remote and dispersed locations has inherent challenges. Additionally, there is increasingly a tension between using the northern rangelands for beef production and other land uses- particularly energy production, and mining for critical minerals. Satisfying the needs of a growing population and their future requirements is likely to put the northern rangelands under pressure.

Changing regional demographics and human capital constraints

In 2020, 76% of people in Australia lived in urban areas (Hill et al. 2021), and this urbanisation of the population is predicted to increase into the future. Attracting and retaining skilled workers in the northern beef industry is currently a challenge, but is potentially an opportunity, particularly for First Nations peoples and remote communities. For example, according to the 2021 census, the percentage of employed people aged ≥15 years in the NT was 76% for non-Indigenous people compared to 28% for Indigenous people (Australian Bureau of Statistics, 2021). However, as Indigenous Business Australia (2023) have said '*Aboriginal people are the most overtrained people in the country and still can't get a job*' and therefore investing in linking talent, training and opportunities is important. As well as attracting and retaining more on-ground staff, the rise of remote working (e.g. working online) is likely to also start to apply in the northern beef industry with the adoption of technologies and remote management opportunities outlined above. Recent climate modelling has suggested that due to rising temperatures, the duration people are able to work outside in northern Australia will be reduced by 20-50% by 2080 in comparison to a 1986-2005 baseline (Hunt et al. 2023). This could increase remote working, as it is likely to affect people's ability to work in the northern rangelands, as well as their desire to live in these conditions.

Conclusions

The global megatrends discussed above provide both opportunities and challenges for Australia's northern beef industry. Access to knowledge and upskilling for livestock producers remains critical for businesses to access new opportunities and compete. Potentially, a review of the varied and complex legislative requirements for diversification needs to be adapted to cover a northern Australian based land system, rather than different and complex rules between arbitrary State borders. This is particularly true where large land holdings span jurisdictions. In summary, future climate challenges will not be insignificant, and primary producers will need access to knowledge, tools, supportive legislation and novel markets to remain competitive in a secure market for animal protein.

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Resistance to water deficits and recovery post-stress of native and naturalized grasses from Campos grasslands

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Key words: forage productivity; adaptative drought management; C3; C4

Abstract

In the context of high and increasing rainfall variability in southern South America, animal production systems in subtropical *Campos* grasslands would benefit from adaptive drought management. To better understand the ability of forage species to cope with, and recover from, water stress episodes of variable intensity, a greenhouse experiment was carried out to evaluate two C3 grasses *(Bromus auleticus, Lolium arundinaceum*) and three C4 grasses (*Andropogon lateralis, Paspalum dilatatum, P. notatum*). To assess resistance to water deficit, plants growing in individual 12-L pots were kept for 52 days at four levels of constant water availability: 10, 30, 50 and 70% of soil field capacity (SFC). To assess the recovery capacity, pots were re-watered and maintained for 42 days at a constant 75% SFC. During the stress phase, the minimum proportion of SFC that allowed maximum forage productivity was lowest in *P. notatum* (39%), intermediate in *P. dilatatum (50%), B. auleticus* (61%) and *A. lateralis* (64%), and highest in *L. arundinaceum* (70%). During the recovery phase, the minimum proportion of SFC from which maximum growth was re-attained was ~30% in all species, except for *P. notatum*, which was able to fully recover even from the 10% SFC treatment. Therefore, species differed in their ability to resist drought, but less so in their capacity to recover post-stress, with the notable exception of *P. notatum*, which exhibited the lowest critical soil moisture for both resistance and recovery. Integrated with information on the potential of each species to stockpile forage, these results could inform the design of adaptative drought management strategies targeted to specific plant communities of the highly diverse *Campos* grassland, so that extensive animal production systems can be effectively buffered from recurrent, frequent, but difficult to predict in their timing and intensity, episodes of water deficits.

Introduction

Water availability is a major factor limiting grasslands productivity in southern South America (Huxman et al. 2004; Rodríguez Palma et al. 2024). Future climate change scenarios are expected to further increase inter- and intra-annual rainfall variability (Grim 2010). Severe droughts sometimes induce large plant mortality, thus decreasing livestock production (Breshears et al. 2016) or increasing supplementation costs (Cazzuli et al. 2024). Therefore, understanding the implications of different rainfall regimes on dominant native and naturalized species of high-diversity *Campos* grasslands is key to adaptive management strategies that help these grasslands resist and recover from drought episodes.

The response of productivity to extreme rainfall variability varies among species (Jentsch et al. 2011), ranging from minor effects to severe declines accompanied by prolonged recovery periods (Breshears et al. 2016). Such variability in grass species' drought resistance (capacity to grow under drought) and drought recovery (production after drought) (Tilman and Downing 1994) depends on grass species attributes and the magnitude, duration, and season of the drought. Since effective plant strategies under drought depend on drought-stress intensity (Lüscher et al. 2022), dominant grasses response (productive response) must be evaluated concerning this climatic driver (drought) at different available water levels.

Soil water availability is a primary factor limiting grassland productivity (Knapp et al. 2002). When soil water availability increases, an increase in forage plant growth is observed. However, this relationship between soil water availability and plant growth has a limit. Once an optimal level of soil water is reached, adding more water may not result in extra plant growth. In this context, different species have different water requirements, so some plants may be more drought-tolerant.

Estimating the impacts of droughts on high-diversity grasslands is challenging due to a limited understanding of the nonlinear responses of plant species to increasing drought conditions (Ingrisch et al 2022), specifically the ability of dominant forage species to cope with and recover from water stress periods of varying intensity. The main hypotheses of this study are: i) water stress periods of variable intensity generate different responses in forage production in five native and naturalized grasses and ii) drought-resistant species exhibit the highest capacity for recovery following water stress periods.

Methods

Experiment Location

The experiment was carried out with potted plants in a glasshouse at the INIA Tacuarembó research station, Uruguay (31°44´19.30´´S, 55°58´41.48´´W). The experiment began on 07/01/2021 and ended on 14/04/2021. The mean air temperature was 24°C in January and 21°C in April, similar to historical averages (24 and 18°C).

Treatments, Experimental phases and Measurements

Two C3 grasses (*Bromus auleticus* and *Lolium arundinaceum* (Schreb.) Darbysh.) and three C4 grasses (*Andropogon lateralis*, *Paspalum dilatatum,* and *Paspalum notatum*) were planted in a 12-L pot (30 cm diameter) three months before the start of the experiment. The soil substrate contained 38 ppm of Bray 1 phosphorus; 0.46 meq/100 g of potassium; 11 % organic matter, 16.6 meq/100 g of calcium and pH=5.8. Furthermore, the equivalent of 40 kg N/ha (urea) and 10 kg P/ha was applied. The soil field capacity (SFC) was calculated as 0% when the substrate was completely dry and 100% at full capacity after 48 hours of free drainage.

Plants were subjected to four constant water availability treatments (10, 30, 50, and 70 % of SFC) for 52 days, from 07/01 to 03/03/2021 (Phase I "resistance"). Then, pots were re-watered to bring them to 100% field capacity for 3 days, and then all the pots were maintained at 75% SFC for 42 days, until 14/04/2021 (Phase II "recovery"). Pots were weighed daily and watered to the required level according to the treatment. The foliage was harvested in all the pots at the beginning of the experiment, at the end of phases I, and II by cutting plants at 2 cm. Fresh shoot mass was weighed and then dried at 60 ºC for 72 hr to determine dry matter concentration.

Experimental design and statistical analysis

Treatments were arranged in a completely randomized design with four replications (pots). Analysis of variance (ANOVA) of forage production was performed for the drought phase and the recovery phase, using the Tuckey method to compare means with a 0.05 significance level.

The relationship between shoot growth and SFC percentage was modelled using nonlinear segmented regression to find threshold SFC percentages for maximal shoot growth of each species (i.e. critical SFC) and estimate the range using the SFC mean +/- two standard errors. Afterwards, to check whether the most resistant grass species has a greater capacity for recovery at different percentages of soil field capacity (SFC) a regression analyses were performed to analyse the relationship between critical SFC and recovery ability, calculated as the relative rate of shoot growth in a specific SFC treatment compared to the 70% SFC treatment. All the statistical analyses were performed with the INFOSTAT program.

Results

Drought resistance

The magnitude of the reduction in grass shoot growth in response to lower water availability in Phase I was species-dependent (Fig. 1). *P. notatum* had higher biomass production than C3 grasses when water was most limiting (10% SFC). During the drought resistance phase, the modelled critical relative moisture content -the minimum percentage of SFC that allows maximum forage productivity- was lowest in *P. notatum* (39%), intermediate in *P. dilatatum (50%), B. auleticus* (61%) and *A. lateralis* (64%), and highest in *L. arundinaceum* (>70%).

Post-drought recovery

An interaction between species and SFC treatment was also identified for biomass production in the recovery phase (Fig. 1). Like in the previous phase (resistance), *P. notatum* had a higher biomass production than C3 grasses after the 10% SFC treatment. However, after 30% SFC treatment, *L. arundinaceum* produced more forage than both species of *Paspalum*, and *B. auleticus* produced more than *P. dilatatum*.

Relationship between drought resistance and recovery phases

Paspalum notatum combined greater drought resistance with better recovery from the most limiting water level (10% SFC) than any other species. In both species of *Paspalum*, forage production in the resistance phase was not related to recovery phase production. However, *L. arundinaceum, B. auleticus,* and *A. lateralis* showed some positive linear relationships between their growth in the resistance phase and during the recovery phase (Table 1) but only for the most extreme drought treatment (10% of SFC). Nonetheless, the water needed to reach the optimal productive level was negatively correlated with subsequent recovery only in the most limiting water level of 10% SFC (Fig. 2).

Table 1. Relationship between forage production at 10% SFC in the moisture stress phase and that grown during post-stress recovery.

Festuca arundinacea	Recovery = 8,22 + (0,28 x Resistance)	(R^2= 0,39; P<0,01)
Bromus auleticus	Recovery = 5,02 + (0,69 x Resistance)	(R^2= 0,56; P<0,01)
Andropogon lateralis	Recovery = 2,66 + (0,72 x Resistance)	(R^2= 0,60; P<0,01)
Paspalum dilatatum	No significant relationship	
Paspalum notatum	No significant relationship	

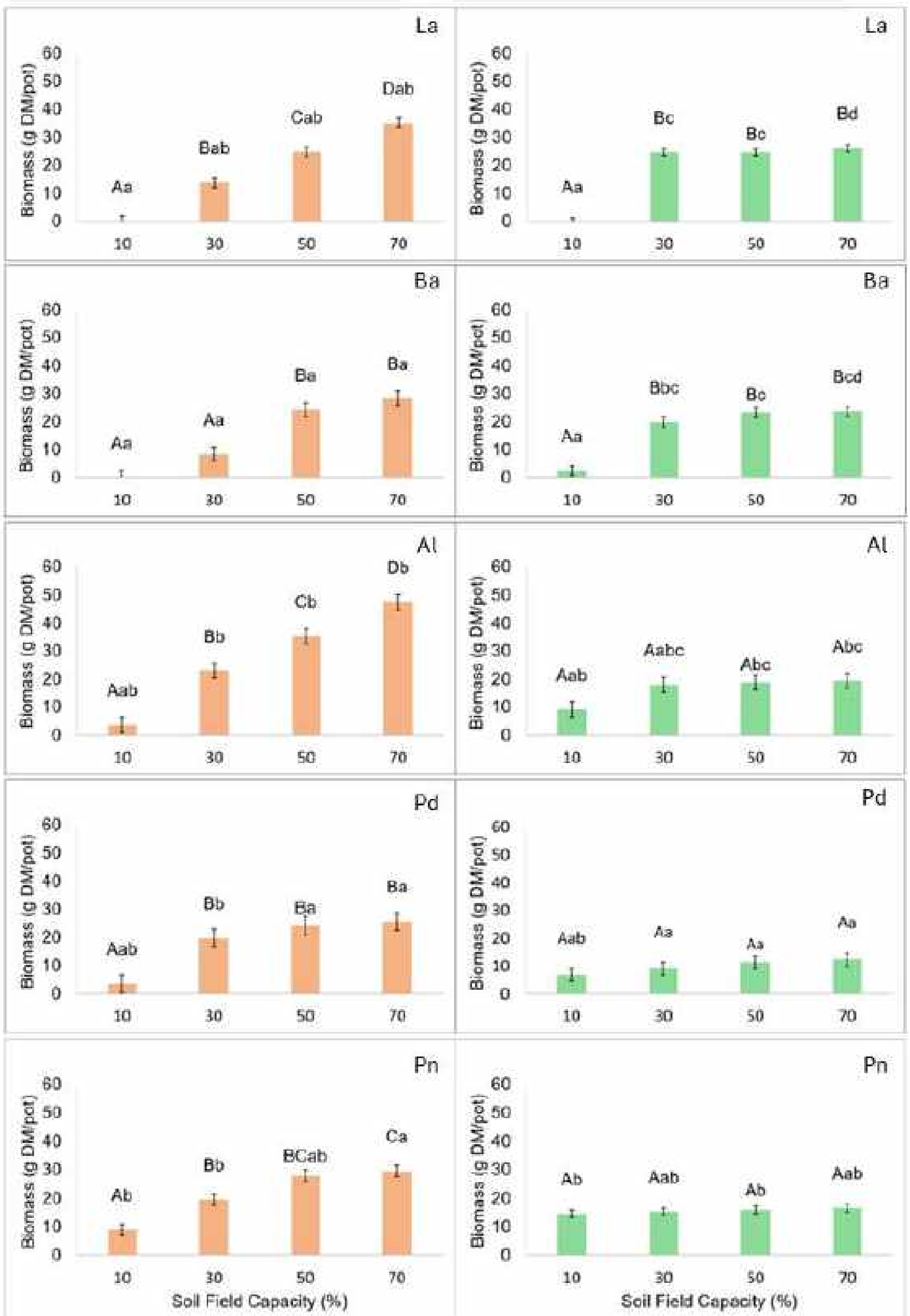

Fig. 1. Resistance (orange) and recovery (green) of forage grasses depending on the soil water content. 100%=Soil Field Capacity (water remaining in soil after 48 hours of drainage) and 0%=dried soil. La (*Lolium arundinaceum)*; Ba (*Bromus auleticus)*; Al (*Andropogon lateralis); Pd* (*Paspalum dilatatum);* Pn (*Paspalum notatum)*. The uppercase letters indicate statistical differences between the different levels of available water (SFC), while the lowercase letters represent the statistical differences between the species assessed for the same level of water in the soil (SFC).

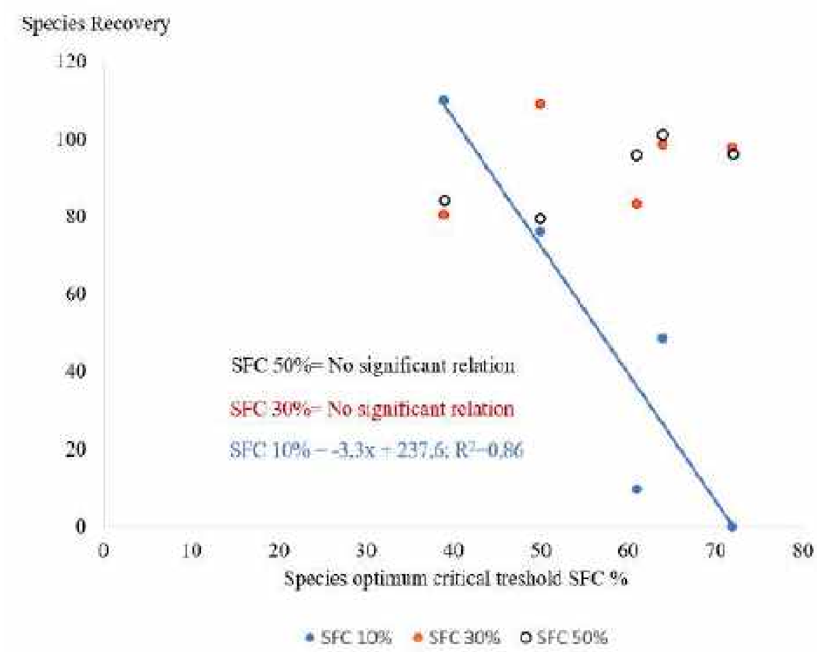

Fig. 2. Relationship between critical grass SFC water threshold and their recovery ability, calculated as the relation of species water threshold (% SFC) with their shoot production recovery in a specific SFC to the 70% SFC treatment.

Discussion
Grass species showed different growth responses to reduced soil moisture, confirming the first hypothesis that drought resistance was species-dependent. The most drought-tolerant species were *P. notatum* (39% SFC) and *P. dilatatum* (50% SFC), while *L. arundinaceum* requires wetter conditions (>70% SFC). Therefore, our results are in line with Mackie et al. (2019) who suggested that drought resistance and recovery are more sensitive to plant community composition than to community productivity. The higher resistance of *P. notatum* to drought and its full productive recovery from low levels of water means that its management in communities where *P. notatum* is dominant is key for stability during drought disturbance. This may explain why *P. notatum* was one of the most frequent species in the *Campos* grasslands (Andrade et al. 2018). However, its advantage in subsequent recovery applies only in the most limiting water conditions, partially confirming the second hypothesis.

The negative relationship between drought recovery and forage production under severe moisture stress may be useful to improve grassland adaptive management decisions in the face of droughts. However, such responses need to be evaluated in grassland communities and integrated with information on the potential of each species to stockpile forage. Such a synthesis would provide a framework for the development of decision support systems to help design adaptative drought management strategies targeted to the specific plant communities present on individual farms in *Campos* grasslands.

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Assessing trigger points for flexible livestock management decisions in rangelands

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Key words: Tactical decisions; climate variability; drought; systems modelling

Abstract

Making management decisions (e.g. livestock sales and feeding) that involve predicting future weather conditions is difficult, especially in variable climates like the southern Australian rangelands. This project assessed tactical management options and trigger points using modelling to inform flexible stocking decisions. The study focused on a lamb production system on chenopod shrubland at Balranald, NSW Australia. A focus group of producers held in March 2019, during a lengthy drought, identified August as a key decision point for adjusting ewe numbers based on available feed. The SGS pasture model was validated for this location against historic vegetation and animal data from grazing studies, the GRASP model and producer experience of feeding periods between 2016 and 2020. Five different grazing systems were modelled. A base system of Merino ewes with lambs sold on 1 November that were containment fed with grain during periods of feed deficit was compared with two flexible options that adjusted livestock numbers in relation to available feed. The first was to reduce ewe numbers by half when green herbage mass was <0.7 t DM/ha in August (Flex ewe). The second was to retain lambs to 50 kg if green herbage mass in October was either > 1.2 t DM/ha (Flex lamb – 1.2) or >0.5 t DM/ha (Flex lamb – 0.5). The fifth system was to retain lambs to 50kg regardless of available feed (50kg lamb). The flexible ewe sale strategy reduced gross margin by 11% from $23.04 to $20.55 (per DSE; based on the long-term carrying capacity), due to lower income in the recovery years. The flexible lamb sale strategies (Flex – 1.2 – $26.76 and Flex – 0.5 – $33.30) were also lower than retaining lambs to 50 kg ($35.84). While modelling suggested lower returns from adjusting stock numbers in relation to trigger points identified by producers, other practical considerations such as experience with supplementary feeding also need to be considered.

Introduction

Livestock production in the southern Australian rangelands faces the difficult challenge of reconciling the dynamic nature of forage availability with relatively stable feed demands from domestic livestock. The region is characterised by high seasonal and annual fluctuations in vegetation growth, primarily driven by climate variability and its consequent impact on soil moisture. While livestock populations remain relatively constant, the underlying feed resources can vary dramatically—sometimes changing by orders of magnitude within a single growing season or across different years. Further, producers may only have contact with livestock 3-4 times per year so have limited opportunities to make and act on decisions.

These environmental uncertainties create significant management challenges for producers. This inherent unpredictability is typically managed by adopting conservative stocking strategies and maintaining lower herbage utilisation rates (Godde *et al.* 2019). This approach helps mitigate risks associated with potential feed shortages, such as the need for expensive supplementary feeding or forced destocking and prevents long-term environmental degradation of rangeland ecosystems (Hacker and McDonald 2021).

However, such conservative management strategies come with substantial economic trade-offs. By limiting stocking rates and forage utilisation, producers potentially sacrifice productive potential and economic returns. The critical question emerges: Can more adaptive management approaches be developed that balance economic efficiency with environmental sustainability and decrease risk?

This research project was designed to address this fundamental challenge in southern Australian rangelands. Its primary objective was to assess tactical decision-making frameworks that could help producers optimise their management strategies to maintain their feedbase whilst maximising economic return. The central hypothesis proposed that introducing more flexible management systems would yield improved financial outcomes while maintaining ecological integrity.

Methods

This study examined different flexible decisions and trigger points to make decisions for a sheep production system at Balranald (34.64 °S, 143.56 °E, average annual rainfall of 317 mm), NSW Australia.

Producer consultation

In March 2019, during an extended drought period, researchers conducted a focus group with local producers to explore their decision-making processes regarding livestock destocking and feeding under variable seasonal conditions. The consultation revealed that August was a critical trigger point for adjusting ewe numbers, with numbers often reduced by half when feed is limited. One producer illustrated this approach, stating, "Rainfall at the end of the winter growth period is the trigger point. Last winter [we] went from 3000 to 1500 ewes because of the rainfall deficit." The discussion also revealed considerable variation in lamb sale strategies, with some producers incorporating regular supplementary feeding while others did not, highlighting the variation in rangeland livestock management in response to environmental uncertainties.

Modelling

The SGS pasture model was used to simulate the rangeland grazing systems. The model has four main modules (water, nutrients, pastures and animals) that are interconnected. The model is hierarchical in structure and most processes are described in terms of a series of fluxes (or, more specifically, flux densities) that have dimensions of amount per unit area per time step (for details see Johnson et al. 2003).

The livestock system modelled was Merino ewes (60 kg reference weight) joined to a terminal sire with lambing on the 1 June and lambs sold on the 1 November or at 50 kg and run at a stocking rate of 0.1 ewes/ha. The pasture in the model was a C4 native grass and subclover (representing naturalised/native annual grasses and forbs) that had been calibrated to be slightly higher than ground level herbage to account for browse from perennial shrubs (e.g. *Atriplex spp.*; based on data from Wilson *et al.* 1969). The soil used had low hydraulic conductivity and low organic matter. Long Paddock weather data were used for Balranald (https://www.longpaddock.qld.gov.au/silo/). Since this area has a low level of trees, the tree level was set at 30% to account for the natural patchiness of semi-arid rangelands, which concentrate and retain resources in fertile patches that are interspersed with bare areas. Further validation of seasonal conditions was achieved using GRASP (Rickert *et al.* 2000), a pasture growth model commonly used in rangelands. Model output from 2016 to 2020 was presented to producers to confirm that predicted feeding periods matched their experience. The simulation was run for the 1910 to 2019 production years.

Flexible decisions

The base system was as described above, with all ewes retained and supplemented with grain as required in a drought feedlot. Two flexible decision scenarios were simulated; 1) adjusting ewe numbers, with half ewes sold when green herbage mass in August is <0.7 t DM/ha (flex ewe) and 2) adjusting sale time of lambs in the base system, by retaining lambs to 50 kg when green herbage mass in October is >1.2 t DM/ha (flex lamb – 1.2) or is >0.5 t DM/ha (flex lamb – 0.5) or selling on 1 November when not. A final scenario retained lambs until 50 kg regardless of herbage mass (50kg lamb).

Gross margin and analysis

A gross margin analysis was undertaken using the biophysical model output with costs and prices from NSW DPI 2020 gross margins (https://www.dpi.nsw.gov.au/agriculture/budgets/livestock). The sheep prices and feed grain prices were assessed against High, Medium and Low CPI-adjusted prices for the last 20 years. The sheep meat and the feed grain prices were based approximately on the 9th decile (High; lamb AUS$7.20 /kg cwt), average (Medium; lamb AUS$5.00 /kg cwt) and 1st decile (Low; lamb AUS$3.00 /kg cwt) years. The gross margins per DSE are reported, based on the long-term average DSE capacity of the system (rather than DSEs in a particular year). As the model feeds to meet animal requirements, differences in profitability are primarily driven by the cost of supplementary feeding rather than production differences. All analyses were performed using ANOVA in Genstat (22nd edition).

Results

Developing trigger points

The number of days of confinement feeding that occurred from 1 August onwards for 12 months was assessed against average green herbage mass in August (Fig. 1a). In 9% of instances there was feeding for >150 days and this always occurred when green herbage mass was below 0.7 t DM/ha in August. There was also a relationship between average October green herbage mass and average per head supplement intake, with high levels of feeding only occurring below 1.2 t green DM/ha (Fig. 1b).

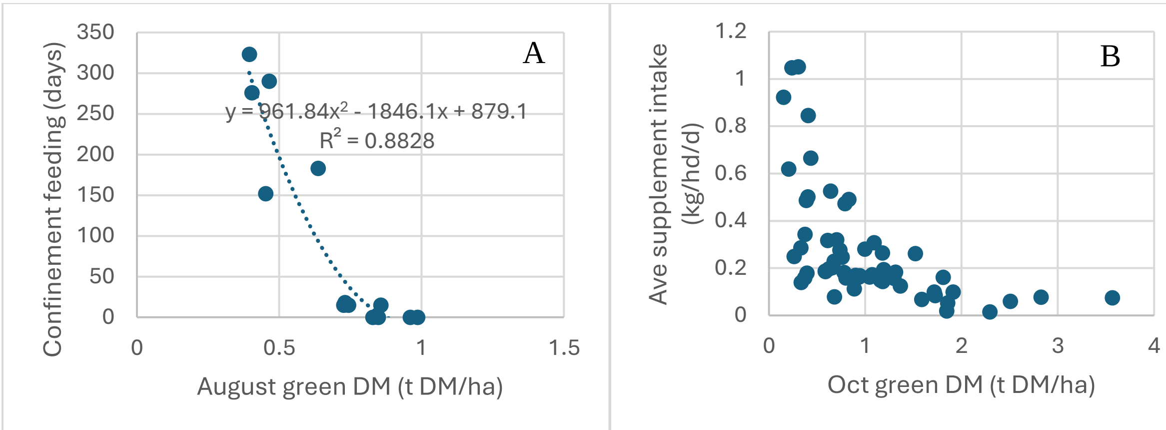

Figure 1. a) The green herbage mass in August (instances where green herbage mass was < 1 t DM/ha) compared to the average days of confinement feeding over the following 12 months. b) October green herbage mass and average per head supplement intake.

Flexible decisions

Flexible ewe numbers did not greatly influence gross margin compared to the base system. On average the base system was $2.49/DSE more profitable (P < 0.001; Table 1) with a lower CV (90% v 113%). There was an interaction between sheep price and the difference between the flex ewe and base system gross margins (P < 0.001). At a moderate sheep price there was no difference between selling or retaining ewes, while there were benefits to the base system at the high and low sheep prices.

In the year the flex ewes were destocked there was no difference in gross margin when compared with the base system, but in the following year there was a higher gross margin for the base system than for the flex ewe system (P<0.001).

Under all price and feed scenarios, the more often lambs could be retained to 50 kg, the greater the average profitability (Table 1) and the lower the CV (Flex lamb - 1.2 – 89% Flex lamb - 0.5 – 78% 50 kg lamb – 69%). Even with significantly increased supplementary feeding below 0.5 t DM/ha of green herbage mass, there was still an advantage in retaining lambs to 50 kg as supplementary feeding was required for a relatively short period of time (2 months) and increased the value of lambs.

Discussion

The research revealed nuanced complexities in livestock management strategies during poor seasonal conditions. Reducing ewe numbers did not consistently provide the expected financial advantages initially anticipated by producers. While selling ewes generated additional income and reduced feeding costs in the first year, the strategy's effectiveness was compromised by instances where ewes were purchased back within a month, negatively impacting overall profitability. Even excluding these short-term repurchases, the financial benefits remained marginal. In the second year, the flexible ewe sale approach encountered increased repurchase costs and lower lambing rates due to delayed rejoining, further diminishing its comparative advantage. The analysis suggested that a more gradual, staged approach to selling ewes might offer greater operational flexibility.

Many rangeland livestock producers lack experience, specialised infrastructure or labour resources for confinement feeding. In these instances, selling livestock may be a seemingly lower risk management option, despite generating slightly lower returns. The modelling, while quantifying risks, potentially underestimated complexities such as animal health considerations associated with prolonged feeding. The research also identified an alternative adaptation strategy: growing lambs to heavier weights when feed was adequate, which could help offset increased drought-related expenses and price differentials. Confinement feeding to the target sale weight of 50kg was the most profitable strategy and had the lowest risk.

The study's assumptions included access to confinement feeding infrastructure, recognising that paddock feeding could cause significant vegetation damage. Any substantial infrastructure investment would require a thorough return-on-investment assessment. Moreover, the researchers acknowledged the model's limitations, emphasising that the identified herbage mass thresholds would likely vary across individual farms, particularly in rangeland systems where saltbush browsing contributes significantly to feed availability under low rainfall conditions.

This study reveals that while flexible decision-making strategies may appear promising, their advantages were not conclusively demonstrated under the cost and price assumptions examined. The economic benefits of flexible decision making may have been understated without considering the potential additional labour and infrastructure costs associated with confinement feeding. Recognizing that modelling inherently simplifies complex real-world scenarios, the nuanced insights of experienced managers could potentially reveal subtleties and opportunities that were not captured by this analysis. Nevertheless, the research identified a clear advantage in strategically feeding lambs to a target weight across all seasonal conditions, which consistently demonstrated improved economic returns, with lowered risk.

Table 1. Average gross margin per DSE (long-term average) for different management treatments, sheep prices and grain prices. The management treatments included: 1) Base system - all ewes retained, lambs sold 1 November; 2) Flex ewe – ewes reduced by half when August green DM <0.7 t DM/ha, lambs sold on 1 November; 3) Flex lamb - 1.2 - all ewes retained, lambs retained to 50 kg when October green DM >1.2 t/ha; 4) Flex lamb – 0.5 - all ewes retained, lambs retained to 50 kg when October green DM >0.5 t/ha; and 5) 50 kg lamb: all ewes retained and lambs retained to 50 kg. High (9th decile; or based on 2020), Medium (average) and Low (1st decile) sheep prices CPI adjusted over 20 years. High (9th decile; or based on 2020), Medium (average) and Low 1st decile) feed grain prices CPI adjusted over 20 years. P values and least significant difference (P<0.05) are presented.

System		Treatments					lsd	P-value
		Base	*Flex ewe*	*Flex lamb - 1.2*	*Flex lamb - 0.5*	*50kg lamb*		
Management		$23.04	$20.55	$26.76	$33.30	$35.84	$0.51	P<0.001
		High		*Medium*		*Low*		
	Sheep price	$48.82		$26.63		$8.24	$0.40	P<0.001
		High		*Medium*		*Low*		
	Feed grain	$21.34		$28.29		$30.36	$0.40	P<0.001
Management	**Sheep price**	*Base*	*Flex ewe*	*Flex lamb - 1.2*	*Flex lamb - 0.5*	*50kg lamb*		
	High	$41.34	$40.00	$46.64	$56.09	$60.02	$0.89	P<0.001
	Medium	$21.52	$21.05	$25.13	$31.50	$33.95		
	Low	$6.27	$0.61	$8.49	$12.31	$13.54		

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Resilient livelihoods: re-examining mobility social solidarity for climate change adaptation in east Africa's drylands.

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Key Words: Resilience; social protection; mobility and safety net

Abstract

The Horn of Africa has recently faced one of the worst droughts in over forty years, resulting in the death of nearly 11 million livestock, displacement, and loss of livelihoods. The drought condition is exacerbated by the compounding structural conditions arising from protracted conflict, marginalization, malnutrition, disease, and food insecurity. Notwithstanding these challenges, pastoral livelihood has persisted and often thrived due to adaptive practices, such as strategic mobility, livestock diversification, intensifying income portfolios, and investing in solidarity relationships and external support. Owing to the proliferation of transport, communication, and mobile money transactions, including in the remote pastoral villages in Northern Kenya's drylands, the adaptive capacities of the pastoralists to share information, transport produce, and engage with a growing market have improved.

The customary social solidarity and redistributive practices through moral economy have rekindled, thanks to the connectivity to urban and diaspora communities. Drawing on ethnographic data collected between 2018 and 2024, this research re-examines social solidarities in enhancing pastoralists' capacity to withstand and transform their livelihoods in response to climate shocks. In a context characterized by a lack of financial services, restricted mobility, and limited government support, local solidarity and redistribution provide continuous access to resources, including labour and cash, to support livelihoods. The reliance on a social solidarity network allows for a more agile and timely response, not only to co-variate shocks but also to idiosyncratic pressures arising from everyday calamities. However, such practices remain unrecognized and sometimes undermined by the mainstream social provisioning, cash transfers and relief aid that provide inflexible finance with sedentary bias without considering the changing pastoral context and adaptive practices. The findings will contribute to the recent approaches to link humanitarian and development action with local resilience-enhancing practices.

Introduction

Pastoralism has been persisting in the Horn of Africa despite multiple indications that pastoralism is under pressure and needs to be replaced by alternative livelihoods. Pastoralists have often been blamed for causing desertification and keeping livestock beyond the land's carrying capacity (Hardin, 1968). These assumptions led to agricultural and environmental policies and investments that promoted forced sedentarization, large-scale irrigation and land grabbing for nature conservation, undermining pastoralists' mobility (Behnke and Kerven, 2013; Eriksen *et al*., 2021). Although pastoral drylands are predisposed to multiple shocks, including climatic-induced drought, floods, animal diseases and other social instability, the livelihoods are sustainable. Pastoralism is a viable livelihood suited to variable and non-equilibrium environments (Krätli *et al*., 2013). Still, pastoral development has often remained in classic thinking that sees pastoralism as backward and vulnerable in constant needs. This paper examines how external interventions such as social protection and livestock insurance intersect with local social solidarity in pastoral drylands. Can social protection from above (external interventions) be connected to pastoralists' solidarity networks to improve livelihoods in the face of multiple shocks and stresses?

The recurrent disasters in the Horn of Africa, including drought, compounded by protracted conflict, political instability, and food insecurity, have attracted manifold interventions, including humanitarian and development support. Humanitarian assistance includes emergency food aid, water and sanitation and cash assistance. In contrast, development response includes rangeland rehabilitation through re-seeding, market infrastructure development, and projects that support diversification out of pastoralism (see Mohamed et al., 2025). Following the 2011 famine in Somalia and subsequent severe drought in the greater Horn, countries in this region adopted resilient strategies through IGAD Drought Disaster Resilience and Sustainability Initiatives (IDDIRSI) (see IGAD, 2013). Countries domesticated IDDIRSI through country-specific programming, and robust drought management institutions emerged, including Kenya's National Drought Management Authority (NDMA). Resilience building later topped the national agenda for drought response (Hargreaves et al., 2012). The focus of resilience-building initiatives included market infrastructure development, rehabilitation of water systems and investment in social protection, specifically cash transfers and livestock insurance, as a route to de-risking pastoral settings (Lind *et al*., 2022; Johnson *et al*., 2023).

In Kenya, the Hunger Safety Net Programme (HSNP) provides unconditional cash transfers of US$27 to vulnerable households across eight pastoral counties every two months. In Ethiopia, the Productive Safety Net Program provides cash or food to vulnerable populations against public works or unconditional cash to more vulnerable households. Later, linked to protecting livestock assets, Index-based Livestock Insurance (IBLI), grounded on statistical analysis and modelling of vegetation index, emerged as a form of state-private sector-led intervention (Bageant and Barrett 2017). All three forms of social assistance (HSNP, PSNP, and IBLI) have predictive and targeting mechanisms that identify households based on geographical region, vulnerability status and individualized contributions to premium, often ignoring the predominant characteristics of pastoral societies and knowledge (Derbyshire et al., 2024). Although these social assistances have contributed to household-level food security, the coverage is limited to a few households. It does not provide adequate long-term resources for herd reconstruction post-disaster.

On the other hand, pastoralists have relied on different forms of informal social solidarities, some founded on cultural norms and values, while others rooted in religious obligations (Mohamed, 2023). Among the pastoralists in Northern Kenya, these practices are sometimes called' moral economies'-a redistributive practice that helps pastoralists respond to a crisis. Such practices can be institutionalized redistribution, labour sharing, and the moral economy of diversification (see Mohamed 2022) for a broader overview of the concept. Examining the changes and continuities of the moral economy through time (between 1975 and 2020), space (rural-urban) setting and within generations (young, wealthy and old), Mohamed highlighted that such informal social solidarity remains essential and has been modified by the dynamic social, technological and market transformation in the drylands. Mohamed noted that the moral economies in near urban areas and remote areas differed. In remote areas with limited infrastructure and weak government support, pastoralists invest primarily in comradeship, reciprocal labour exchange and redistribution. In contrast, pastoralists near urban centres invest more in diverse economic relationships and saving groups.

In the ensuing section, I present the methods used for data collection, examine both formal and informal social protection and highlight its role in helping pastoralists respond to different crises.

Methods

This study is based on qualitative ethnographic research conducted between 2018 and 2024 among the pastoralists in Northern Kenya's Marsabit and Isiolo Counties. It combines data collected for different but related research on pastoralists' livelihoods, resilience, and the evolving social safety nets in responding to various shocks and crises. Among these projects are the politics of social protection in Kenya undertaken through the Effective States and Inclusive Development (ESID) project at Manchester University. It also largely emerged from the author's PhD research within the Pastoralism, Resilience and Uncertainty (PASTREs) programme in Northern Kenya, which explored social safety net and the moral economies among the diverse pastoralist's social groups. It also drew on an ongoing qualitative postdoctoral research that examines the nexus between humanitarian aid and resilience programmes in the Horn of Africa in managing crisis, using institutional-based interviews and stakeholder workshops.

The data is also drawn from various policy convening and discussions examining the disconnect between pastoralism and social protection. Secondary data from academic, conferences and policy papers were used to guide the discussion. The data is analyzed thematically, comparing the pastoralist's social security with the conventional social assistance in the Drylands of Eastern Africa.

Contrasting social protection and the pastoralist's social solidarities

a. **Pastoralists social solidarity**

Pastoralists have traditionally managed different forms of crisis within the variable and erratic drylands and mountainous regions of the world. Among the most notable practices are movement to relatively better-resourced areas for adaptive utilization of water, pasture and security. This movement sometimes entails splitting livestock into different categories, the milk animal, weak, dry and young (Dahl, 1979; Mohamed, 2022). Labour organization is essential to enable spatial utilization of the resources and manage different animal needs. Owing to the various seasons of plenty and scarcity, sharing resources among families, neighbours, clans, and religious ties is a central survival strategy (Mohamed, 2023). This redistribution strengthens social relations among the groups but also ensures resources are accessed at differing times, primarily due to the uncertain nature of production. Such sharing is reinforced by religious and cultural norms embedded in daily practices and shown through sayings, such as a Borana proverb, '*Ollomaf duudaan ejjaani'* (we could only stand because of our neighbours and our backbone) (See Mohamed, 2022).

In a study that examined 'resilience from below', we mapped critical networks and forms of solidarity that people turn to in a time of crisis (Mohamed et al., 2023). We found herders at the centre of these networks, but they must also link with other motorcycle riders to transport goods, deliver medicines and scout for safe grazing. They also rely on mobile money agents that provide cash for urgent needs, to purchase medicine and animal feeds. The agrovet dealers offer advice on animal disease and loan medicines. At the same time, a livestock market broker links the herders to the market and provides the herd owners with upfront cash to manage different needs. At the heart of these is also redistribution and sharing of resources, especially herders pulling labour to reduce the high cost of livestock management and exchanging animals for milk access. All these essential services are accessed through mutual relationships and trust. It is often based on flexible, reliable and attuned to different needs, but is not equally distributed among the pastoralists.

b. Livestock Insurance system

The index-based livestock insurance (IBLI) has recently emerged as a ‘de-risking’ tool for individual protection against drought peril. IBLI has been scaled in Kenya’s ASAL counties through the Kenya Livestock Insurance Programme (KLIP) in the early 2000s as a form of private-public partnership and involved international research institutions, the World Bank and the government (see Fava *et al*., 2021). The insurance systems are designed based on the correlation between rainfall distribution and pasture availability through a forecasted Normalized Difference Vegetation Index (NDVI). The assumption is that a payout is given to the affected premium holders whenever pasture levels reach certain thresholds (Johnson *et al*., 2023). The new De-risking and Value Enhancement (DRIVE), a regional livestock insurance programme, has been scaled in the Horn of Africa to enhance pastoralists' access to innovative climate risk financing and boost disaster resilience. But who does insurance benefit, and for how long?

A study by Taye (2022) challenged key assumptions in insurance and revealed that drought is not a singular peril that affects a singular area but a process involving constant livestock mobility. Its risks are experienced and perceived differently, depending on wealth and gender. The study noted that livestock insurance is mainly utilised by wealthier male herd owners, with others excluded. Bageant and Barrett 2017 have also cautioned against the potential gendered exclusion of IBLI owing to the paternalistic culture in most pastoral areas. Insurance tools are based on continuous data collection, which, if well-coordinated with the existing early warning institutions, might prove effective but remain costly. IBLI has recently adopted a bundled approach, and the policy is tied to other services like veterinary and feed support (Banerjee et al., 2024) to increase policy uptake among pastoralists. There is a potential for livestock insurance to prevent distress sales and improve food security. The challenge remains on how to sustain such a costly investment for the long-term, protect families from falling back into poverty and whether insurance has the potential to survive outside government subsidy.

c. Social protection for humanitarian assistance

Uganda’s social assistance is primarily implemented by the humanitarian agencies through disaster risk financing following government withdrawal linked to the structural adjustment programmes of the 1980s. Cash transfers are tied to workforce and feeding programmes to protect vulnerable households during emergencies. Third Northern Uganda Social Action Fund (NUSAF), a disaster risk finance safety net programme supported World Bank, provides labour-intensive public works after a disaster. NUSAF has contributed to short-term household food security during disasters but promoted sedentarization and dependency among the beneficiaries, undermining productive mobility (Caravani, 2024). In Libya, the Government created the Zakat Fund, which was co-financed by the national government and local religious leaders and distributed by young volunteers. Caravani et al., 2021 highlighted that the Zakat fund, through its robust delivery mode, has delivered effective aid in line with social and moral obligations and revealed a high level of accountability in a politically unstable state.

Both Libya and Uganda’s social assistance are forms of disaster risk financing, but the mode of delivery has shown a significant degree of effectiveness. Trust and accountability are improved when delivered through local systems and capitalizing on existing infrastructure such as Zakat. On the contrary, conventional humanitarian and social assistance is often forward with fixed plans that guide humanitarian response and is less adaptable to pastoralists' planning and response to shocks.

Conclusion

Social protection and insurance in pastoral areas potentially improve short-term food crises; they are not enhancing sustainable food security nor improving long-term livelihoods due to their short-termism and crisis-driven intervention. These programmes sometimes disrupt pastoral systems by creating perversive incentives, mainly in sedentary camps near urban centres and operate in parallel to pastoralists' social solidarities. The disconnect between these forms of assistance can be summed into four: first, properties and assets are not individualized but collectively owned through large family alliances and networks, and individual policy holding is parallel to pastoral systems. Secondly, crisis response requires collective efforts for safety and strengthening labour relations for livestock management and future security. Thirdly, formal assistance is often tied to quotas, fixed amounts and predictive targeting, with high chances of excluding eligible households. Such fixed targeting does not consider dynamic commodity prices that undermine people's purchasing power. Moreso, it needs to attune to pastoralists' mobile context and access to infrastructure as the experiences of pastoralists in remote and urban connected areas are much different (See Mohamed 2022).

Finally, overlapping social provisioning, especially around severe drought, creates confusion for pastoralists but also for government entities as well. For instance, some insurance is subsidized, and others are not, while some cash transfers are upscaled in crisis time and reduced in lean seasons.

As the Horn of Africa grapples with poly-crisis, climate change, conflict and structural problems, bringing external and local assistance together is essential; otherwise, the longstanding disaster and emergency response will continue, and the most anticipated resilience will not be built. Both insurance and social protection must go beyond pro-poor emergency assistance limited to the availability of funding to supporting existing relational and networked solidarities that strengthen continued food security and long-term resilience. For social protection to be adequate, it must capitalize on linking public-private partnerships, while centring community practices. Future studies should explore how formal social protection crowd out informal social assistance and ways to align the two systems better.

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Intersecting risks for rangelands in Asia, Africa and the Middle East

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Impacts of covid-19 lockdown measures on pastoralism on the Tibetan plateau: risk analysis of pastoralism under increasing marketization

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Key words: Pastoralism; COVID-19; Marketization; Risks; Tibetan Plateau

Abstract

With the animal husbandry production transformed from subsistent to commercial, the marketization in China pastoral areas has been increasingly developed. It is characterized by increasing dependency on fodder purchase, pasture lease, microcredit, and strategic livestock sale in response to market fluctuations. Marketization is a double-edged sword, offering both opportunities and challenges. However, the mechanisms leading to negative outcomes, especially in pastoral areas, have been understudied. The COVID-19 pandemic and subsequent lockdowns provide a natural experiment to understand the impacts of sudden shocks on marketized pastoralism. Here we examine the lockdowns' impacts on herders' daily life and livestock production in two counties with different marketization degree on Tibetan Plateau, using data from semi-structured interviews and field surveys conducted from December 2022 to August 2023. We find that the lockdowns' effects on herders' daily life and livestock production, revealing a direct link between market engagement and vulnerability of facing lockdown. This vulnerability stems from lacking local risk-management institutions through the nascent marketization in Tibetan pastoral areas. The replacement of traditional uncertainty management by market mechanisms has also amplified market risks. Therefore, we recommend enhancing herders' involvement in designing markets to reduce risks and integrating traditional pasture knowledge with market mechanisms to build a more resilient and sustainable pastoral economy.

Introduction

The pastoral rangeland is a complex nexus of social, economic, and ecological systems. Over millennia, the interplay between human activities and the natural rangeland ecosystem has culminated in an intricate and inseparable triadic system of "grass—livestock–humans".Pastoralism–the extensive use of rangelands through mobile livestock—is a vital livelihood practice globally（Scoones and Nori, 2023）. Today, rangelands are home to billions of people, providing food that feeds us. Rangelands are vast and diverse, covering over half of our planet’s land（ILRI et al., 2021）. This system delivers key ecosystem services and contributes to landscape functionality, thereby benefits a broader demographic (Hoffmann et al., 2014).

Pastoralism has encountered risks from natural disasters such as droughts, heavy snow, and storms, yet the nomadic practices rooted in traditional customs have demonstrated resilience and adaptability. However, nowadays, herders confront a wider spectrum of risks and uncertainties, which are caused by structural shifts within global political and economic spheres, including land acquisition and marketization as well as climate change (Scoones and Nori, 2023). In China's pastoral regions, along with the privatization of livestock ownership and rangeland management rights, marketization mechanism has been increasingly applied to cope with the risks and uncertainties, rather than the traditional nomadic practices. . Consequently, the livestock production and herders' livelihoods have been becoming more market-dependent (Dalingtai et al., 2010; Gongbuzeren, 2019). The dynamics of pastoralism under marketization needs to be in-depth studied..

Following the emergence of COVID-19 in China in December 2019, the pandemic outbroke and spread across the nation. Consequently lockdown was taken as the main measure to control the pandemic in China in the next 3 years until the official lifting on December 5, 2022, although the stringency and timing of lockdown varied by regions. For herders on the Tibetan Plateau, the primary lockdown period was from June 2022 to the early December 2022, which lasted around half year. The COVID-19 crisis presents a unique opportunity to re-evaluate the human-environment relationship. Additionally, the lockdown provides a natural experiment to study the impacts of sudden external shocks on pastoralism under a marketized context.

Current researches related to the impacts of the COVID-19 pandemic on pastoralism mainly focus on two aspects. Firstly, some studies examined pastoral health conditions and disease prevention from health and safety perspectives, proposing comprehensive public health measures such as the "One Health approach" (Egeru et al., 2020; Elsevier, 2020; Griffith et al., 2020; Griffith et al., 2021). Secondly, by rapid surveys and interviews during the pandemic, scholars investigated the immediate and direct effects of the lockdown on herders' lives(Gelgelo and Tsedu, 2022), focusing on human and livestock mobility(Simula G, et al.,2020; Gelgelo and Tsedu, 2022), livestock product sales(Ilukor J et al., 2022;), children education(Simula G, et al.,2020;), and herders' coping strategies(Maryam R et al., 2020). These studies underscored the flexibility, innovation, and resilience of herders in the face of restrictions of lockdown (Simula G et al., 2020; Simula G, 2023; Joana et al., 2023). However, the lockdown's impacts on pastoralism transcends regional and temporal boundaries, affecting not only the immediate and local system but also continuous and broader ones, particularly in the context of increasing marketization.

In this paper, taking two pastoral counties with varying degrees of marketization on the Tibetan Plateau as case study sites, we assess the impacts of the COVID-19 lockdown on herders' lives and livestock production, including both immediate and post-pandemic impacts. By using comparative analysis, we evaluate the lockdown's impacts on these areas, and explore the the causes behind the different outcomes from the perspective of institutional risks

The marginal contributions of this article include two aspects. First, in addition to the immediate impacts, our studies report the subsequent impacts on post-pandemic pastoralism. Second, we report the new challenges that market and credit brings to pastoralism, which are often considered effective ways to avoid or mitigate risks caused by climate or natural disasters (Lu, et al., 2022). We suggest that increasing herders' participation in market design to mitigate risks and integrating traditional pasture knowledge with market mechanisms to foster a more resilient and sustainable pastoral economy.

Methods

1. Case areas

This study examines two case areas on the Tibetan Plateau: Qilian County within the Haibei Tibetan Autonomous Prefecture of Qinghai Province, and Maqu County within the Gannan Tibetan Autonomous Prefecture of Gansu Province (Figure 1). Both regions are characterized by their high-altitude pastoral settings. Qilian County is nestled in the central part of the Qilian Mountains in northeastern Qinghai, whereas Maqu County is positioned on the eastern periphery of the Tibetan Plateau. Despite their similarities in altitude, topography, and climate, the two areas exhibit distinct marketization levels, with livestock husbandry being the principal economic activity for the local herders. Yak, Tibetan sheep, and a modest number of horses constitute the primary livestock, and the herder demographic is predominantly Tibetan.

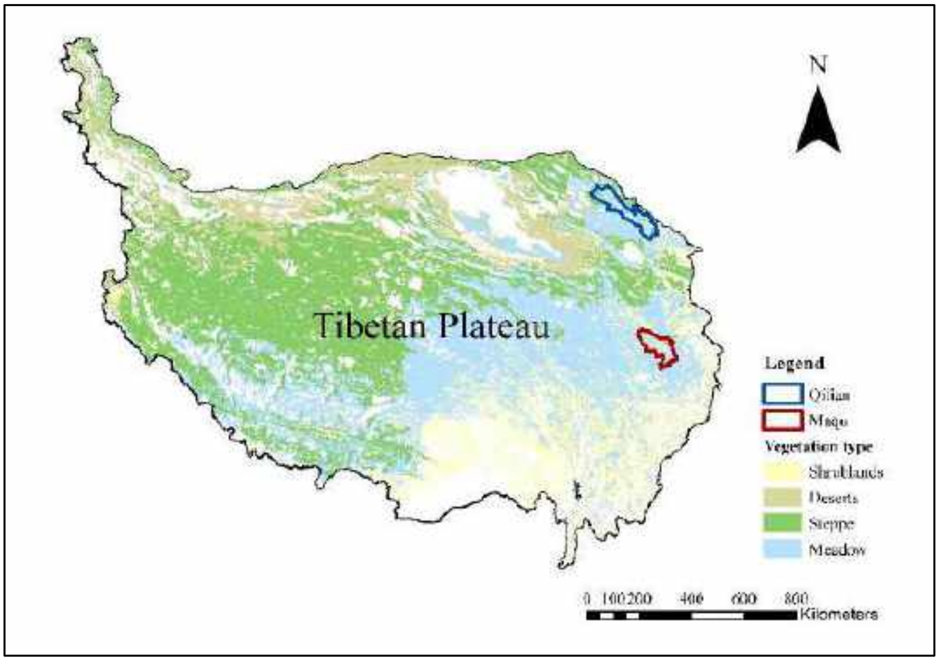

Figure 1. Map of the study case areas, Qilian and Maqu

2. Data collection

The research methodologies encompassed in-depth interviews and the administration of questionnaires, with key informants including village authorities, and the survey was directed at herder households within the villages. The in-depth interviews with principal stakeholders delved into lockdown protocols, overall impacts, coping strategies, and timelines, which shaped the questionnaire's content and pinpointed potential variables of impact. Employing a snowball sampling technique, one village per case area was selected for the survey, yielding data from 51 households: 20 from H Village in Qilian County and 31 from G Village in Maqu County. The study captured the strict lockdown period from June to December 2022, with the nationwide lockdown being rescinded on December 7, 2022. Data was collected for one year prior to and one year following the lockdown, encompassing 2021 (pre-pandemic), 2022 (pandemic period), and 2023 (post-pandemic), facilitating a comparative analysis. However, certain variables, such as loans livestock mortality and reproduction exhibited delayed effects: the majority of herders procured bank loans in early 2023 to meet heightened living and production expenses, suggesting that 2023 loan data is indicative of the 2022 pandemic impacts, while 2022 loan data reflects pre-pandemic cash needs from 2021. Similarly, despite the stringent lockdown measures being implemented in the autumn of 2022, the production impact leading to increased livestock mortality and decreased reproductive rate occurred in the following spring. Therefore, the data for 2023 represents the effects of the 2022 lockdown, while the data for 2022 represents a normal year before the lockdown. Other variables align with this pattern: 2022 data signifies the lockdown's impacts, 2021 pre-lockdown, and 2023 post-lockdown conditions. The questionnaire's first section evaluated the lockdown's overall impacts on herders' lives, including effects on routine herding practices, healthcare accessibility, shopping, and education. The second section concentrated on livestock production data across eight dimensions: livestock, pricing, fodder costs, pasture leasing or quota trading, loans, livestock mortality, reproduction and growth. Additionally, as ancillary data, the study collected temperature and precipitation statistics for the case areas from the EU and the European Centre for Medium-Range Weather Forecasts. Moreover, the principal author of this paper, being a Tibetan scholar, ensured that language barriers were surmounted during interviews and surveys.

3. Research Hypothesis

During our fieldwork in the two case study areas, a striking disparity was observed by the research team regarding the perceived impacts of COVID-19 lockdown measures on herders. Despite the lockdown's duration and nature being uniform across both locations, the experiences of herders in Qilian and Maqu diverged markedly. Herders in Qilian articulated a significantly heightened impacts from the lockdown, which impeded their ability to sell yak and sheep. Consequently, they encountered substantial financial strain, resulting in economic losses, accumulated debt, and the looming threat of insolvency. Conversely, Maqu herders reported a negligible impact from the lockdown. Although they also encountered challenges in livestock sales, they viewed the deferral of such transactions as a minor inconvenience, confident in their ability to sell their animals in the subsequent year. This observation begets a critical inquiry: under seemingly identical geographical and social conditions, how did uniform lockdown measures yield such divergent outcomes?

Considering transportation, regional connectivity, and pasture usage methods in our two case studies, we speculate that Qilian's pastoral region exhibits a higher degree of marketization compared to Maqu. This leads us to wonder if the marketization levels affect a region's resilience to external shocks or disaster mitigation. Consequently, we advance the central hypothesis of our study: There is a positive correlation between the level of marketization in pastoral areas and the severity of the impacts on livestock production due to pandemic-induced lockdowns.

4. Variables and Measurements

4.1 Life and Production

From initial in-depth interviews, it emerged that China's "zero-COVID" policy had kept COVID-19 infections nearly non-existent in pastoral regions prior to the lockdown's end in late 2022. The pandemic's influence in these areas was largely indirect, stemming from lockdown measures' disruption to the daily lives and livestock operations of herders. Consequently, this study identifies two key dependent variables: the lockdown's impacts on herders' lives and on livestock production (Table 1). The effects on herders' lives are distilled into four core domains: herding, healthcare, shopping, and schooling. Herding, while a production component, is primarily a daily life aspect for herders, encompassing tasks like looking after livestock, watering, feeding, and so forth. Healthcare captures non-COVID-19 hospital visits for illnesses, check-ups, childbirth, and medication. Shopping pertains to the procurement of daily necessities, and schooling covers the educational continuum from primary to university levels for students in pastoral regions.

The pandemic lockdowns' influence on livestock production is primarily evident in three key areas: impediments to sell, increased herding expenses, and production losses. This study employs these indicators to gauge the lockdowns' production effects. Firstly, livestock sale, a vital economic activity for herders, were disrupted by lockdowns that hindered mobility and transportation, affecting the trade between herders and traders. The impact on sale is twofold: timing and volume. Timing refers to sale delays or cancellations due to lockdowns, typically aligning with the optimal selling period from September to mid-October when livestock are in peak condition. In 2022, this period coincided with strict lockdowns, severely limiting trader movement and livestock transport, obstructing sales during this critical time. Volume indicates whether the number of livestock sold decreased or vanished due to lockdowns, compared to planned sales. Although some traders re-entered pastoral areas post-lockdown in December 2022, the prime selling window had passed, with livestock in poorer condition, leading to lower purchase offers. Consequently, some herders refrained from sale or sold only a portion of their livestock due to unsatisfactory prices, while others remained unsold due to lack of trader contact. Thus, livestock sale is deemed the primary indicator for assessing the lockdowns' impacts on production in this study. Secondly, restrictions on livestock sale pose dual financial challenges for herders: a cash flow crisis for livelihoods and increased costs for retaining livestock over winter, which demands more capital for feed and herding. To cope, herders often turn to loans to cover both living expenses and production costs. Therefore, this study analyses production costs for herders by examining expenses related to feed purchasing, pasture leasing, and loan status. Thirdly, the impediment to livestock sale not only raises production costs but also indirectly results in production losses. Herders may prolong their stay on overgrazed pastures, reduce feed to cut costs, or neglect livestock care due to pandemic-related distractions like assisting with online education. These practices can degrade livestock health, leading to higher mortality rate in spring and reproductive issues like infertility or miscarriages, thereby affecting breeding success. Hence, this study employs mortality and reproductive rate of livestock as metrics to evaluate the production losses incurred by pandemic lockdowns.

4.2 Degree of Marketization

To substantiate or refute the hypothesis that increased marketization in pastoral regions exacerbates the impacts of pandemic lockdowns on livestock production, this study adopts the level of marketization as the independent variable. It encompasses four precise indicators: the status of pasture use rights transactions, the ratio of feed purchases and pasture leasing costs to overall production expenses, the ratio of livestock sold relative to the total herd size, and the ratio of breeding livestock to the total herd (Table 1).

Sudden impact of pandemic lockdown measures shares similarities with natural disasters. Under market mechanisms, when faced with disastrous weather, herders need to purchase more fodder externally, rent more pastures through the market, or buy herding quotas to supplement the shortage of forage (Gongbuzeren, 2016). Conversely, in areas lacking market systems, herders, confronted with reduced natural forage during disasters, often resort to selling more livestock unless they practice communal rangeland use. In such cases, by reallocating pastures, they can optimize the use of remaining natural rangelands, thereby internalizing external costs. Hence, the exchange of pasture use rights, including leasing and quota trading, and feed purchases are pivotal metrics for gauging marketization levels. The volume of livestock sale by herders is indicative of their integration with the market. Herders with a higher degree of marketization typically sell more livestock annually to maximize economic returns. Thus, the paper adopts the ratio of livestock sold to total livestock as the third marketization indicator. As marketization intensifies, so does the proportion of female livestock in herds. Herders in market-accessible regions, aiming to maximize commercial profits (Scoones, 1994), prioritize output under constrained rangeland resources and herd size. In profit-driven livestock farming, after accounting for the production costs of male livestock, herders opt not to raise males beyond a few breeding animals. The herd predominantly consists of females, with young livestock being sold annually (in Qilian, female livestock can comprise up to 70% of a herder's herd). Post-sale, the remaining livestock are mostly female. Traditional subsistence farming, focused on herd expansion rather than direct economic profit, sells mature males over six years old and maintains a higher proportion of males aged two to six. Consequently, non-breeding females may constitute nearly half the herd, with the remainder being females. Hence, the proportion of female livestock serves as the fourth indicator in this paper for assessing marketization levels.

4.3 Meteorological Conditions and Infrastructures

Additionally, variations in infrastructures and extreme weather events significantly affect livestock production. On the Tibetan Plateau, the presence of shelter facilities for livestock can mitigate mortality and boost reproductive rate during winter and snowy conditions. Moreover, extreme climate events like snowstorms and droughts can escalate production costs and diminish livestock output. Consequently, this study incorporates these factors as control variables to isolate their effects from the study's competitive explanations.

Table 1 Variable Definitions and Measurements

Variable		Indicator		Measurement	Assessment Criteria
Dependent Variables	Life	Herding, Healthcare, Shopping, and Schooling		The proportion of affected households to the total sample, but in schooling only to samples with students	Higher affected proportion indicates more severe impact
	Production	Livestock Sale		The proportion of households affected in terms of selling time or quantity out of the total sample size.	Higher proportion of affected households compared to pre-lockdown indicates more severe impact
		Herding Costs	Foder and Pasture rent	Per household expenditure on foder purchase + pasture rent (unit:10 thousand yuan)	Higher increase compared to pre-lockdown indicates more severe impact
			Loans	Loan coverage rate (loan households/total sample households, %); Loan amount (households with different loan amount /total sample households, %)	Higher increase compared to pre-lockdown indicates more severe impact
		Production Loss	Livestock Mortality Rate	Per household livestock deaths/total livestock number (%)	Higher increase compared to pre-lockdown indicates more severe impact
			Reproductive Rate of Female Livestock	Number of offspring born and survived in the year/number of breeding female livestock (%)	More significant decline in reproductive rate compared to pre-lockdown indicates more severe impact
Independent Variables	Marketization Level	Pasture Use Rights Transactions		Whether there are pasture lease or herding quota transactions	Yes indicates high marketization level; No indicates low marketization level
		Total Foder Expenditure (purchase of foder + rent cost + purchase of herding quotas)		Proportion of foder expenditure/total production cost (%)	Higher proportion indicates higher marketization level
		Per Household Selling Rate		Number of sold livestock/end-of-year livestock number (%)	Higher proportion indicates higher marketization level
		Per Household Female Livestock rate		End-of-year female livestock number/total livestock number (%)	Higher proportion indicates higher marketization level
Control Variables	Infrastructures	Shed Construction		Whether there are modern warm sheds	Yes requires excluding the impact of shed facilities from the study's

				competitive explanations
	Meteorological Conditions	Abnormal Weather	Whether there are abnormal changes in temperature and precipitation before and after the lockdown	Yes requires excluding the impact of climate factors from the study's competitive explanations

Results

1. Marketization Level in the Case Areas

In Qilian, with winter pastures managed and fenced individually, pasture use rights are commonly traded among herders, which all sampled households participate in. Despite summer and autumn pastures being collectively managed, there is a clear system for herding quotas and compensations. Conversely, in Maqu County, pastures are collectively managed without clear household boundaries, and pasture leasing is absent. Although a quota system exists, it is restrictive, and none of the sampled households partake in pasture leasing or quota transactions. To sum up, the marketization level in Qilian County is higher than in Maqu County, as evidenced by four key indicators (Figure 2).

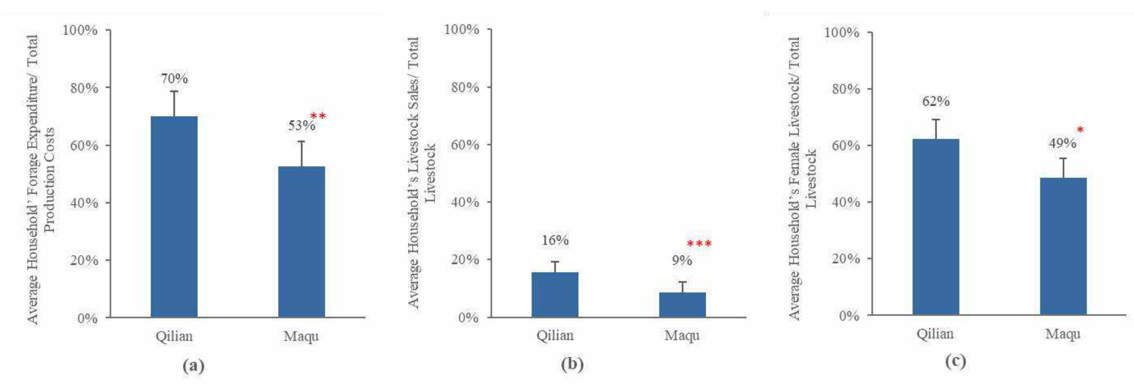

Figure 2. Marketization Level: a) Proportion of Average Household' Foder Expenditure to Total Production Costs ; b) Proportion of Average Household's Livestock Sales to Total Number; c) Proportion of Average Household's Female Livestock Number to Total Livestock Number

2.Impacts of Herder's Lives

Analysis of interviews indicates that daily life was moderately disrupted in both areas, with Qilian experiencing slightly greater impacts than Maqu (Table 2). More households in Qilian report difficulties with herding, healthcare, shopping, and schooling. Disruption to students' schooling is the most severe impact across both areas. Our findings (Table 3) detail specific disruptions to herding activities, with herders unable to reach herds 7–10 kilometers away during lockdowns, leading to water shortages for yaks and conflicts over stray animals (Case #1). Healthcare access was impeded, with some herders missing timely medical care (#2) and facing disruptions back to pasture after hospital quarantine (#3). Lockdowns also led to increased expenses and difficulties in procuring food (#4) and daily necessities (#5). Education was severely impacted, with families buying additional phones for online classes, renting accommodations in town (#6), or driving over 30 kilometers daily for internet access to continue their children's education (#7). In both areas, lockdown's impacts led to increased household expenses and indirectly effects on livestock production.

Table 2. Number and Percentage of Households Affected by Lockdowns in Daily Life (The "Schooling" Category Includes Only Households with School-Aged Children)

Case Areas	Herding	Healthcare	Shopping	Schooling
Qilian（20 in total, 12 with students）	4(20%)	4(20%)	2(10%)	12(100%)
Maqu(31 in total, 18 with students)	1(3%)	5(16%)	1(3%)	18(100%)

Table 3. Case Descriptions of the Impacts of COVID-19 Lockdowns on Herders' Lives

Case	Aspect of Life	Description of the Impacts During the Lockdown	Case areas
#1	Herding	I come from a single-parent household with a school-age son, residing in our village's pastoral area while our livestock were herded 7-10 kilometers away in the mountains. With only yaks in my herd, which are confined by barbed wire, I usually visit them every few days on my motorcycle to provide water. However, lockdown measures sealed all roads, preventing me from reaching the pasture. After several days, I learned from a villager that my yaks had broken the fence and entered another's pasture, prompting a demand for my immediate presence or risk losing my livestock. Despite my pleas to the roadblock guards, I was denied passage. Left with no alternative, I embarked on a grueling journey, traversing mountains and streams, to reach the pasture on foot. It consumed an entire day, but I managed to resolve the conflict by compensating the affected villager and returned my herd to safety.	Qilian
#2	Healthcare	My wife, who has a chronic stomach condition, was hospitalized for two months before the lockdown and was due for a follow-up in six months. However, her condition worsened during the lockdown, making it impossible to reach either the provincial or county hospital. We had to postpone her treatment until late 2023, resulting in a three-month delay.	Maqu
#3	Healthcare & Herding	In late August 2022, I was admitted to a Tibetan hospital in the prefecture for a minor ailment, planning a week-long stay. However, a COVID-19 outbreak in a neighboring county led to a prefecture-wide lockdown on my third night, halting all traffic. Initially, I received basic care, but within days, most staff were redirected to COVID-19 testing, leaving only a few nurses for us stranded patients. Treatments ceased, and we were confined to the inpatient building, receiving meager meals from centralized distribution. I remained stranded for nearly a month, coinciding with my family's seasonal pasture migration, which was also impeded by travel bans. Unable to move without me, my family managed to pick me up under cover of night and we evaded checkpoints via a mountain path, effectively "escaping" to our home.	Qilian
#4	Shopping	Over the pandemic's three-year span, pastoral area prices saw a notable uptick. The cost of flour, a staple for herders, escalated from 90 yuan per bag in 2019 to 95 yuan in 2020, then to 105 yuan in 2021, and during the 2022 lockdowns, it spiked to a range of 125 to 150 yuan per bag. Similarly, a 5-pound bag of tsampa climbed from 10 yuan in 2021 to 12 yuan in 2022.	Qilian
#5	Shopping	From early to late November 2022, our county faced a severe "smoke shortage", prompting the emergence of cigarette smugglers who inflated prices drastically—selling packs that normally cost 5 yuan for 30-40 yuan, and individual cigarettes, like Black Lanzhou, for over ten yuan, despite the market price being 18 yuan per pack. Compounding this, a gasoline shortage arose during the continuous mass nucleic acid testing period, when we were confined to our village and all stores and gas stations were shuttered. The dilemma was	Qilian

		exacerbated by the need to drive or ride a motorcycle for tests, often leading to cars running out of fuel. Fortunately, the lockdown was short-lived, and in its final days, restrictions were relaxed, permitting one person per household to refuel.	
#6	Schooling	I have two sons, one in the first and the other in the third year of middle school, both studying at our county's ethnic middle school. During the pandemic, our greatest wish was for our children to return to school as online learning was challenging for us. I initially bought each son a phone for online classes, but after two months in the autumn pasture, their phone bills soared past 400 yuan. The situation deteriorated further when we moved to the winter pasture, where there was no internet signal. Unable to provide for their online education despite the expenses, I rented a small house in town for them to study. Their mother would join them occasionally due to our busy home life.	Qilian
#7	Schooling	I have a son in high school and another in elementary school, both of whom required online classes during the 2022 pandemic. Lacking signal or electricity on our farm, I had to drive them daily to an area with reception, a round trip exceeding 30 kilometres. This daily commitment to their education significantly reduced my time for tending to our yak and sheep, leading to a high mortality rate among our livestock that year.	Maqu

3. Impacts on Herders' Production

3.1 Livestock Sale

In both areas, livestock sale constitutes the predominant source of income, with Maqu over 75% and Qilian 85% out of total household's income. Notably, Qilian's reliance on livestock sale is 10% greater than Maqu's, suggesting a higher dependence on such sell to cover living and production costs. Among the sampled herders in Qilian, 90% encountered impediments to livestock sell due to pandemic-induced lockdowns, significantly higher than the 31% reported in Maqu. This result underscores the more pronounced adverse effects of lockdown on livestock sale in Qilian. The description of herder household BC (Table 6) provides a typical example of the lockdown's effect on livestock sale.

3.2 Herding Costs

（1） Expenditure on foder purchases and pasture rentals

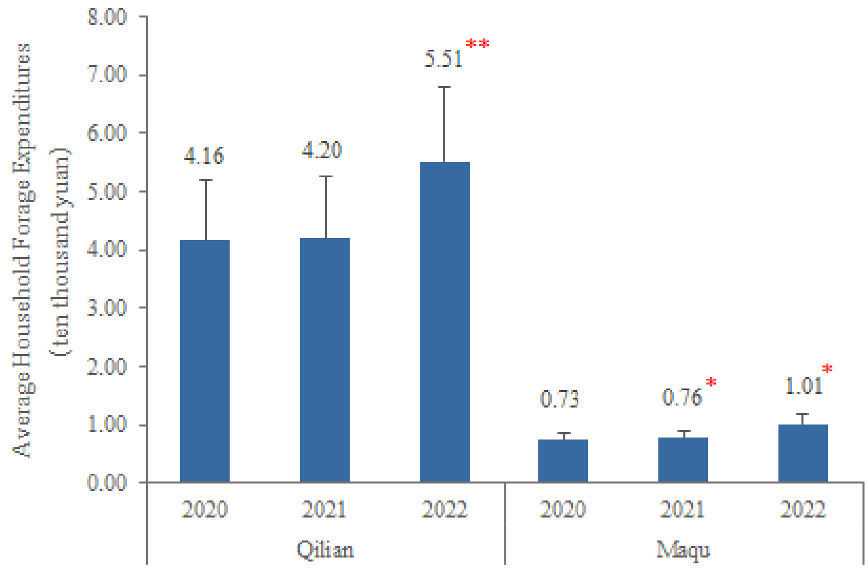

Figure 3. Average Household Foder Expenditures (Foder Purchases + Pasture Rentals + Herding Quota Purchases) (Note: Asterisks indicate significant differences, *p<0.05, **p<0.01, ***p<0.001)

Table 5. Comparison of Foder Prices in Qilian County from 2020 to 2022(Unit: Yuan)

Year	Mixed Foder (per ton)	Alfalfa Hay (per bale)	Oat Hay (per bundle)
2022	3100-3500	45-60	6
2021	2800-3100	35-50	3
2020	2800-3000	34-48	3

（2） Loans

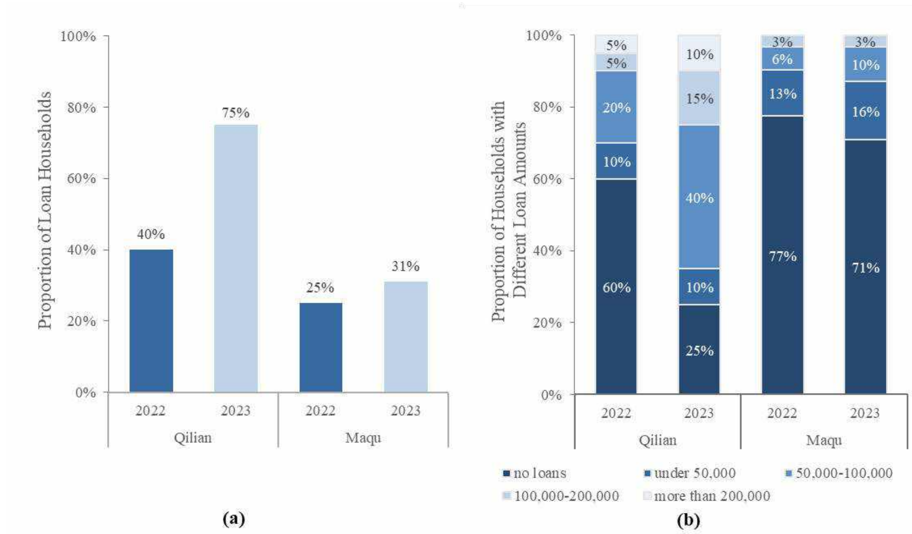

Figure 4. Loans: a) Changes in the Proportion of Loan Households Pre-and Post-Pandemic Lockdown; b) Changes in the Proportion of Households with Different Loan Amounts Pre-and Post-Pandemic Lockdown

3.3 Production Loss

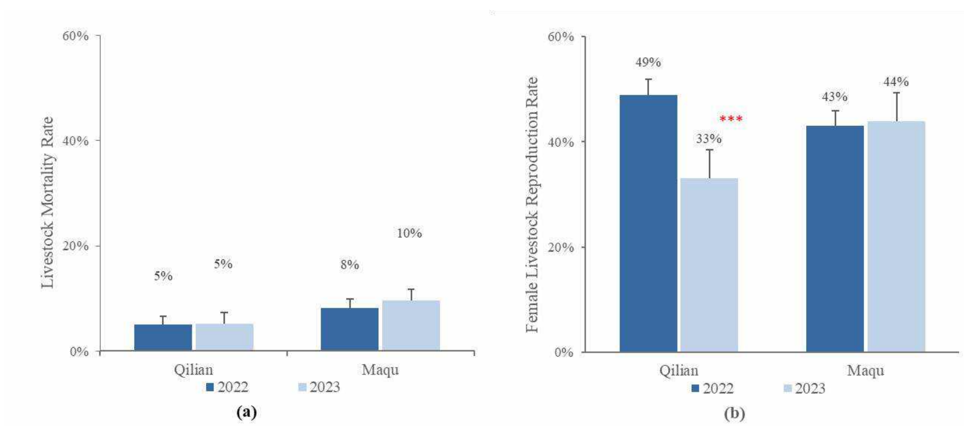

Figure 5. Livestock Morality and Reproductive rate: a) Changes in Average Household Livestock Mortality Rate Pre-and Post-Pandemic Lockdown; b) Changes in Average Household Female Livestock Reproductive rate Pre-and Post-Pandemic Lockdown (Note: Asterisks indicate significant differences, *p<0.05, **p<0.01, ***p<0.001)

Table 6. Case Descriptions of the Impacts of the Lockdown on Herders' Production

Case	Aspect of Production	Descriptions of the Impacts During Lockdown	Case areas
#BC	Livestock Sale & Loans	Herder BC, a relatively well-off member of his community with a family of four, started 2023 with a livestock count of 500 sheep (350 ewes) and 280 yaks (180 female), with over 65% being female. His usual strategy is to sell 90% of the lambs and culled animals annually, constituting 60% of his stock. He had planned to sell 300 sheep and 60 yaks in late 2022, expecting 1,300 yuan per ewe and 850 yuan per lamb. The pandemic lockdown disrupted these plans, and he could only sell a fraction in November 2022 at reduced prices—900 yuan per ewe and 700 yuan per lamb. Consequently, he sold only 35 ewes and 65 lambs, totalling 100 sheep, which was one-third of his intended sales, with no yak sold. Being unable to sell as anticipated meant he had to buy additional foder for the winter to feed his livestock. To cover these costs, BC took a bank loan of 250,000 yuan, of which 44,000 yuan was used to purchase foder and 100,000 yuan was allocated for pasture rental, totalling 144,000 yuan in production costs for 2022.	Qilian
#MJ	Rise of Production Cost	Herder MJ’s household consists of five members, with herding rights to two portions of pasture (800 mu). In 2023, he had a livestock inventory of 510 sheep and 106 yak, compared to 100 sheep and 206 yak in 2022. From 2020 to 2022, he leased an additional four portions of pasture (1,200 mu), with rental costs rising from 30,000 yuan in both 2020 and 2021 to 50,000 yuan in 2022—an increase of 20,000 yuan compared to the previous year. In 2021, MJ's feed expenses were 3,000 yuan, which jumped to 30,000 yuan in 2022. His foder costs also increased from 5,000 yuan to 12,000 yuan over the same period. Overall, pasture rental costs tripled, while foder and feed expenses quintupled from 2021 to 2022.	Qilian
#Q	Livestock Sale, Production Cost & Loss	Herder Q, part of a four-member household with rights to two pasture sections (800 mu), had a herd of 180 yak and 718 sheep in 2023. Due to pandemic restrictions in 2022, he missed the optimal time to sell livestock and had to rely on supplemental feeding to maintain and fatten the herd. His foder-related expenses included 74,000 yuan for pasture rental, 79,000 yuan for foder, 50,000 yuan for renting wheat fields, and 10,000 yuan for other production costs, totalling 213,000 yuan—a 67,300 yuan increase compared to 2021. After three to five months of fattening, the selling price was nearly the same as it would have been during the regular season. However, the fattening process required significant labour and herding resources, reducing the attention available for other livestock. Additionally, to cut costs, he delayed moving to winter pastures by staying on (communal) summer pastures for an extended period, which not only damaged the summer pasture but also led to higher livestock mortality rate and lower reproductive rate in spring 2023. Livestock mortality more than doubled from 2022, with 14 yak and 28 sheep deaths, to 40 yak and 53 sheep in 2023, with a significant number of losses among the young.	Qilian
#Z	Livestock Sale, Production Cost & Loss	Herder Z's household, comprising three members with herding rights to two pasture sections (350 mu), owned 56 yak and 226 sheep in 2023. Pandemic lockdowns in 2022 resulted in the sale of only 15 yak, generating 90,000 yuan. However, that year's production costs escalated to 96,550 yuan, including 47,000 yuan for additional pasture rent, 18,750 yuan for foder, and 40,800 yuan for feed. The household also suffered the loss of 37 sheep and took a 300,000 yuan loan, leading to expenses that dwarfed income and brought the family to the brink of financial ruin.	Qilian

1. Meteorological Conditions and Infrastructures

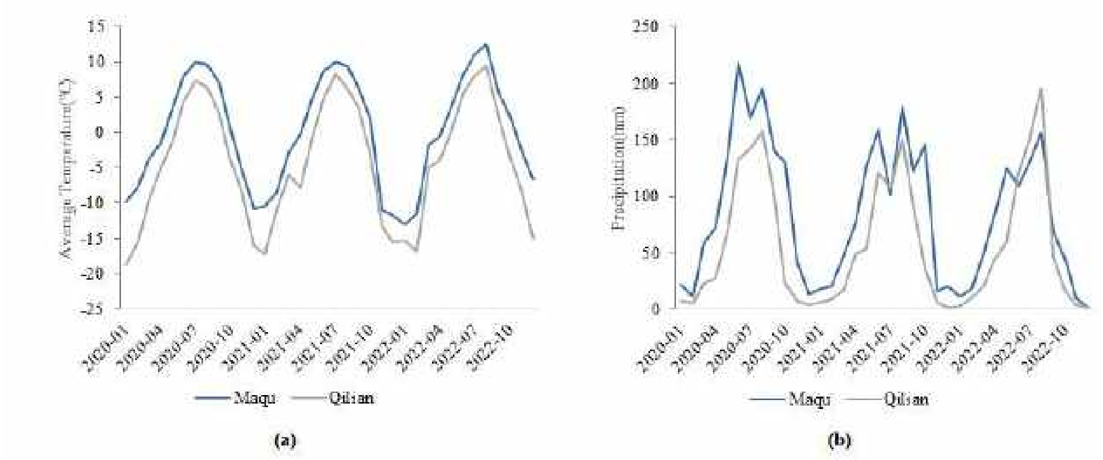

Figure 6 Meteorological Conditions: a) The Monthly Average Temperature Changes From 2018 To 2022; b) The Cumulative Monthly Precipitation From 2018 To 2022.

In terms of livestock infrastructure, Qilian herders are all equipped with at least one modern warm shed, which is crucial for protecting new-born lambs from freezing during winter lambing. Conversely, Maqu herders lack access to such facilities, including warm sheds, which are essential for livestock management.

5.Argumentation: The Closer the Connection with the Market, the Greater the Impacts of Lockdown

Drawing from the research data and information presented, it has been observed that the pandemic-induced lockdown had impacts on herders' daily lives in both areas, with Qilian experiencing a marginally greater effect than Maqu. However, when considering production, the lockdown's effects on Qilian were markedly higher than those on Maqu. In the following analysis, we will first delve into the factors contributing to the lockdown's influence on livestock production in Qilian. Subsequently, adopting a marketization lens, we will elucidate the divergent impacts of identical lockdown measures on the two areas, thereby validating or refuting our initial research hypotheses.

5.1 Lockdown Hindered Livestock Sale

As previously highlighted, the sale of livestock constitutes the principal source of household revenue for herders in both areas, implying that their annual earnings are contingent upon the sale of livestock considerably. The COVID-19 lockdown imposes constraints on livestock sale for that year, impacting both the transaction avenues and price.

The lockdown restrained the transaction avenues for herders. Within China's pastoral regions, the sale of livestock is heavily reliant on the role of "middlemen," who function as intermediaries in the procurement of yak and sheep. Customarily, the livestock selling season spans from early September to mid-October, a period during which middlemen from diverse regions converge on herders to engage in livestock purchases. However, the 2022 selling season coincided with the most stringent phase of the pandemic lockdown. The lockdown's restrictions on human and vehicular movement impeded middlemen from accessing herders, thereby preventing herders from executing their planned sales (Table 6, herder BC, Q, and Z).

The pandemic lockdown exerted indirect influences on livestock sale prices, diminishing the herders' willingness to sell. Following the relaxation of restrictions in mid-December 2022, while some middlemen ventured into the pastoral regions, the livestock had passed their optimal selling condition. On one hand, the livestock's condition had declined relative to the peak selling period. On the other hand, middlemen, who have the pricing power, lowered the purchase price as they predicted an increased livestock inventory (Table 6, herder BC). From the perspective of market demand, the pandemic lockdown also impacted the market price indirectly. Interviews with middlemen revealed that during the lockdown, tourists to the Tibetan Plateau were significantly depressed. Restaurants and butcher shops experienced prolonged closures, leading to a contraction in local demand for beef and mutton. Concurrently, slaughterhouses grappled with inventory backlogs acquired before the pandemic. Resulted surplus ultimately depressed the prices of beef and mutton, influencing herders' selling decisions.

Different levels of marketization have precipitated distinct pastoral strategies, amplifying the lockdown's impacts on herders with higher marketization. In Qilian, a substantial 90% of herders encountered obstructions in their sale, contrasting with only one-third of Maqu herders who perceived an inability to execute their livestock sale as anticipated. Despite of equivalent lockdown durations and measures, under distinct pastoral strategies generated from different marketization level, their reliance on livestock sale is varied.

Maqu herders, with a lower degree of marketization, adhere to a more traditional, subsistence-based pastoralism. They invest less capital in livestock production and prioritize herd stability over economic profit maximization. Their annual sales are relatively modest (Figure 2.b), directed at covering basic livelihood expenses, thereby reducing their dependence on any certain livestock sale round. In contrast, Qilian herders engage in a more commercially oriented pastoralism. They frequently incur debts to augment investments in foder, feed, or leased pastures, leading to a significantly higher cash outlay expenses in livestock production compared to Maqu herders (Figure 3). In Qilian, the proportion of breeding livestock is more substantial (Figure 2.c), and a larger segment of the herd is marketed (Figure 2.b), with an emphasis on little livestock (mainly lambs) for enhanced output. Livestock sale serve two purposes: meeting living expenses and covering current production costs. Consequently, Qilian herders exhibit a heightened dependence on every livestock sale round to satisfy both subsistence and investment demands. Thus, the pandemic lockdown's restrictions on sale had a more remarkable effect on Qilian herders, attributable to their increased reliance on sale to fulfil cash flow and production cost.

5.2 The Increasing Number of Livestock in Hand Lead to Increased Feeding Costs and Greater Production Losses

Impediments to livestock sale leading to herders with higher levels of marketization incurring higher production costs and losses. The blockage of livestock sale resulted in an increased livestock on hand, which subsequently rose the demand for fodder and natural pastures, thereby augmenting production expenses. The impacts on the two areas are distinct, characterized by varying degrees of marketization. Qilian herders, already heavily reliant on market-procured fodder and pasture rentals, faced an increased prices of commodities in response to the heightened demand because of the market mechanisms (Table 5). This surge significantly magnified herding costs, and the concomitant rise in fodder demand and prices substantially escalated the cash requirements for herders (Table 6, herder MJ). In this context, loans become herders' only solution, resulting in a notable increase in both the numbers and amount of loans taken by Qilian during the lockdown (Figure 4,a). In the pastoral context, loans not only fail to alleviate risks but also introduced the burden of interest and repayment obligations, exacerbating the financial strain on herders

(Table 6, Herder Z). Consequently, when the sale in Qilian were impeded, herders whose predominant revenue stream is livestock sale, confronted escalating production costs, particularly for fodder.

Moreover, an increase in livestock numbers necessitates additional labour input for feeding and care. Any shortfall in fodder supply or animal care can lead to heightened risks of livestock mortality or reduced reproductive rate among female animals, as demonstrated in the case of herder Q (Table 6). Without adequate funds to procure sufficient fodder to sustain livestock through the winter, there is an elevated risk of increased mortality rate (Table 6, herder Q and Z) and malnutrition among female animals, which, in turn, adversely impact reproductive performance (Figure 5,b).

In contrast, Maqu herders exhibit a lower cash outlay expenses in livestock production. With no market for herding rights and limited fodder usage, Maqu's production costs are much lower than in Qilian, resulting in fewer loans. Therefore, when faced with impediments to livestock sale, Maqu herders incur no additional financial losses beyond basic living expenses. Additionally, since the Maqu herders share grazing land within small groups and do not engage in market-based leasing or quota trading, an increase in herding demand by certain herders due to sale disruptions does not lead to intense competition over pasture resources. Instead, they mitigate herding costs through multiple relocations within the group, thereby externalizing herding costs and avoiding the risk of increased expenses from rising pasture prices. Consequently, after the pandemic lockdown, Maqu herders, with their lower degree of marketization encounter less production costs and production losses in comparison to Qilian herders.

5.3 Exclusion of Competing Explanations

Beyond the sufficiency of fodder supply, livestock mortality and reproductive rate are also contingent upon natural disasters and the state of livestock production infrastructure. Meteorological data indicate that neither of the areas exhibited anomalous temperature or precipitation patterns in 2022 (Figures 7, a and b), and herders surveyed reported no occurrences of droughts, snow disasters, or other climate-related events during the lockdown. This excludes any correlation between production losses in the two areas with climatic anomalies or natural disasters. In the sampled populations of the two areas, all herders in Qilian County possessed at least one modern warm shelter and sheep pen, in contrast to none of the sampled herders in Maqu. The slightly elevated livestock mortality rate in Maqu, relative to Qilian, is partly ascribed to less supplemental feeding and inadequate livestock infrastructure. Although the post-pandemic increase in livestock mortality rate was not significant in either area, mortality rate alone does not comprehensively represent production losses in livestock farming. Reproductive rate explicitly indicate that Qilian witnessed a marked decline in production following the pandemic lockdown, while Maqu's reproductive rate not only remained stable but actually increased by 1% (Figure 5,b).

In conclusion, the research findings substantiate the initial hypothesis of this study: the primary reason for the more serious impacts of the pandemic lockdown on Qilian compared to Maqu is associated with the level of marketization. The closer the market ties, the more severe the lockdown's impacts.

Discussion and Conclusion

This study illustrates the divergent impacts of a uniform pandemic lockdown on two case study areas with varying marketization level. The research findings underscore that Maqu, characterized by a lower degree of marketization, experienced muted effects from the lockdown. Qilian, however, with a higher degree of marketization, encountered more substantial repercussions. Maqu exhibited enhanced stability and sustainability when facing the pandemic lockdown's abrupt external shock. However, the market-integrated Qilian endured severe outcomes, with numerous herders encumbered by significant loan debt, and some even confronting insolvency, such as herder Z (Table 6). Hence, the inquiry into the root cause of this divergence arises.

Marketization is a pivotal avenue for economic growth and modernization; however, it can engender risks concurrently. The extant mainstream research on credit and fodder markets for pastoral socio-ecological systems, particularly in the context of extreme climatic events, has predominantly posited that market mechanisms facilitate herders' resilience to disasters (Agrawal, 2010; Addison and Brown, 2014; Carter et al., 2007; Ouma et al., 2011; Turner and Williams, 2002; World Bank, 1994; Horn et al., 2003; Müller et al., 2015; Schulze et al., 2016). Nevertheless, some case-based studies have unveiled that while market mechanisms might offer short-term alleviation for herders confronting disaster-induced impacts, over the long term, they may result in a severe deterioration of natural rangeland ecosystems, potentially generating the collapse of the pastoral economic system (Li and Li, 2021; Lu et al., 2022; Briske et al., 2015). This phenomenon arises from the dependency on external loans to procure fodder, which can disrupt the negative feedback loop between the pastoral economic system and the local ecosystem, culminating in an imbalance within the local socio-ecological system (Lu et al., 2021; Zhang et al., 2018).

The advent of the COVID-19 and its attendant control measures bear resemblances to the meteorological calamities commonly encountered in pastoral regions, given their inherent unpredictability and catastrophic nature. However, diverging from prior research that highlighted the potential long-term perils associated with market forces, this study discerns that in the context of abrupt occurrences, such as the pandemic, the risks intrinsic to market integration materialize swiftly, manifesting even within the short term.

In pastoral areas with high climate variability, pastoralists have historically employed strategies such as livestock mobility, livelihood diversification, communal herding, and storage to navigate such fluctuations (Scoones 1994; Xie and Li 2008), thereby sustaining a resilient socio-economic system (Fernández-Giménez and Swift 2003). However, the advent of land privatization (Fernández-Giménez 2001; Li et al. 2007; Li and Huntsinger 2011) and shifts in policy direction (Gongbuzeren et al. 2015) have encumbered the sustainability of these traditional practices. Consequently, pastoralists have sequentially gravitated toward market-oriented tactics. Through market mechanisms, they have amplified their socio-economic systems by integrating external resources, including fodder, feed, and credit facilities. Nevertheless, in the face of sudden incidents akin to pandemic lockdowns, these market-reliant pastoralists are exposed to associated risks, culminating in a surge of production costs and economic losses. This mode of livestock production, heavily contingent upon external resources, has transcended local ecological thresholds, with the socio-economic system effectively expanding outward and progressively diss-embedded from the indigenous ecosystem, leading to deleterious environmental impacts (Table 6, herder Q). The elevated stocking rates, sustained by substantial external fodder inputs, have intensified the overgrazing of indigenous pastures, further depleting natural forage reserves. This, in turn, fosters an increased dependency on external market inputs, establishing a vicious cycle that jeopardizes the stability of the pastoral economic system and potentially precipitating its collapse.

The incursion of market mechanisms does not inexorably signify the obsolescence of traditional strategies designed to navigate uncertainty. A crucial factor that attenuated the pandemic lockdown's impact on Maqu herders, relative to Qilian, is the preservation of a communal pasture management approach. Despite some households confronting heightened herding demands consequent to impeded livestock sale, they effectively internalized financial burdens by employing community-based practices, such as rotational herding. This traditional strategy showcased a more robust resilience to abrupt shock compared to the scenario in Qilian, where herders, who wholly dependent on market mechanisms, were severely affected by the COVID-19 lockdown.

In the process of transitioning from traditional subsistence-based pastoralism to commercialized livestock production, pastoral areas on the Tibetan Plateau have yet to establish effective mechanisms for managing market risks. This study reveals that herders lack direct channels for livestock sale and depend on intermediaries to access the market, highlighting the vulnerabilities and risks inherent in pastoral markets. To enhance the stability and sustainability of rangeland pastoralism amid market-oriented development, this study offers the following recommendations: 1. Enhance herders' participation in market design: strengthen herders' involvement in various market stages, from purchasing fodder to selling livestock, by developing a market chain that centers on herders. This approach would mitigate the risks associated with market fluctuations. 2. Support traditional pastoral strategies: recognize and support traditional pastoral strategies and knowledge, such as community-based reciprocal herding and resource-sharing systems, which are crucial for coping with uncertainties and sudden disasters. Policy measures should encourage the preservation of these traditional practices, allowing local experience to play a more significant role in sustainable development.

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Can legume inclusion in pasture systems improve forage carbon (δ13C) and nitrogen ($\delta^{15}N$) nutrition? Findings from Tsolo, Eastern Cape, South Africa.

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Abstract

The supply of nitrogen (N) to plants limits primary productivity in numerous ecosystems and these limitations in N concentrations in plants also limit herbivores, by limiting their productivity in relation to both plant nutritional quantity and quality. Carbon isotope ratio can provide insight about the photosynthetic pathways utilized by different plant species. Plant C and N isotope ratios were studied for different species growing in old arable lands in Kubedlana communal area, located at 32◦11′53 S and 28◦14′1 E and at 1020.8 m altitude in the Eastern Cape, South Africa. The vegetation type of the study area is the Foothill Moist Grassland. The area receives an annual rainfall between 600 mm and 750 mm. The study was aimed at testing whether there was seasonal shift amongst different plant species in relation to δ13C and δ15N isotopes. Leaf samples of *L. cuneata* (legume), forbs (weeds) and native grasses from the area were sampled to determine carbon and nitrogen isotope ratios. Plant samples were dried for 48 h at 70 °C and ground with a ball mill. All sampling was done once in spring (November) 2022, summer (February) 2023 and autumn (March) 2023 and winter (May 2023) seasons, respectively. Permutational multivariate analysis of variance (PERMANOVA) was used to test the effect of plant type (forbs, grass and legume) on $\delta^{13}C$ and $\delta^{15}N$ isotopes. There was a significant difference (P = 0.001) between the three plant species and seasonal change regarding $\delta^{15}N$ ratios. $\delta^{13}C$ ratios, plant type also significantly (P = 0.001) affected plant carbon ratios. These findings emphasize the importance of

legume inclusion into old lands which is crucial in promoting nutrient cycling in pastures and ultimately nutritive value which is critical for improved animal performance.

Introduction

Nitrogen (N) is a significant limiting resource in numerous terrestrial ecosystems and N cycling influences most aspects of ecosystem function (Thomas *et al*., 2013). The supply of N to plants limits primary productivity in a myriad of ecosystems (Oberson *et al*., 2013). The limitations in N concentrations in plants also result in limitations to herbivores, by constraining the productivity of herbivores in relation to both nutritional quantity and quality of plants (Craine et al. 2015b; Zavala *et al*., 2013).It is therefore crucial to understand how patterns in terrestrial N cycling occur within and across ecosystems in order to predict patterns of plant productivity, ecosystem carbon sequestration, nutrient fluxes and trace gas losses to the atmosphere (Goll *et al*.,2012; Hudman *et al*., 2012). Photosynthesis is also strongly affected by nitrogen availability because the photosynthetic machinery accounts for more than half of the N in the leaves (Pinder *et al*., 2012). Typically, plant leaves are used as an index of δ^{15}N of the whole plant. Although there may be differences that exist among leaves, roots, and stems (Unkovich, 2013), the N isotope ratios generally correlate among plant fractions and any average differences are generally minor. For example, a study that was done, across 90 grass species collected from 67 sites in four grassland regions worldwide for the determination of δ^{15}N, the δ^{15}N of leaves averaged just 0.3‰ less than those of roots compared to a range of 18 ‰ for leaves and 14 ‰ for roots (Craine *et al*., 2015b). Although the N cycle is consisting of numerous processes that are difficult to measure, the ratios of δ^{15}N in plants or soils provide an indication on patterns of crucial aspects of the N cycle. These aspects comprise of the following: N supply rates to ecosystems and plants, N availability to plants, the N pathways by which N is lost from ecosystems, and the quantity of N lost. There is evidence that plant species differ in their capacity to assimilate inorganic and organic N however, there is limited known information and how interactions with companion plants affect the use of different N sources (Unkovich, 2012).

Therefore field (farm) research was carried with the aim to conduct a full investigation into the plant carbon (δ^{13}C) and nitrogen (δ^{15}N) nutrition of *L. cuneata*, a leguminous plant species, and its companion plants growing in old arable lands at Kubedlana communal area near Tsolo, Eastern Cape, South Africa. The study of *L. cuneata* and its companion plants' carbon and nitrogen nutrition is particularly relevant for understanding the long-term effects of land-use changes and the potential for ecological restoration. By examining the δ^{13}C and δ^{15}N signatures of *L. cuneata* and its companion plants, researchers can clarify the plant-soil-microbe interactions, nutrient cycling, and the potential for these abandoned lands to support diverse and resilient plant communities. Additionally, this analysis can contribute to an in-depth understanding of the nitrogen cycling dynamics within the old arable lands' ecosystem. Furthermore, the insights gained from this research can inform sustainable land management practices, such as the integration of *L. cuneata* and other leguminous species into agroecosystems, to enhance soil fertility, improve nutrient cycling, and promote the overall ecological health of these agricultural landscapes. This research was also aimed at elucidating the complex interplay between the carbon and nitrogen dynamics within this plant community, with a particular focus on understanding the adaptive strategies and resource partitioning mechanisms employed by *L. cuneata* and its associated plant species in the context of the old arable land ecosystem as influenced by seasonal change.

Study Area

The research was conducted in old arable lands at Kubedlana communal area near Tsolo under OR Tambo district municipality in the Eastern Cape Province, South Africa. Kubedlana is located at 32◦11′53 S and 28◦14′1 E and at 1020.8 m altitude. The vegetation type in the study area is classified as Foothill Moist

Grassland (Mucina and Rutherford, 2006). The annual rainfall of the area is estimated to range between 600 mm and 750 mm, while temperatures range between 3 ◦C in winter and 28 ◦C in summer. The soil chemical properties are as follows: P (5.99 mg/kg), K (0.20 mg/kg), Ca (4.26 mg/kg), Mg (1.16 mg/kg), and Zn (6.28 mg/kg).

Plant sampling and preparation

Samples of the uppermost fully expanded leaves of legumes, forbs (weeds) and native grasses from the legume and control (grass only) plots were sampled to determine dry matter production and other biochemical contents. Leaf samples were dried for 48 h at 70 °C and ground with a ball mill. Leaf nitrogen and carbon isotope ratios (i.e. foliar $\delta^{15}N$ and $\delta^{13}C$) and N were determined from approximately 3 mg with an isotope-ratio mass spectrometer (IRMS; Deltaplus XP and Delta C prototype Finnigan MAT, respectively, Finnigan MAT, Bremen, Germany; 0.1‰ precision). The $\delta^{15}N$ values represent nitrogen isotopic composition of the sample relative to that of atmospheric dinitrogen in ‰: δ 15N = (Rsample Rstandard − 1) × 1000 (1), where R = sample is the sample isotope ratio (15N/14N) and Rstandard is the $\delta^{15}N$ ratio for atmospheric N_2.

Data analysis

R vegan package statistical package was used to analyse all data, utilising a permutational multivariate analysis of variance (PERMANOVA) (Anderson, 2001; McArdle & Anderson, 2001). PERMANOVA was used to test the effect of the season (summer, winter, spring, and autumn) and plant type (forbs, grass and legume /*L. cuneata*) on foliar nutrient content. To graphically ordinate variation in plant isotope composition among the plant types and seasons, nonmetric multidimensional scaling (NMDS) was applied. Then a Non-Metric Multidimensional Scaling (NMDS) using Manhattan distance to assess the compositional dissimilarity among samples based on plant nutrient and isotope data was also used. The NMDS analysis was performed in R using the vegan package, with the dimensionality reduced to two axes to facilitate visualization. In addition, the generalised linear mixed model (GLMM) for each variable, with season as a random effect was also used to analyse data.

Results

There is a difference in the $\delta^{13}C$ isotope composition, and the shift is clear and inclined to plant type. Grasses had high ^{13}C content in comparison to forbs and legumes (Figure 3). In contrast, forbs and legumes usually utilising the C3 photosynthetic pathway, have a different carbon-concentrating mechanism as C4 plants, and they tend to have a higher discrimination against the ^{13}C isotope during carbon fixation. Consequently, C3 plants, including forbs and legumes, typically have lower ^{13}C content (more negative $\delta^{13}C$ values) compared to C4 plants. There was also a distinct observed differences in the ^{15}N isotope composition among the plant types in the old arable lands and this can be related to the fact that legumes, such as *L. cuneata*, can fix atmospheric nitrogen (N_2) through a symbiotic relationship with nitrogen-fixing bacteria called *Rhizobium*. The biological nitrogen fixation process preferentially incorporates the lighter ^{14}N isotope into the plant biomass, resulting in the lower (more negative) $\delta^{15}N$ values observed in legumes in current study. Grasses and forbs primarily obtain their nitrogen from the soil, and soils often have higher $\delta^{15}N$ signature due to various soil nitrogen transformation processes such as mineralization, nitrification, denitrification. Therefore, the non-leguminous plants tend to have higher $\delta^{15}N$ values as they assimilate the heavier ^{15}N isotope from the soil. When the data were classified seasonally according to drier (Winter and Autumn) and rainy seasons (Spring and Summer), there was a notable response ($p = 0.001$) in $\delta^{15}N$ values to variations in precipitation. Higher ($p = 0.001$) $\delta^{15}N$ values were observed during the dry and lower during rainy seasons, respectively. This seasonal tendency was observed throughout sampling seasons, but a variation in the scale on $\delta^{15}N$ values was noted, both for legume and non-legume species. (Table 1; Figure 2).

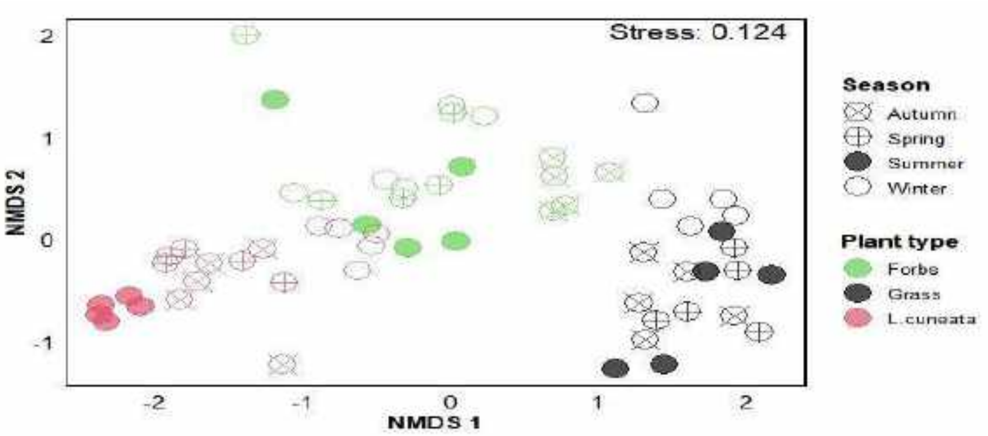

Figure 1: NMDS ordination of samples based on species plant nutrition and isotope data using Manhattan distance. Sites that are closer together in the plot have more similar plant nutrition and isotope compositions, as determined by Manhattan distance. Plant nutrients and isotope variables showed distinct spatial separation between the three plant types.

Table 1: Seasonal and plant type effect and their interaction on $\delta^{15}N$ content

Group variable	**df**	**R^2**	**F**	**P**
Season	**3**	0.072	10.399	0.001
Plant type	**2**	0.691	148.398	0.001
Season*Plant type	**6**	0.124	8.918	0.001
Residual	**48**	0.111		
Total	**59**	1.000		

There are significant differences in season ($r^2 = 0.072$ and $P = 0.001$), plant type ($r^2 = 0.691$ and $P = 0.001$), and in their interaction ($r^2 = 0.124$ and $P = 0.001$).

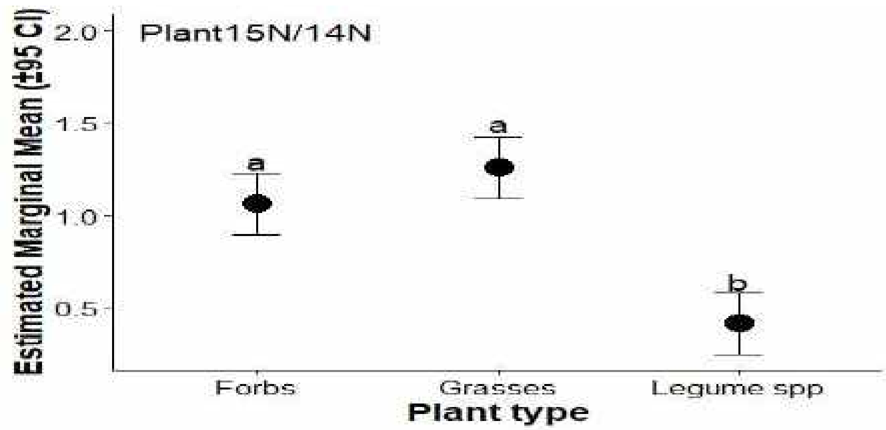

Figure 2: Nitrogen isotope ($\delta^{15}N$) nutrition of legume *(L. cuneata*) and different companion plant species growing in Kubedlana communal area.

Plant 12C/13C

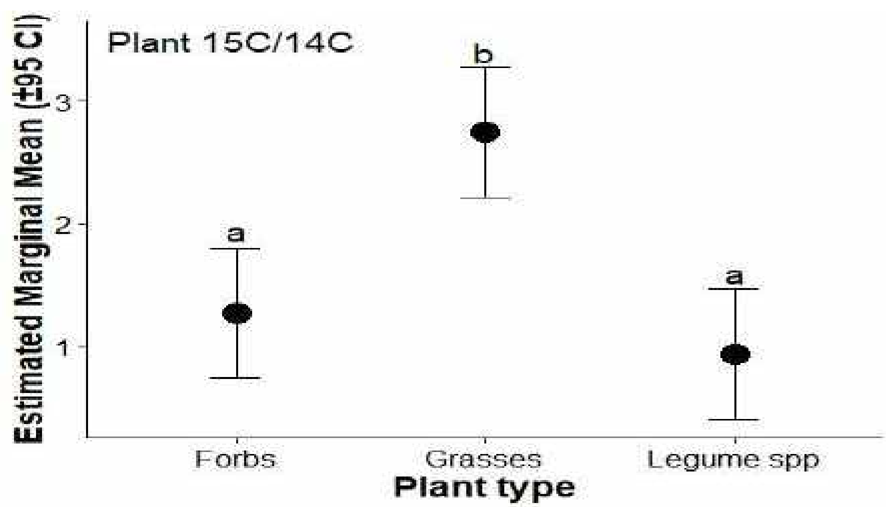

Figure 3: Carbon isotope ($\delta^{13}C$) nutrition of legume *(L. cuneata*) and different companion plant species growing in Kubedlana communal area.

Discussion

The $\delta^{13}C$ signature of grasses was significantly higher (less negative) than that of forbs and legumes. The type of pasture had a significant effect on $\delta^{13}C$. Grasses typically have higher $\delta^{13}C$, whereas legumes typically lower $\delta^{13}C$ than both forbs and grasses due to differences in C isotopic fractionation during CO_2 assimilation. The basis of the use of $\delta^{13}C$ procedure is that legumes (C3) species discriminate against ^{13}C during photosynthesis to a greater extent than do grasses (C4) species. Due to this fractionation during photosynthesis, C3 plants typically contain approximately 14 parts per thousand less carbon-13 than C4 plants. There was a notably clustering of plant functional groups where legumes and grasses separated along NMDS 1. The observed range of foliar $\delta^{15}N$ values for the legumes was notably smaller in comparison to grasses and forbs; respectively. This finding is consistent with the findings made by (Gerschlauer *et al*.,2019); who argued that $\delta^{15}N$ values of plants that mainly rely on N_2 fixation are usually - 0 ‰, reflecting atmospheric isotopic N values (Enriquez-Hidalgo *et al*.,2015). Craine *et al*.,2015b), also alluded that most N_2-fixing plants show significant departures from 0 ‰ due to differences in reliance on fixed N. The strong depletion of $\delta^{15}N$ in legumes compared to the forbs and grasses is an indication that legumes largely relied on atmospheric N. Foliar N concentration ranging at (-3.14 ‰ and -7.02 ‰) for legumes, which was lower than (4.65 ‰ and 7.91 ‰) for grasses and (-0.88‰ and 4.35 ‰) for forbs, respectively were found in the current study. Unkovich (2013); also argued that variations in $\delta^{15}N$ of symbiotic N_2 fixation were not necessarily the product of N_2-fixation, but rather a combination of measurement errors, intra-plant fractionation events resulting in tissue differences and possible preferential losses of ^{15}N-depleted NH_3. Higher values of $\delta^{15}N$ depicted by grasses are an indication that grasses depend, to some extent, on N from non-symbiotic N_2 fixation or from the soil.The $\delta^{15}N$ value, is a widely used indicator of nitrogen cycling and sources within ecosystems. The observed pattern in the current study, where grasses and forbs exhibit higher $\delta^{15}N$ values compared to legumes, can be ascribed to numerous underlying mechanisms such as nitrogen fixation, nitrogen cycling and fractionation, nitrogen acquisition strategies and environmental conditions. Legumes have the unique ability to fix atmospheric nitrogen (N_2) through a symbiotic relationship with nitrogen-fixing bacteria (e.g., *Rhizobium*). Consequently, legumes typically exhibit lower $\delta^{15}N$ values compared to plants that rely on soil-derived nitrogen sources, such as grasses and forbs.

Conclusion

In conclusion, the observed differences in the ^{13}C isotope composition among the plant types (grasses, forbs, and legumes) growing in the old arable lands of the Eastern Cape, South Africa, are primarily driven by their distinct photosynthetic pathways and carbon acquisition strategies. The observed shift in ^{13}C content, where grasses exhibited higher ^{13}C content compared to forbs and legumes, can be attributed to the distinct photosynthetic pathways employed by these plant types. Grasses, which primarily utilize the C4 photosynthetic pathway, usually possess higher ^{13}C content due to the efficient carbon-concentrating mechanisms involved in this pathway. In contrast, forbs and legumes, which predominantly utilize the C3 photosynthetic pathway, exhibit lower ^{13}C content. This difference in ^{13}C content reflects the distinct carbon isotope discrimination patterns associated with the C3 and C4 photosynthetic pathways. Therefore, the observed differences in the ^{15}N isotope composition among the plant types (grasses, forbs, and legumes) in the old arable lands of the Eastern Cape, South Africa, can be attributed to the distinct nitrogen acquisition and cycling processes associated with each plant functional group. The higher $\delta^{15}N$ values in grasses and forbs reflect their reliance on soil-derived nitrogen, while the lower $\delta^{15}N$ values in legumes are a result of their ability to fix atmospheric nitrogen. The observed higher δ15N values during the dry season and lower values during the rainy season can be attributed to the variations in water availability and its impact on nitrogen cycling processes. Several studies have shown that water availability is a key driver of $\delta^{15}N$ values in ecosystems, regardless of other factors such as soil nitrogen stock. During drier periods, reduced water availability can lead to increased soil nitrogen mineralization, nitrification, and volatilization, which preferentially remove the lighter 14N isotope and enrich the remaining soil nitrogen with the heavier 15N isotope.

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The grazing effects on GPP in Inner and Outer Mongolia grasslands under climate change and divergent grassland use systems

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Key words: Temperate grassland; GPP; Grassland-use system; Trans-boundary research

Abstract
Global climate change and divergent grassland use systems may lead to divergence and degradation of grassland systems in arid and semi-arid regions. However, the effects of grazing intensity on the gross primary productivity (GPP) of grasslands under climate change and the nomadic versus sedentary grazing systems are still unclear. Here, we investigate the grazing effects on different steppe ecosystems by comparing a ratio index change of nomadic GPP to sedentary GPP (NS) under different grazing intensities. The grassland GPP increased significantly between 2001-2023 across three grazing intensities under nomadic and sedentary grazing systems. The NS index in desert and meadow grasslands increased and then decreased across grazing intensities, with 2012 being the turning point. Surprisingly, the typical grasslands exhibited the opposite characteristics. The impact of differences in grazing systems did not exceed the regulatory role of climatic factors. Random forest analysis revealed that the minimum temperature ratio of the coldest month of nomadic to sedentary sites was the dominant factor influencing the NS index in desert and meadow grasslands. In typical grassland, the precipitation ratio of the warmest quarter of nomadic to sedentary sites is predominantly the NS index. Our study highlights the impact of changing climatic environments on the grassland GPP in the semi-arid region.

Introduction
Grazing reshapes vegetation communities' structure, composition, and function through feeding, urination, trampling, and seed dispersal (Ren *et al.*, 2024). The protection of semi-natural grasslands has relied on the maintenance of traditional nomadic systems for hundreds or even thousands of years (Deng *et al.*, 2023).

The traditional nomadic system is an inheritance that simulates the migratory behavior of wild herbivores. With the development of society and economy, some traditional nomadic grazing methods on common grasslands have gradually been transformed into fenced sedentary grazing on private pastures (Parra *et al.*, 2025). However, to our knowledge, the differences in the impacts of different grazing systems and intensity changes on grassland vegetation communities under the context of climate change remain unclear.

The grasslands of the Mongolian Plateau (MP), a significant portion of the Eurasian continent's temperate grasslands, are primarily found in Mongolia (UM) and China's Inner Mongolia Autonomous Region (IM). They are vital for regional ecological security and the livestock economy. However, the interaction of grazing and climate change has led to severe grassland degradation, posing an urgent challenge for sustainable grassland management in the region. The MP is a complete physical geographical unit. The parts of IM in China and UM have the same climate, biological evolution history, and similar modern climates, soil, and vegetation types. However, human activities driven by changes in land use policies show significant differences in the two countries. In the IM, an extensive sedentary grazing utilization mode has been formed, while in UM, traditional grassland nomadism is still practiced. Although many studies have focused on the impact of the combination of grazing methods, intensities, and climate change on the UM grassland ecosystem, most of them are limited to a single region within IM or UM and focus on the grassland conditions under different land uses. There is a need for comprehensive, cross-border studies to assess the impact of varying grassland utilization systems on vegetation productivity. Understanding these impacts and mechanisms is crucial for restoring degraded grasslands and developing sustainable management practices, ensuring regional ecological security.

Methods

The study area, situated in the central MP, encompasses desert, typical, and meadow grasslands in the IM and UM regions. July–August 2023, we identified 18 paired fenced experimental areas, which have been enclosed for 10 to 60 years, across these grassland types. Within a 30 km radius of each fenced plot, we established 36 additional paired experimental areas with varying grazing intensities, including light and heavy grazing under different methods (traditional nomadic grazing in UM and free grazing within fenced paddocks in IM). These 54 experimental areas served as the basis for a 4 km^2 buffer zone, which was used to analyze MODIS GPP data for each site in 2001-2023 (Fig. 1). The RFM method was used to analyze the driving mechanisms of the differences in GPP under different climatic conditions and grassland utilization patterns.

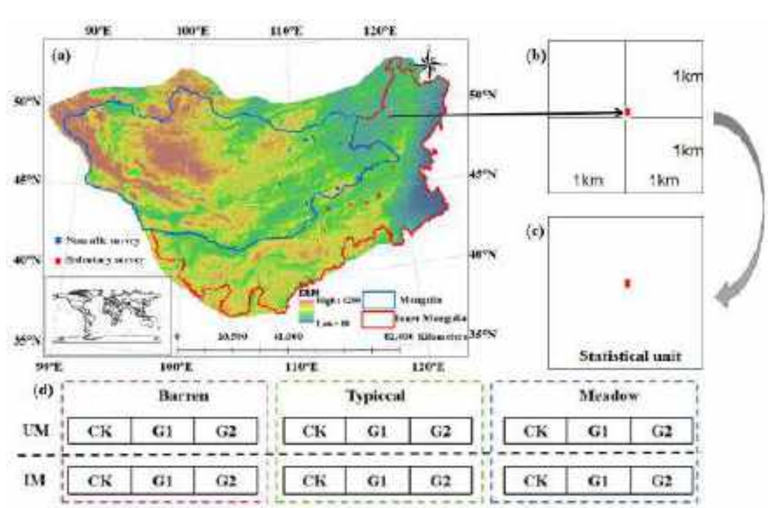

Fig. 1 Study area and experimental design. CK: Fenced, G1: Medium Grazing, G2: Heavy Grazing.

Results

Moderate grazing promotes the increase of vegetation GPP

From 2001 to 2023, the vegetation GPP in the fenced, lightly grazed, and heavily grazed experimental areas all showed a significant increasing trend (Fig. 2(a-c)). Under both the traditional nomadic grazing and fenced grazing systems, the typical grasslands and meadow grasslands are both applicable to the "Intermediate Disturbance Hypothesis" (IDH). The average value of vegetation GPP from 2001 to 2023 was the highest under light grazing, followed by the fenced and ungrazed grasslands, and finally the heavily grazed plots. Regardless of the grazing system, the vegetation GPP of the desert was more suitable for the Dynamic Disequilibrium Hypothesis (DDH).

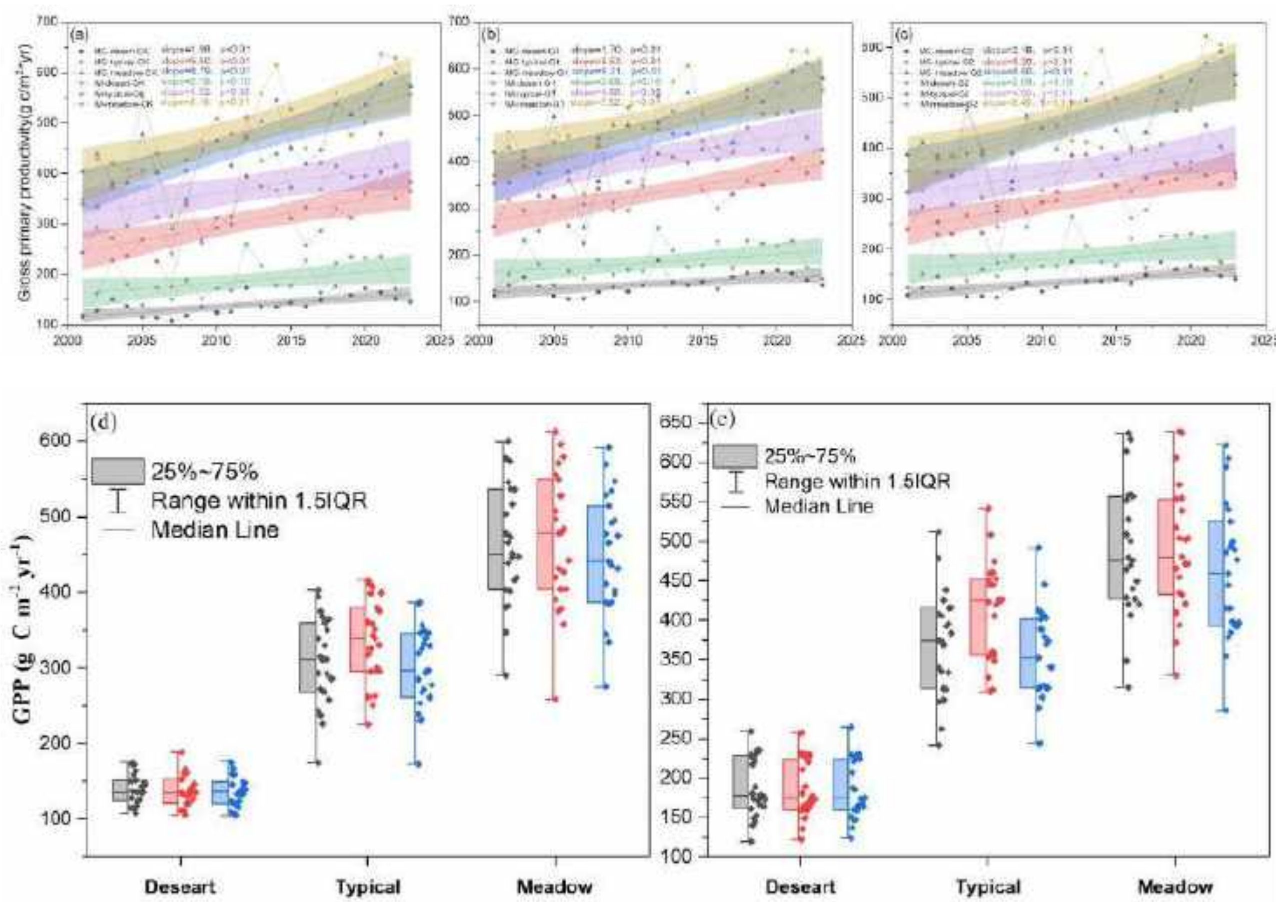

Fig. 2 Vegetation GPP changes along the grazing gradient under different grazing systems in 2001-2023.

Climate Impacts on Vegetation Surpass the Effects of Grazing Regimes

In 2001-2023, the ratio changes of vegetation GPP in the nomadic vs sedentary grazing systems in the enclosed and grazed experimental zones across desert grasslands and meadow grasslands both exhibited a pattern of initial decline followed by an increase, predominantly driven by the minimum temperatures during the coldest months. However, the ratio changes of vegetation GPP in the fenced experimental areas of typical grasslands showed a trend of increasing and then decreasing, which was mainly regulated by the average temperature in the warm season. The impact of differences in grazing systems did not exceed the regulatory role of climatic factors. Under the traditional nomadic system, the trend of the ratio change of

GPP of vegetation under light and heavy grazing to that under free grazing within fenced paddocks was consistent with the trend under the fenced state. However, under the influence of grazing factors, the regulatory factors became the variability of temperature (for desert and meadow grasslands) and the rainfall in the warm season (for typical grasslands)

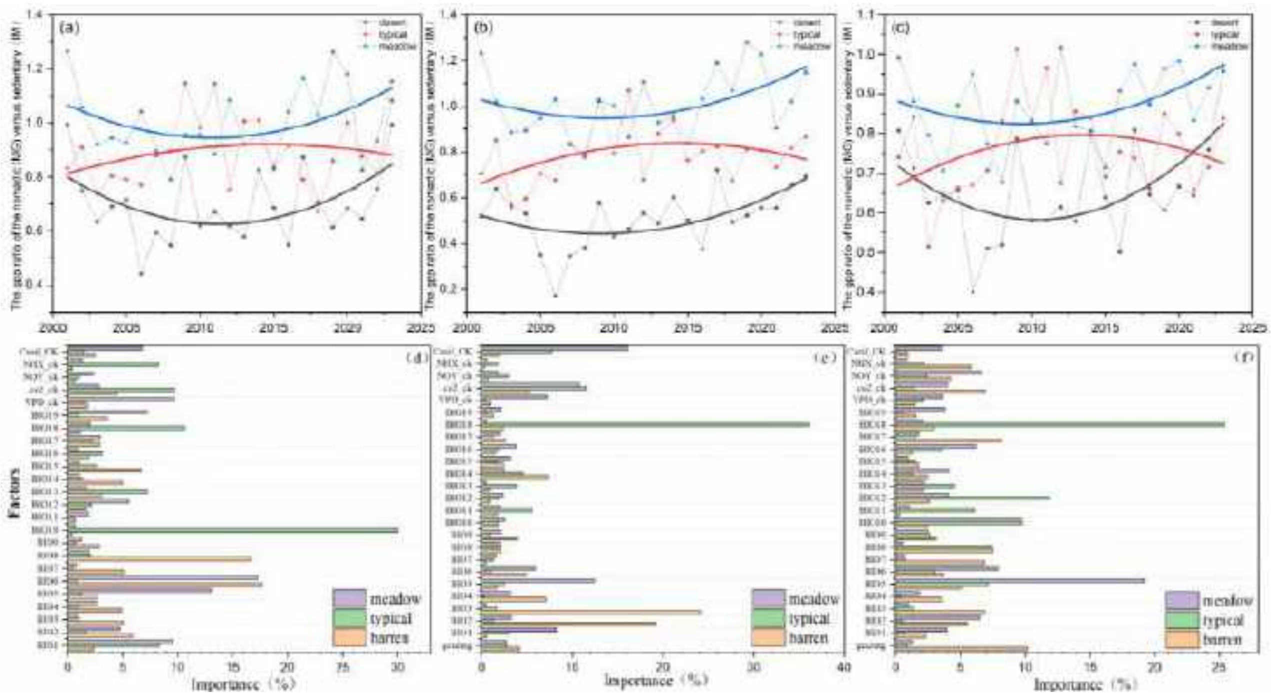

Fig.3 The differential changes in vegetation GPP under different grazing systems in 2001-2023 and their driving factors. (a), (b), (c) and (d), (e), (f) represent the grazing gradients of CK, G1, and G2 respectively.

Discussion

Grazing practices and climate change influence vegetation community productivity, with temperature variability being a key driver of GPP changes across different grazing systems. The IDH applies to the vegetation in the typical grassland areas and meadow areas that are semi-arid and semi-humid (Vidaller *et al.*, 2022). Whether under the traditional nomadic system or the sedentary grazing system, medium grazing will promote the vegetation productivity of the typical grasslands and meadow grasslands; while heavy grazing will reduce the vegetation productivity of the typical and meadow grasslands (Parra *et al.*, 2025). Desert vegetation GPP is highly unstable under any grazing system (Deng *et al.*, 2023; Palmer *et al.*, 2016). In fenced areas, the productivity difference between nomadic and sedentary grazing systems is primarily controlled by the annual minimum temperature, whereas under grazing conditions, it is influenced by temperature variability. Thus, controlling grazing intensity in desert areas and implementing moderate grazing in typical and meadow grasslands is crucial to restoring productivity. Additionally, strict policies to reduce greenhouse gas emissions and temperature variability are essential for mitigating extreme climate events and enhancing regional vegetation productivity.

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Understanding the challenges in Libyan rangeland conservation: exploring pathways to sustainable rehabilitation

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Key words: arid rangelands; degradation; rehabilitation; paradigm shift.

Abstract

Libya, spanning 1.75 million km², has rangelands covering 7.7% of its area, supporting approximately six million sheep, goats, and camels. Historically, pastoralism has been the primary land use, deeply intertwined with the socio-economic fabric for millennia. Despite significant government investments in agricultural and rangeland development, these ecosystems have suffered extensive degradation in terms of declining vegetation cover, biodiversity loss, reduced soil fertility, and diminished productivity reflect a broader pattern seen across North Africa. The degradation of Libyan rangelands is rooted in decades of mismanagement, exacerbated by the government's frequent disregard for scientific recommendations and reliance on external consultants unfamiliar with local ecological and socio-economic contexts. Additionally, socio-economic changes, particularly following the oil boom of the 1960s, disrupted traditional grazing systems, while the limited involvement of local communities hindered effective conservation efforts. A significant challenge lies in balancing conservation initiatives with the livelihoods of pastoralists and local communities, often leading to conflicts of interest. This overview work underscores the urgent need for a paradigm shift toward holistic and adaptive strategies that integrate ecological, socio-cultural, and governance dimensions to address the challenges facing Libya's rangelands. Reforming rangeland survey methodologies, adopting sustainable rehabilitation techniques, and implementing controlled grazing regimes are critical steps in this process. Equally important is fostering active community participation to align conservation goals with local needs and interests. By pursuing locally informed and inclusive approaches, Libya can restore the resilience of its rangelands, ensure ecological sustainability, and support the livelihoods of local communities.

Introduction

North Africa is dominated by extensive steppe and Saharan landscapes, where pastoralism has been a cornerstone of human activity since ancient times. Traditionally, pastoralism was nomadic, relying on herding and animal husbandry under an open communal grazing system. Over the past century, profound societal transformations have significantly impacted the region's rangelands (Dutilly-Diane, 2007). Harsh environmental conditions, a history of mismanagement, population growth, and increasing demand for livestock products have collectively disrupted ecological processes in these semi-arid and arid regions.

Libya's landscapes in particular, are distinguished by diverse terrains, geological formations, and significant climatic variations across its regions. Rangelands form a considerable part of the country's territory, covering approximately 13.2 million hectares. These rangelands primarily consist of arid ecosystems, stretching across the northern regions, around oases, and in mountainous areas within the desert interior. They are characterized by sparse vegetation, with limited perennial grasses and a dominance of drought-resistant shrubs (Shaghlan et al., 2023).

Pastoralism has been the predominant land use across Libya for countless generations, with rangelands serving as a vital resource for indigenous communities (El-Barasi and Saaed, 2013). These ecosystems have historically provided resources for animal fodder and ethnobotanical services. They have also been essential as hunting grounds for wild birds and animals (Saaed et al., 2022). Furthermore, they act as a critical barrier against desert encroachment from the south. However, extensive research (e.g., El-Barasi et al., 2013; Saaed et al., 2019; Habib et al., 2022; Saaed et al., 2022) reveals that Libyan rangelands face escalating threats from unsustainable anthropogenic activities and climate change. These ecosystems are particularly fragile due to limited and unpredictable rainfall (Al-Bukhari et al., 2018), low soil organic matter and nutrient levels, sparse vegetation cover, and a non-equilibrium ecological system (El-Barasi and Saaed, 2013; Habib et al., 2022).

This overview work aims to shed light on Libya's rangeland experience, detailing its historical context, current condition, and outlining a future vision for sustainable rehabilitation and management. It emphasizes the critical, yet often overlooked, factors that have contributed to the persistent failure of past efforts to improve Libya’s rangelands over recent decades.

Environmental settings

With its vast area (1.75 million km²), Libya is the second-largest country in North Africa, lying along the southern Mediterranean coast and heavily influenced by the arid Sahara Desert (Fig. 1). Over 90% of its land is desert, except for a narrow coastal strip up to 150 km wide (El-Barasi & Saaed, 2013). The country has a 1,900 km Mediterranean coastline, with a predominantly flat topography broken by the Jabal Nafusa in the west, El-Jabal El-Akhdar in the east, and southern mountain ranges (Jansen, 1988). Libya is divided into two main phytogeographical regions: the Sahara, characterized by extreme aridity and sparse vegetation, and the Mediterranean coastal belt, which receives higher rainfall and supports richer vegetation (Saaed et al., 2019).

Situated between 19° and 33° north latitude, Libya is one of North Africa's driest regions, dominated by subtropical high-pressure systems that create pervasive aridity. Rainfall is limited to winter, with high variability and localized "thunderstorm cells," making it the primary surface water resource in the absence of perennial water sources (Saaed et al., 2022). About 91% of Libya is hyper-arid desert with under 50 mm of annual rainfall, 8% is rangeland receiving 50–200 mm, and only 0.7% is agricultural land receiving 200–400 mm. Forests make up 0.3% of the land in areas with over 400 mm of rainfall. Annual plants flourish briefly in the rainy season, while perennials form the main vegetation framework, varying with soil, water, and climate conditions. Temperatures range from 5°C to 35°C in the north and from below freezing to over 45°C in the southern desert. The harsh climate and sandy soils dominate much of Libya, with clay and loam soils found in localized northern areas, red soils in highlands, and saline soils along coastal regions and interior oases.

Fig. 1. The distribution of rangeland and forest areas in Libya

Rangelands current state

Archaeological evidence shows that human populations in Libya have been herding sheep and goats for over 7,000 years (Barker et al., 2012). Land use historically included grazing, grain cultivation, firewood collection, charcoal production, and harvesting plants for food, medicine, and construction and handicraft raw materials. Valleys and mountains provided habitats for birds and wildlife, essential for food and traditional medicine as well (Saaed et al., 2019). Pastoralism has long been privately managed, with nomadic households once comprising >5% of the population (Le Houerou, 1975). However, nomadism has nearly vanished, and most rural people now live-in cities. Livestock ownership has shifted from small subsistence flocks to larger commercial herds exceeding a thousand animals. Mechanized water transport and supplemental feeding allow year-round grazing in the same range, disrupting ecological balance and exacerbating rangeland degradation (Sidahmed, 1996).

Since 1960, Libya's livestock population has grown 3.5 times, surpassing the rangelands' carrying capacity, estimated at 2.8 million mature sheep (Le Houerou and Aly, 1982). Currently, livestock numbers are approximately 190% of this capacity, with rangelands contributing about 25% of livestock forage (Dutilly-Diane, 2007) in good years. This limited production is attributed to reduced reliance on rangelands, driven by sedentary production systems and complementary feeding practices. Degradation is evident in declining vegetation cover, biodiversity loss, and the spread of invasive species. In many areas, perennial vegetation has fallen below 25%, while soil erosion and fertility loss have rendered the landscape increasingly dysfunctional, jeopardizing ecosystem stability and wildlife survival (El-Barasi et al., 2013; Shaghlan et al., 2023).

Challenges and limitations in rangeland rehabilitation

Since Libya's independence in 1951, agriculture, livestock, and rangelands were prioritized as key economic sectors before the discovery of oil. Early efforts included studies and rehabilitation initiatives in collaboration with international organizations, like the FAO, involving numerous experts in rangeland management. However, despite these efforts, limited progress has been achieved in improving rangelands. Key obstacles include inadequate understanding of ecosystems, ineffective resource management, and insufficient awareness of the long-term consequences of degradation (Saaed et al., 2019). Management practices often conflicted with regional ecology, such as large-scale tree planting in areas naturally dominated by sparse shrubs, disrupting ecological balance. Additionally, rangeland projects have largely excluded local communities, whose involvement in protection and rehabilitation remains minimal despite recent acknowledgment of its importance. Political instability and weak legal protections have further hindered progress, leaving rangelands vulnerable to degradation and overexploitation. Foreign-led conservation efforts often overlooked local cultural, historical, and tribal dynamics, while unregulated communal grazing continues to exacerbate degradation. The population surge, from 1.089 million in 1954 to 6.931 million in 2020, has added further strain on natural resources. Balancing the economic, cultural, and social needs of rangeland residents with conservation objectives remains a significant challenge, particularly as these fragile landscapes, dominated by xerophytic shrubs, are highly vulnerable and challenging to rehabilitate.

Looking forward

Rehabilitation in arid and semi-arid regions, such as those in Libya, is inherently complex and challenging due to their unique biodiversity, limited rainfall, and the intricate spatial and biological dynamics driven by stochastic events (Carrick et al., 2015). Additionally, these areas are often subject to significant anthropogenic pressures due to the scarcity of natural resources (Saaed et al., 2022). To enhance biodiversity, maintain ecological processes such as clean air and water, and achieve sustainable management and rehabilitation of Libya's degraded rangelands, several strategies are proposed. First, comprehensive ecological studies should be conducted to better understand the drivers of rangeland degradation, ecological thresholds, and potential recovery opportunities, with an emphasis on soil studies, vegetation mapping, and climate impact assessments. Second, protected areas should be established, aiming to safeguard at least 5% of the rangelands within the next decade, accompanied by clear management plans focused on conservation and sustainable use. Third, a reform of the pastoralism system is necessary, transitioning from communal grazing to a controlled, closed, rotational grazing system that enhances vegetation recovery and soil stability. This could be supported by education programs for local communities and infrastructure like fenced enclosures and designated grazing zones, while also reducing the number of domestic grazing animals to under three million head. Fourth, enforcing a ban on rainfed agriculture in arid zones with less than 250 mm/year of rainfall is critical, with incentives for alternative practices like greenhouse farming or agroforestry. Fifth, anthropogenic activities such as wood gathering, medicinal plant collection, overhunting, and pollution need to be regulated through strict laws and monitoring systems, promoting sustainable alternatives like regulated harvesting and waste management. Sixth, providing alternative livelihoods for local communities can mitigate dependence on unsustainable practices, through programs such as ecotourism, solar energy jobs, and small-scale industries like beekeeping and craft production. Special attention must be paid to local populations; their activities should not be banned but adapted to the area's potential, with a focus on altering behaviour to maximize economic gain while minimizing environmental costs (El-Barasi and Saaed, 2013). Seventh, long-term rehabilitation programs should focus on landscape functionality, prioritizing soil health, water retention, and the recovery of native vegetation, supported by large-scale seeding programs and the use of modern techniques like hydrological interventions and remote sensing. Eighth, the promotion of renewable energy, particularly solar power, should be encouraged through community-based solar projects and subsidies for solar panel installation to reduce reliance on traditional fuels. Ninth, local communities must be educated and empowered through workshops, awareness campaigns, and training programs on sustainable practices and the importance of preserving rangeland ecosystems. Lastly, strong policy frameworks are essential for supporting sustainable rangeland management. This entails updating national policies to prioritize rangeland conservation, enforcing anti-degradation laws, and securing funding for rehabilitation and research. Implementing these strategies can transform Libya's rangelands from degradation to a sustainable and productive system that supports both the environment and local communities.

Conclusion

The sustainable management and rehabilitation of Libya's rangelands require a multifaceted approach that integrates ecological understanding, community engagement, and effective policy frameworks. The proposed strategies—ranging from ecological studies and the establishment of protected areas to the promotion of renewable energy and alternative livelihoods—aim to address the root causes of degradation while ensuring the resilience and profitability of rangeland systems. By prioritizing both environmental conservation and the socioeconomic needs of local communities, Libya can foster a balanced and sustainable future for its rangelands, securing their ecological integrity and long-term viability for generations to come.

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Modeling the distribution of *Vachellia tortilis* (forssk.) in Tunisian drylands under climate change scenarios

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Key words: Climate change; habitat; modeling; drylands.

Abstract

Biodiversity conservation, through the creation of national parks, is generally helping to maintain a greater level of resilience within ecosystems and to protect the natural plant cover and threatened plant species. This research was conducted in Bou Hedma national park, a UNESCO-MAB biosphere reserve containing the unique *Vachellia tortilis* (Forssk.) Gallaso & Banfi steppe with trees in Tunisia. The focus is to explore how the distribution of suitable habitat for *V. tortilis*, might shift under climate change scenarios using Maxent modeling algorithm. The Canadian Earth System Model version 5 (CanESM5) was used for projecting the future distribution. The model was run under two Shared Socioeconomic Pathways (SSP245, SSP585) during four time periods (2021-2040, 2041-2060, 2061-2080 and 2081-2100). The tested climate change scenarios seem affecting the specie's suitable habitat in the park. Three soil variables (Clay, Coarse, WRB Classes) are significant factors in determining *V. tortilis*'s suitable habitat. Distribution modeling provides valuable information for managers to implement suitable strategies to conserve this endemic, rare and threatened plant tree and the overall ecosystem.

Introduction

Dryland ecosystems are threatened both by climate variations and human disturbance (Millennium Ecosystem Assessment (MEA) 2005). Increased temperature, variability in rainfall and severe droughts are the main climatic conditions threatening the ability of these ecosystems to produce (Yao et al. 2020) and represent significant problems to biodiversity conservation both by altering habitats and affecting species distributions (Hilbert et al. 2007). Active management is recently considered as the major challenge for maintaining biodiversity and reducing natural resource degradation and combat desertification (Gamoun and Louhaichi 2021). The establishment of national parks is one of the main strategies to achieve biodiversity conservation (Ouled Belgacem et al. 2019) and to preserve the natural plant cover as well as the threatened plant species in arid and desert area of Tunisia and all around the world (Ouled Belgacem et al. 2008).

Vachellia tortilis (Forssk.) Gallaso & Banfi (Fabaceae) is a "Keystone species", widely distributed in arid and semi-arid ecosystems of North, East and Southern Africa, the Middle East and the Arabian Peninsula

(Taha et al. 2022). It is well adapted to disturbances (drought, fire and browsing) (Noumi and Chaieb 2012). It is also known by the ability to improve the soil fertility and to increase biodiversity (Abdallah et al. 2008). This study focuses on modeling the distribution of *V. tortilis* in Bou Hedma national park under both optimistic and pessimistic climate change scenarios. By examining the shifts in suitable and unsuitable habitats, we aim to understand the potential impact of climate change on this vital species and inform conservation strategies to optimize its future safeguarding.

Methods

Study area

Bou Hedma national park (34.476102 N, 9.649239 E; Figure 1), created in 1980, plays a key role in the conservation of flora and fauna biodiversity and contains the unique *V. tortilis* steppe with trees in Tunisia (Tarhouni 2003). It is characterized by an arid Mediterranean bioclimate (Le Houérou 1969). The average annual rainfall varies between 100 and 200 mm. The average annual temperature is about 17.2°C.

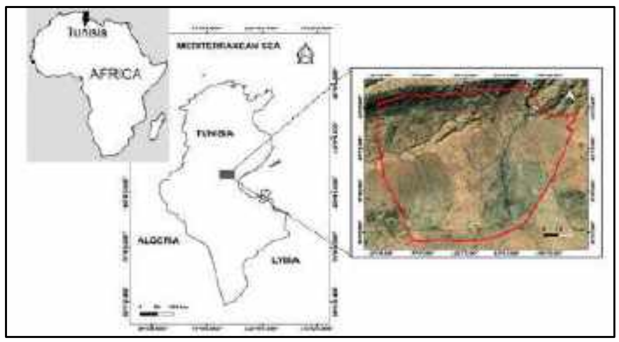

Fig. 1 Geographical location of Bou Hedma national park

Environmental variables & species distribution modeling

The undertaken environmental data is downloaded from the "WorldClim" database (www.worldclim.org) (19 bio-climatic variables from each time-period (2021-2040, 2041-2060, 2061-2080 and 2081-2100) in addition to three topographical ones) and from the soil grids database (www.soilgrids.org) (12 soil variables). All these variables are used to model the current and future distribution of *V. tortilis* according to the Canadian Earth System Model version 5 (CanESM5) predictions under two Shared Socioeconomic Pathways (SSP245, SSP585).

Results

Model validation and influencing variables

It is clear from table 1 that the Maxent model showed good predictive ability with an Area Under Curve (AUC) ranging from 0.854 to 0.894.

Table 1 Area Under Curve (AUC) of the distribution of Vachellia tortilis under current (2018) and future climate scenarios (SSP245, SSP585) according to the Canadian Earth System Model version 5 (CanESM5) in Bou Hedma national park.

	Current	**SSP245**				**SSP585**			
	2018	**2021-2040**	**2041-2060**	**2061-2080**	**2081-2100**	**2021-2040**	**2041-2060**	**2061-2080**	**2081-2100**
AUC	0.855	0.866	0.871	0.888	0.862	0.854	0.877	0.894	0.855

Under both scenarios, it seems that coarse and soil classes-WRB are the strongest predictors of *V. tortilis* distribution with respectively 42.15% and 14.87%, under SSP245, and 31.92% and 27.6% under SSP585 (Figure 2). Bio17 and clay are also important but with lesser contributions (respectively 6.47% and 7.92% under SSP245; 5.9% and 6.05% under SSP585).

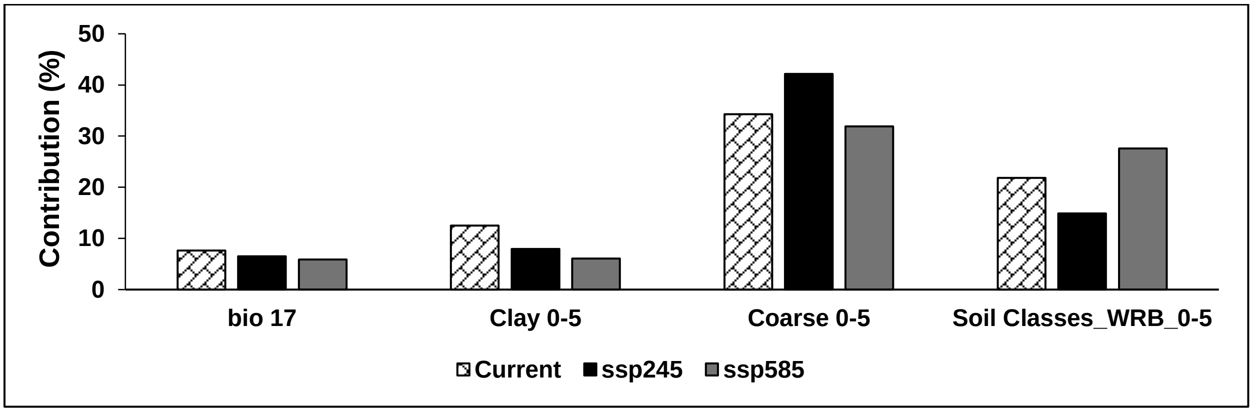

Fig. 2 Contribution (%) of bio-climatic and soil variables when predicting the distribution of Vachellia tortilis in Bou hedma national park using MaxEnt model.

Habitat suitability for Vachellia tortilis

The results of Maxent are represented in table 2 and figure 3. Under current climate condition, Maxent indicated that 214.30ha are suitable (very high potential, VHP) for *V. tortilis* to grow (table 2). The species is covering some hectares in the south-western and the south east parts of the park (figure 3). In the center, it occurs over a large area of Moderate (MP) to high (HP) potential (911.24ha and 650.41ha respectively) (table 2). In the North parts, the habitat of the species seems to be completely unsuitable (low potential, LP) (1386.23ha).

Table 2 Changes in suitability of Vachellia tortilis habitat (ha, %) from the current situation to 2100 according to SSP245 and SSP585 scenarios from the Canadian Earth System Model version 5 (CanESM5).

		Area (ha)				**Changes (%)**			
		LP	**MP**	**HP**	**VHP**	**LP**	**MP**	**HP**	**VHP**
2018	**Current**	1386.23	911.24	650.41	214.30	-	-	-	-
2021-2040	**SSP245**	1438.74	877.33	604.44	241.66	3.79	-3.72	-7.07	12.77
	SSP585	1483.95	776.50	620.90	280.82	7.05	-14.79	-4.54	31.04
2041-2060	**SSP245**	1563.42	968.24	400.14	230.38	12.78	6.25	-38.48	7.50
	SSP585	1532.24	836.02	529.69	264.23	10.53	-8.25	-18.56	23.30
2061-2080	**SSP245**	1770.51	765.44	385.30	240.92	27.72	-15.10	-40.76	12.42
	SSP585	1579.14	890.07	470.93	222.04	13.92	-2.32	-27.60	3.61
2080-2100	**SSP245**	1350.39	986.24	620.32	205.23	-2.58	8.23	-4.63	-4.23
	SSP585	1579.47	967.20	386.48	229.04	13.94	6.14	-40.58	6.88

Under SSP245, climate change could increase the most suitable habitat (very high potential) with 12.77%, 7.50% and 12.42% in 2040, 2060 and 2080 respectively, and a decrease of 4.23% in 2100. SSP585 showed also a great increase of very high potential that reached 31.04% by 2040 (table 2). Using the future MaxEnt layers, the predicted distribution map (figure 3) indicates a decrease in areas of moderate and high potentials in the center of the park, where the unsuitable areas (low potential) will dominate.

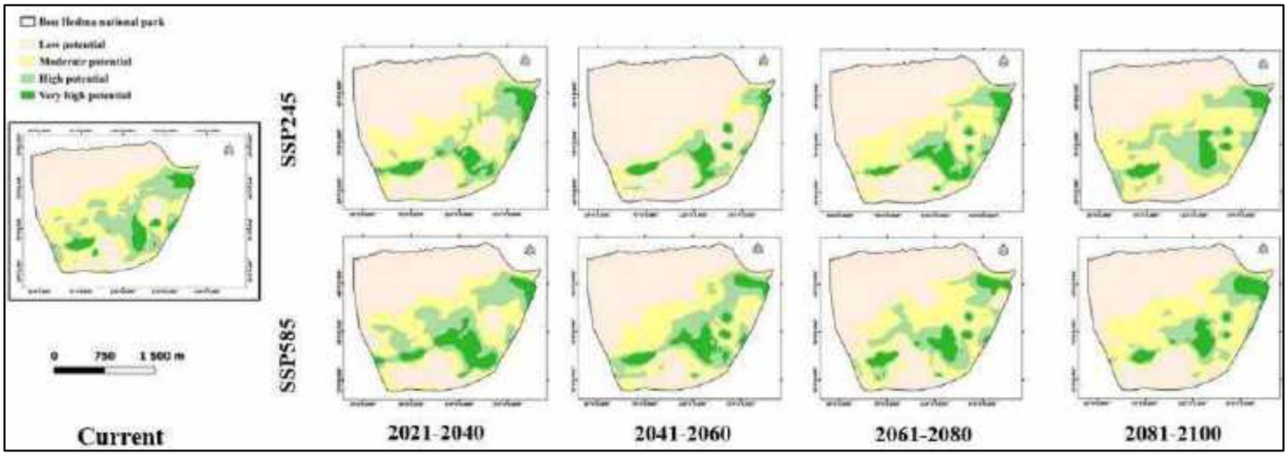

Fig. 3 Changes in suitability of Vachellia tortilis habitat under SSP245 and SSP585 climate change scenarios of the CanESM5 model.

Discussion

To guide conservation priorities and management planning, predictive vegetation models could help to identify hotspots of environmental change or plant habitat suitability (Bedair et al. 2023). Species distribution and predictive vegetation models represent excellent tools to mitigate the impact of climate change (Capera et al. 2023), especially the MaxEnt model, which requires datasets of actual presence called "Occurrences", and will be helpful in identifying suitable area for future habitats. *Vachellia tortilis*, in Bou Hedma national park, seems to follow a kind of regressive dynamic proved by the replacement of suitable area by the unsuitable ones. Similar results are showed by Anthelme and Michalet (2009) who demonstrated the absence of regeneration of *V. tortilis* in the Air-Tenere Nature Reserve (Sahara, Niger) under climate change. The low regeneration of *V. tortilis* in Bou Hedma could be explained by the dominance of large and aged individuals in one hand (Noumi and Chaieb 2012) and by the negative interaction between *V. tortilis* and other plant species in the other hand (Noumi et al. 2023).

The obtained results indicate that the distribution of *V. tortilis* is significally influenced by soil texture, especially the presence of clay and coarse particles. Several studies emphasized the crucial role of edaphic factors in enhancing the accuracy of projection (Buri et al. 2017). Clay soils, known for their water retention capabilities (Romero et al. 2011), may provide necessary moisture during dry periods, while Coarse particles enhance soil aeration and drainage (Bigelow et al. 2001). This combination of soil properties creates an optimal environment for the establishment of *V. tortilis* in arid and semi-arid ecosystems (Ludwing et al. 2003; Yadeta et al. 2018).

Conclusion

Distribution of *Vachellia tortilis* is modeled under optimistic and pessimistic climate change scenarios. In the future of Bou Hedma national park, unsuitable habitats of *V. tortilis* will increase and take place of suitable area. This regressive dynamic indicates that the species is situated under greater danger and highly sensitive to climate change. Such results can be very useful to conserve habitats of this threatened species. Recommendations are given to protect and to enhance the current *Vachellia* suitable area.

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Central Asian Winter Cold Desert Rangelands (CACDR): Climate-smart approaches towards restoration and conservation

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Key words. C_3/C_4 plants, halophytes, aridity index, salinization, pasture restoration, Aral Sea basin

Abstract:
The cold winter rangelands of the Aral Sea basin are among the world's biodiversity hotspots, providing unique habitats, breeding grounds, migration corridors, and flyways for rare and endangered species of plants, animals, and birds. Situated along the historic "Silk Road," the Central Asian Cold Desert Rangelands (CACDR) are also the origin of many cultivated crops, including wheat, rye, barley, legumes,

roots, tubers, and fruit trees. However, the increasing frequency of droughts due to climate and human affected changes is expected to exacerbate and further reduce the productivity of already degraded rangelands. Additionally, soil salinization, one of the major issues affecting agriculture, significantly decreases vegetation cover, botanical diversity, and the palatability of key species.

This study introduces a novel assessment of isotope screening for salinity and drought tolerance in key C_3 and C_4 halophytes. These halophytes, cultivated on various arid and semi-arid rangelands, are evaluated based on their life forms, root depths, and biomass yield production. The Circular Halophytic Mixed Farming (CHMF) system is explored as a strategy to improve the productivity of rangelands impacted by salinization and drought. This system involves intercropping halophytes with salt-tolerant non-conventional crops (NCCs) such as wild succulents, amaranthus, foxtail, pearl millet, licorice, artichoke, sesame, and sorghum. Within a single growing season, the CHMF system can remove approximately 1.8 kg of NaCl equivalent per kilogram of dry soil.The harvested biomass from halophytes serves as a bioenergy source and as livestock feed when mixed with traditional crops in specific proportions. Re-seeding and 'seed isles' techniques—utilizing species such as *Haloxylon ammodendron, Xylosalsola paletzkiana, X. richteri, Halothamnus subaphyllus, Artemisia halophylla, Caroxylon orientale*, and *Bassia prostrata*—are employed to establish pastoral agrophytocenoses, shelters, windbreaks, and to enhance the productivity of salt-affected pasturelands. These innovative rangeland restoration technologies aim to address the ongoing degradation of indigenous knowledge systems and promote sustainable management of arid and semi-arid ecosystems.

Introduction

The deserts of Central Asia represent the northernmost and coldest edge of native C_4 plant growth, showcasing a globally unique taxonomic composition alongside diverse and unusual biochemical, physiological, and structural features (Gintzburger et al., 2003; Matsuo et al., 2013). However, the ongoing desiccation of the Aral Sea has caused detrimental changes in the vegetation composition of rangelands with perennial valuable forage species being replaced by less palatable and invasive annual plants. Severe soil salinization in the Aralkum desert rangelands (former seabed of the Aral Sea) is a major driver of land degradation, threatening the crop-livestock ecosystem services essential for food security and rural livelihoods in the region. Recurrent cycles of drought and high soil salinity further exacerbate these challenges, limiting food and fodder production and necessitating large-scale imports of both. Overcoming the winter feed bottleneck remains one of the most pressing challenges for livestock development across Central Asia. Halophytes have shown promising potential in rangeland restoration programs (Toderich et al., 2024) under limited water availability and land salinization. Despite extensive evidence of the benefits desert rangelands offer for livestock grazing and ecosystem services, there is an urgent need to incorporate native forage halophytes and underutilized crops into rangeland restoration schemes. Currently, the salinity and drought tolerance indices, as well as water use characteristics of wild halophytes in the Central Asian Cold Desert Rangelands, remain poorly documented, along with road map cultivation techniques for these species. This study aims to evaluate the adaptation potential of halophytes and the benefits of their domestication to enhance the productivity and economic value of CACDR rangelands degraded by salinization.

Methods

Plant material for stable isotope analysis had been gathered at natural halophytic vegetation of typical desert plant communities. The carbon and oxygen isotope ratios were expressed in standard delta notation (&) relative to the VPDB (Vienna Pee Dee belemnite) and VSMOW (Vienna Standard Mean Ocean Water) standards, respectively: d 13C or d 18O = $(R_{sample} / R_{standard}) - 1$, where R_{sample} and $R_{standard}$ represent the

$^{13}C/^{12}C$ or $^{18}O/^{16}O$ of the samples and the standard, respectively. The d ^{18}O in the stem water were analysed using an isotope ratio mass spectrometer (MAT252; Thermo Fisher Scientific, Rockford, IL, USA) at the Mie University, Japan. R v.3.6.1 software was used for principal component analysis (PCA) with multiple factors. The package “factoextra” was used for multiple correlations between parameters.

Research target area

Uzbekistan, a double-landlocked country in central Eurasia within the Aral Sea basin, is particularly vulnerable to environmental degradation and drought. The majority of its land cover consists of herbaceous vegetation in deserts and semi-deserts, along with piedmont mountainous regions (Fig. 1). The total desert area in the region is estimated at approximately 150 million hectares, accounting for 37% of the total land area. Rangeland soils in these areas have lost 30–50% of their soil organic carbon pool, leading to a significant decline in soil quality due to widespread salinization. The region's climate variability, characterized by an aridity index of 0.065–0.18 and low annual precipitation (80–150 mm), drives successive droughts and extreme temperatures, further exacerbating rangeland degradation. Additionally, changes in land use—such as the conversion of desert and steppe vegetation into new croplands—are accelerating desertification. Agricultural expansion and concentrated livestock grazing near settlements have become the primary drivers of these new land-use practices, intensifying pressure on already fragile ecosystems.

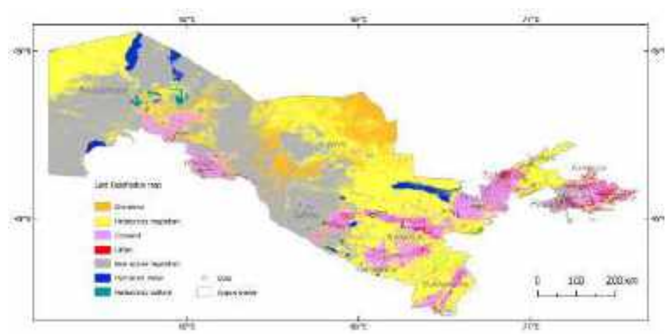

Fig. 1. Land cover of Uzbekistan adapted from
Buchhorn et al. 2020 (modified by Timur

Results

Screening of Halophytes and Non-Conventional Crops. The analysis of stable isotope ratios (d^{13}C and d^{18}O) in 53 wild rangeland halophytes across diverse pasture types, characterized by varying climatic conditions (precipitation, elevation), groundwater levels, reproduction strategies, and biomass yield, highlighted the dominance of C_4 species within the *Amaranthaceae* family (>53.2%). Among ten neglected non-conventional, but already naturalized crops, C_4 species (*Amaranthus*, *Setaria*, *Sorghum*, and *Pennisetum*) and C_3 species (licorice, artichoke, sesame, rhubarb, safflower, and alfalfa) were nearly equally represented. Notably, C_4 halophytes and neglected crops exhibited significantly higher $\delta^{13}C$ values in their leaves compared to C_3 plants, indicating higher water-use efficiency under arid conditions. Perennial C_4 plants further displayed elevated d^{18}O values, suggesting deeper root systems and enhanced drought tolerance (Fig. 2a). When categorized by plant types—annual herbs, perennial herbs, and woody species—significant differences in d^{13}C were observed, while perennial herbs had notably lower d^{18}O values in leaves. Additionally, a strong positive correlation was established between d^{18}O and root system depth among the studied species, underlining the adaptive strategies of deeper-rooted plants in accessing water under saline and arid conditions (Fig. 2b).

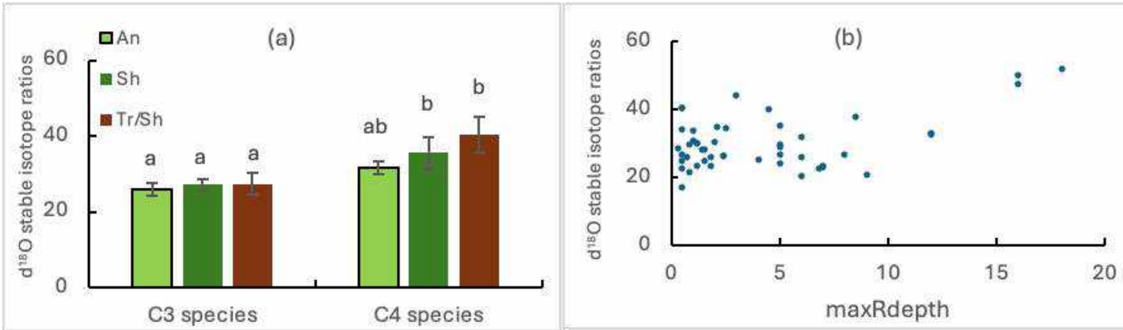

Fig. 2 The oxygen isotope ratio (d ^{18}O) in leaves of annual plants (An), shrubs (Sh) and tree-like shrubs (Tr/Sh) of C_3 and C_4 species (Fig. 2a) in relation to its maximum root depth (Fig. 2b).

Agroforestry and Afforestation technologies for Rangeland Restoration. These techniques revealed significant potential for restoring desert rangelands, severely affected by salinity and drought. Deeply transplanted seedlings of C_3 and C_4 trees, shrubs, and plants during early spring or late fall performed well on both loamy and sandy soils with shallow to moderately saline groundwater. Species such as *Elaeagnus angustifolia*, *Robinia pseudoacacia*, *Populus*, *Tamarix* and *Ulmus*, when intercropped with annual succulent halophytes, legumes, and annual grasses, demonstrated the fastest growth rates and highest water-use efficiency. Optimal agroforestry systems designed for traditional farming practices included 12% tree cover, 20% wild succulents' halophytes, 30% alfalfa, and 38% annual forage crops. This configuration effectively reduced salt accumulation in the root zone, enhanced soil drainage, and provided year-round feed resources for livestock. In addition, these systems contributed by reducing wind erosion and stabilizing soils mitigating the effects of climate variability (Yamanaka et al., 2020).

Circular Halophytic Mixed Farming (CHMF) Technology. The CHMF system was developed by utilizing over 45 economically valuable halophyte species selected from the 760 identified in Central Asia. Following 3.5 to 6 years of continuous cultivation, severely degraded saline rangelands were converted into fertile soils capable of supporting diverse crops, including saltbush, *Karelinia, Suaeda, Amaranthus, Bassia*, cereals (*Agropyron*, foxtail millet, sorghum, pearl millet), sesame, sunflower, and melon (Fig. 3). This system achieved a 1.5–1.8-fold reduction in soil salinity due to the efficient salt uptake and removal by halophytes and reduction of using irrigation water, main source of salts. Additionally, the harvested biomass served as a dual-purpose resource, providing high-quality animal feed and raw materials for bioenergy production. The implementation of CHMF also yielded broader ecological and socioeconomic benefits. Improved soil organic carbon stocks, soil health, and vegetation cover contributed to ecosystem restoration, while promoting biodiversity by supporting rare, endangered, and climate-vulnerable species. The system's capacity for year-round biomass production stabilized fodder availability for livestock through the production of organic products such as honey and high-value fodder. Moreover, CHMF facilitated community engagement, sustainable land-use practices, and integrating indigenous knowledge systems required for rangeland management and conservation.

Fig. 3 Multi-stage salts remediation effect of CHMF technology (Karabuga Site),

Community-based Landscape Restoration actions. Community engagement played a critical role in restoring degraded rangelands through the implementation of "seed isles technique." Pastoral communities were trained to utilize this low-cost approach, which involves spreading mixed seeds of halophytes in uncovered areas. This technique relies on anemochory (wind dispersal) to propagate seeds, achieving significant rehabilitation of degraded *Artemisia* foothill rangelands within three to five years. Without disturbing the topsoil, such approach facilitated vegetation cover and self-regeneration of native species, drastically reducing labour and costs associated with traditional restoration methods.

The results demonstrated remarkable success: in the first year, shrubs yielded approximately 150 kg of dry mass per hectare, increasing to 220 kg/ha of dry mass and 40 kg/ha of seeds in the second year. By the third year, dry yield reached 800 kg/ha, with 100 kg/ha of seeds. Once established, these mixed perennial shrub plantations can sustain grazing forage production for over 20 years. The CHMF approach highlights the importance of integrating indigenous knowledge and community participation work in achieving long-term sustainability for rangeland restoration.

Synergies Between Technologies. The integration of agroforestry and CHMF technologies offers a synergistic approach to combating rangelands degradation in Central Asia. While agroforestry systems provide immediate benefits in soil stabilization, microclimate regulation and resource diversification, CHMF contributes long-term soil recovery and sustainable biomass production. Together, these technologies hold immense potential for reversing land degradation trends, enhancing rural livelihoods, and building climate resilience in arid and semi-arid regions. Although, it is important to address policy regulations and overgrazing practices that are widely spread across the area.

Fig. 4. Foothill improved pastures (seed island techniques) by seeding mixed *Ceratoides*, *Camphorosma*, and *Bassia* (C4 forage halophytes), better known as desert "alfalfa", a high-calorie, year-round small ruminant feed. (Mugol village (Jizzakh region,2022).

Discussion and conclusion

Our study highlights the critical role of abiotic factors (temperature, precipitation, and groundwater) variations in shaping the distribution and abundance of C_3 and C_4 plants in the halophytic flora of desert and semi-desert rangelands, while biotic interactions play a secondary role. As shown in Fig. 5, the distribution of C_3 succulent halophytes is largely influenced by life form and root depth, with a higher prevalence of succulents among perennial species than annuals.

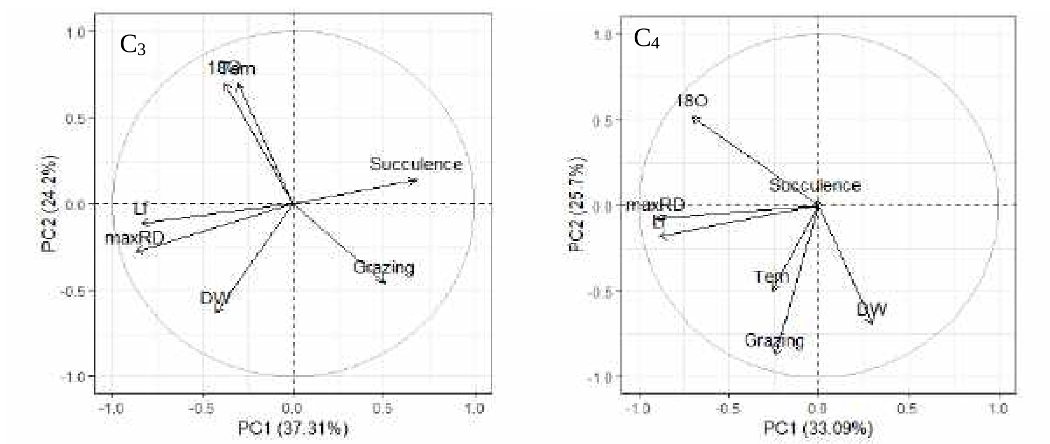

Fig. 5 The multiple correlations between life form (Lf), root depth (maxRD), dry biomass (DW), succulence (Succulence), type of grazing (Grazing), $d^{18}O$ (18O) in leaves of C_3 and C_4 species and mean temperature (Tem).

These findings align with previous studies emphasizing the adaptive strategies of perennial halophytes, which utilize deep root systems to access water from subsurface aquifers. Groundwater-dependent C_3/ C_4 rangeland ecosystems, as noted by Ronde et al. (2024), provide essential drought protection. In cold winter desert rangelands, shallow groundwater aquifers act as "water savings accounts," sustaining ecosystems during periods of low or absent precipitations, particularly during hot summer months. This dependency is evident for C_3 species, where oxygen isotope discrimination ($d^{18}O$) is positively correlated with temperature, reflecting the role of groundwater in supporting physiological functions under temperature stress. Conversely, no such relationship exists for C_4 species, which are more reliant on their inherent water-use efficiency and less dependent on groundwater availability.

Biomass production in these ecosystems is influenced by both abiotic and physiological factors. For C_3 species, biomass is strongly correlated with life form, while for C_4 species, other factors such as water-use efficiency and salinity tolerance appear to play a more prominent role. The study also revealed that the optimal spatial combination of C_3 and C_4 halophytes—considering life form, aridity index, physiological traits, water uptake depth, and adaptation mechanisms to soil salinization—can maximize biomass yield on rangelands. This highlights the potential for leveraging complementary ecological strategies of C_3 and C_4 plants to improve rangeland productivity in short-and long-term use.

A particularly promising approach is the integration of wild native and naturalized rangeland fodder species into the Circular Halophytic Mixed Farming system. Our results suggest that combining C_3 halophytes in open grazing areas with non-conventional crops (NCCs) in cultivated grazing systems creates a synergistic effect, enhancing biomass yield and improving the resilience of rangelands to climate stress. Annual precipitation and grazing type were positively correlated with fodder biomass yield, underscoring the importance of tailoring rangeland restoration strategies to specific climatic conditions and animal grazing schemes. Furthermore, this study reaffirms the ecological niches occupied by C_3 and C_4 halophytes in degraded rangelands. C_3 species tend to colonize nutrient-rich microsites, where their physiological adaptations allow them to thrive, while C4 species are better suited to nutrient-poor microsites due to their efficiency in photosynthesis and resilience to arid conditions (Shuyskaya et al., 2012). By strategically utilizing these species, restoration efforts can optimize both spatial and functional diversity, contributing to sustainable rangeland management and conservation.

In conclusion, the integration of wild native halophytes, naturalized species, and non-conventional crops within the CHMF framework offers a scalable solution for addressing rehabilitation of rangelands affected by soil salinity. The coexistence of C_3/C_4 species under a wide range of soil salinities is essential for developing optimal rangelands rehabilitation technique. This approach not only reduces salinization and enhances climate resilience but also supports biodiversity conservation and the sustainable use of ecosystem services. The findings of this study provide valuable insights for the design and implementation of rangeland restoration programs in arid and semi-arid regions globally.

Acknowledgement
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Innovative tools for addressing risk

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Predicting forage production into the future

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Key words: forage; production; climate

Abstract
Patterns of forage production on California annual rangelands influences an array of critical ecosystem services and functions across almost 50% of the land area in California, including livestock production, soil carbon sequestration, and wildlife habitat, among others. Growth of annual grasses and forbs that make up this forage base are particularly sensitivity to changes in amount and timing of precipitation and seasonal variation in temperature. Thus, forage production on California rangelands is expected to change significantly with future changes in climate. We created a model to quantify how climate changes might impact timing and amount of forage production in the mid-century, as well as spatial differences across the state.

The broad objectives of this project are to quantify how future changes in temperature and precipitation may alter the timing and amount of forage production on California annual rangelands and evaluate how the changes may vary either spatially (e.g. by major land resource area or ecoregion) or vary as a function of historical climatic conditions (e.g. to sites with lower historical precipitation vs. higher historical precipitation). We have integrated three main sources of data, historical weather data for California, a 30m data product that takes a partitioned 16-day Net Primary Productivity (NPP) dataset and uses an equation based on mean annual temperature to separate belowground from aboveground NPP and is available through the Rangeland Analysis Platform, and projections of future climate. The model was created using back-casting to obtain a statistically significant model. Model(s) will be used to predict future changes in NPP in both timing and amount. Models can then be used by land managers to make decisions on how to best prepare for future scenarios under different Representative Concentration Pathways (RCPs) to determine impacts to forage production, wildlife, and carbon sequestration.

Introduction
Climate change and the impacts to NPP have been a concern for many. In California, with predominately annual rangelands relying on annual precipitation to determine NPP, and therefore a forage base for livestock production as well as wildlife habitat and ecosystem services, predictions of an overall warmer

and drier climate as we approach 2100 has many concerned. Researchers are attempting to quantify the impact climate changes will have on NPP, and then extrapolate impacts to managing resources to maintain many ecosystem services. The assumption is that as the temperatures warm and precipitation reduces, NPP will also decrease, resulting in reduction of livestock grazing. We took our teams expertise in forage production (NPP), modelling and GIS to create a model to predict NPP through the end of this century and into the beginning of the next.

Methods

Before we could start to predict forage production, we first needed to define out study area, focusing on grasslands in California. We used freely available data sources for all our efforts. Grassland cover as defined by the California Department of Forestry and Fire Protection's Fire and Resource Assessment Program (FRAP) (CalFire, 2024) was the basis of our data, with the exception of irrigated pastures (Liu et al,. 2021) and unvegetated areas (Felton et al., 2021). Pixels with more than 50% grassland cover were included. Climate data utilized included daily precipitation, daily soil moisture (within the top 10cm layer), minimum temperature, and maximum temperature from the CalAdapt python package for the historical climate period (1950 to 2005). We then converted annual datasets to water years (October 1 to September 30). We defined the start of the growing season based on accumulated precipitation exceeds 25mm (Chaplin-Kramer and George 2013). For the annual rangelands, we also needed to determine the end of the growing season. To do this, we defined the end of the growing season for each pixel using the maximum separation method applied to the top-level soil moisture curve during the water year. This is a phenological algorithm that identifies the two points of greatest change in a given seasonal curve. We utilized only the second point of change to indicate the point in the water year in which soil moisture was depleting. The algorithm is described in Descals et al. (2021). The primary predictor input into our model is the total sum of heat units during our defined growing season for each pixel and each year in the historical period (1950-2005) that we calculated. We were then able to back cast with actual forage production data to ensure a good fit of the model before forecasting. To improve results, the state was broken into fifteen ecoregions: Central California Coast, Central Valley Coast Ranges, Northern Great Valley, Southern Great Valley, Klamath Mountains, Modoc Plateau, Mojave Desert, Northern California Coast, Norther California Coast Ranges, Northern California Interior Coast Ranges, Sierra Nevada, Sierra Nevada Foothills, Southern California Coast, Southern California Mountains and Valleys, and the Southern Cascades. These ecoregions captured seasonal variations in precipitation and temperature and improved the model's ability to predict NPP.

Results

Back casting proved the model's fit in predicting NPP (Figure 1) when predicted NPP was plotted against actual NPP (R^2 equals 0.724). It should be noted that outliers in production at either end did not produce a perfect fit model, and why our R^2 is not higher. The model tends to overpredict NPP at the lower end, and underpredict NPP at the upper end with the strongest correlation from 1,000 kg/ha to 4,000 kg/ha. Extremes on either end did not have enough sample size to provide enough data to accurately predict with the model. We then examined all the variables that were potentially available for the model and looked at the Random Forest Feature Importance of each to see what was driving the overall model. Distance to the ocean and elevation were the two most important features in the model, accounting for approximately 40% of the model (Figure 2).

As the distance from the ocean increased, NPP dropped, as expected. Looking at forecasting NPP by ecoregion, the model's prediction varies across ecoregions, with the southern California Coast predicted to decrease in NPP while the Northern Great Valley as well as other ecoregions will increase in NPP.

Discussion [Conclusions/Implications]

If our current trajectory for climate does not change, the current Representative Concentration Pathway (RCP 8.5) will result in a mix of decreased NPP especially in the southern coastal area of California, but also increases in NPP, in both north and south Great Valley and the adjoining Central Valley Coast Range. The predicted variation in NPP across the state will require managers to shift their management practices. For part of the state, that means increasing management potentially through grazing, to manage NPP. Also of note, the model is not predicting any large swings in NPP across the state between now and 2100, but there are predicted swings at 30-year intervals that could impact management over the next 75 years. Managers will need to continue to implement all drought management tools they have developed over the years and be prepared for the next downward trend in NPP.

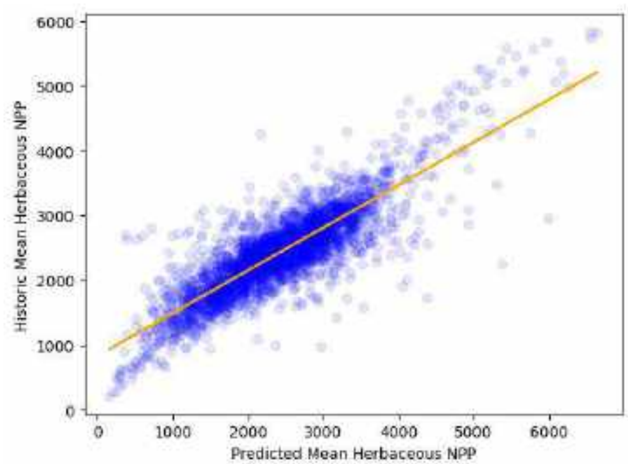

Figure 1. Model prediction of NPP plotted against actual NPP

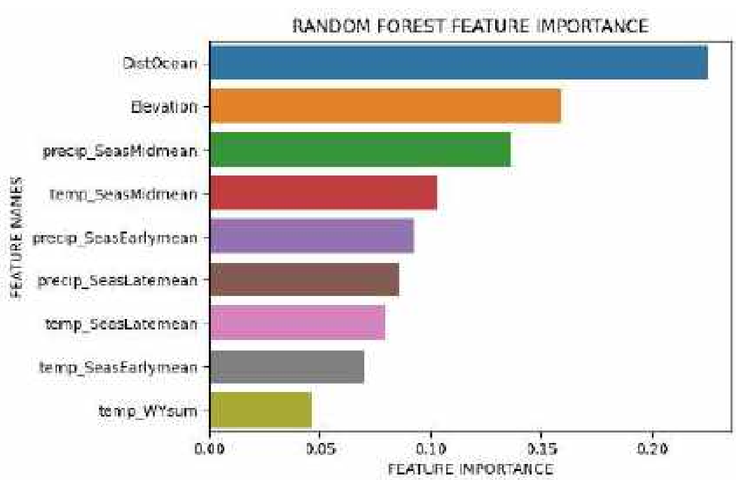

Figure 2. Random Forest Feature Importance of the overall model.

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Impact of drought and flood on land condition across Mitchell Grass Downs rangelands

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Key words: Extreme climate; Erosion; Northern Australia; Mitchell Grass

Abstract

The late January/early February 2019 north-west Queensland flood and associated wind chill event had a devastating impact on the grazing industry and local communities, causing high stock mortality, infrastructure damage, and business disruption. Rangeland condition was also severely impacted by the flood. In some areas, severe erosion stripped away soil, including nutrients and seed bank, while in other areas, soil deposition smothered pasture. Prolonged floodwater inundation (up to two weeks) in low-lying areas also contributed to pasture death. The impacts of the flood were exacerbated by a prolonged drought which impacted the region in the six years prior to the flood, and in the three years following the flood. This project sought to assess land condition recovery on Mitchell Grass Downs rangelands five years on from the flood. In late February and early March 2019 (soon after the floodwaters receded), on-ground land condition assessments were completed at 130 sites across the region. In September 2024, land condition assessments were repeated at 62 of the original sites. In 2024, land condition: improved at least one condition score at 30 sites (48%); remained the same at 29 sites (47%); and declined at least one condition score at 3 sites (5%). Results indicate that land that is maintained in good condition is more resilient to the impacts of extreme weather events (both drought and flood) and recovers more quickly after the event. The observed improvement in land condition at many sites was supported by strategic grazing land management and above average rainfall in recent years. In this region, droughts and floods are likely to increase in frequency and severity. It is critical that we improve understanding of the linkages among drought, floods, grazing land management and land condition to assist producers to build greater resilience in their production systems.

Introduction

High interannual rainfall variability and extreme climate events (e.g., droughts and floods) naturally occur across northern Australia's rangelands (McKeon et al. 2004). In this region, it is common for periods of drought to be immediately followed by periods of intense rain and flooding. During drought, the landscape is most vulnerable to severe impacts associated with flooding, due to reduced surface cover and biomass. The interrelationship between drought and flood impacts on land condition are conceptually understood, but rarely quantified (Barendrecht et al. 2024).

The 2019 north-west Queensland flood, caused by a monsoonal depression, was a particularly significant event. In late January and early February 2019, the Flinders River catchment had 10 consecutive days of widespread heavy rainfall. Julia Creek Airport (Bureau Station 29058), for example, recorded 571 mm over the event, with a maximum daily total of 229 mm. The rainfall event, unprecedented since records started (in the early 1900s), triggered widespread flooding, estimated to cover over 13 million ha (AgForce Queensland 2019). The flood affected area had been in drought for the six years prior to the flood. The flood event, coupled with an extreme wind chill, resulted in the death of over 0.5 million livestock, and caused significant infrastructure damage (Phelps 2019). The flood event also had severe impacts on land condition with widespread soil erosion, soil deposition and pasture death (Hall 2020a,b). Anecdotal evidence from this and other events suggests that land that is maintained in good condition is less susceptible to severe impacts associated with extreme climatic events, and these landscapes recover faster (D. Phelps, pers. Comms). However, this is rarely quantified. In Northern Australia, predicted changes in climate include an increased frequency and severity of extreme climate events (State of Queensland 2019a). Such changes may exacerbate existing pastoral management challenges such as declines in pasture productivity, reduced forage quality, and additional livestock heat stress. An improved understanding of the interrelationships among grazing land management, climatic conditions and pasture responses are needed to help recommend management strategies that build landscape resilience to climate extremes and ensure long-term rangeland productivity.

Methods

The study is focused on Mitchell Grass Downs land types in the Richmond and Julia Creek areas, within the Flinders River catchment of north-west Queensland, Australia (Fig. 1). The study area has a hot semi-arid climate, with high rainfall seasonality. On average, the catchment receives 492 mm of rain per year, 88% of which falls during the wet season (December – March). The topography is relatively flat, intersected by multiple anabranching and ephemeral channels and creeks draining to the Flinders River. In late February and early March 2019, staff from the Queensland Department of Agriculture and Fisheries completed field land condition assessments at 130 sites across the region (Hall 2020a). The land condition assessment utilised the A, B, C, D framework (Karfs et al. 2009). In this framework, A represents the best condition, with good soil condition, high coverage of 3P (perennial, productive, palatable) grasses, and few weeds, while D represents the poorest condition. Sites were limited to land alongside a selection of major highways or secondary roads that could be accessed after the flood. All 3P grasses and seedlings were recorded, as well as annual grasses, legumes and weeds. In August 2020, the land condition assessment was repeated at most of the sites surveyed in 2019 (Hall 2020b). In September 2024, 62 of the original 130 sites were reassessed (Fig. 1).

Results

Out the 62 sites initially surveyed in 2019 and re-assessed in 2024, land condition: improved at least one condition score at 30 sites (48%); remained at the same condition score at 29 sites (47%); and declined at least one condition score at 3 sites (5%) (Table 1, Figure 1). Overall, where the pastures had been well managed during the six-year drought prior to the flood and the Mitchell grass tussocks retained at least 15 cm of basal stem, there was a higher proportion of plants surviving and regrowing within a month of the floodwaters receding. These plants are still surviving. Several sites that were assessed to be in C or D condition in 2019, have improved to a B condition in 2024 (Fig. 2A, B). Despite considerable soil loss during the flood event, enough seed bank remained at these sites to stimulate pasture re-establishment. Anecdotal evidence suggests such re-establishment has been supported by strategic grazing land management and above average rainfall in recent years. Conversely, despite receiving good wet season rainfall over the past two years, some sites have remained in C- or D condition (Fig. 2C), while nearby other properties have A and B condition Mitchell grass pastures. After the flood, tussock rhizomes were exposed at many sites due to severe wash, resulting in tussock death. In 2024, evidence of exposed tussocks still remains at most sites, but the surviving tussocks seem to be in relatively good health (Fig. 2D). The impact of the flood appeared to be more severe in lower parts of the undulating landscape where flow depths, velocities and periods of inundation are likely to have been higher than on the more elevated parts. The flood impact also appeared to be more severe closer to the main drainage channels, creeks and the Flinders River.

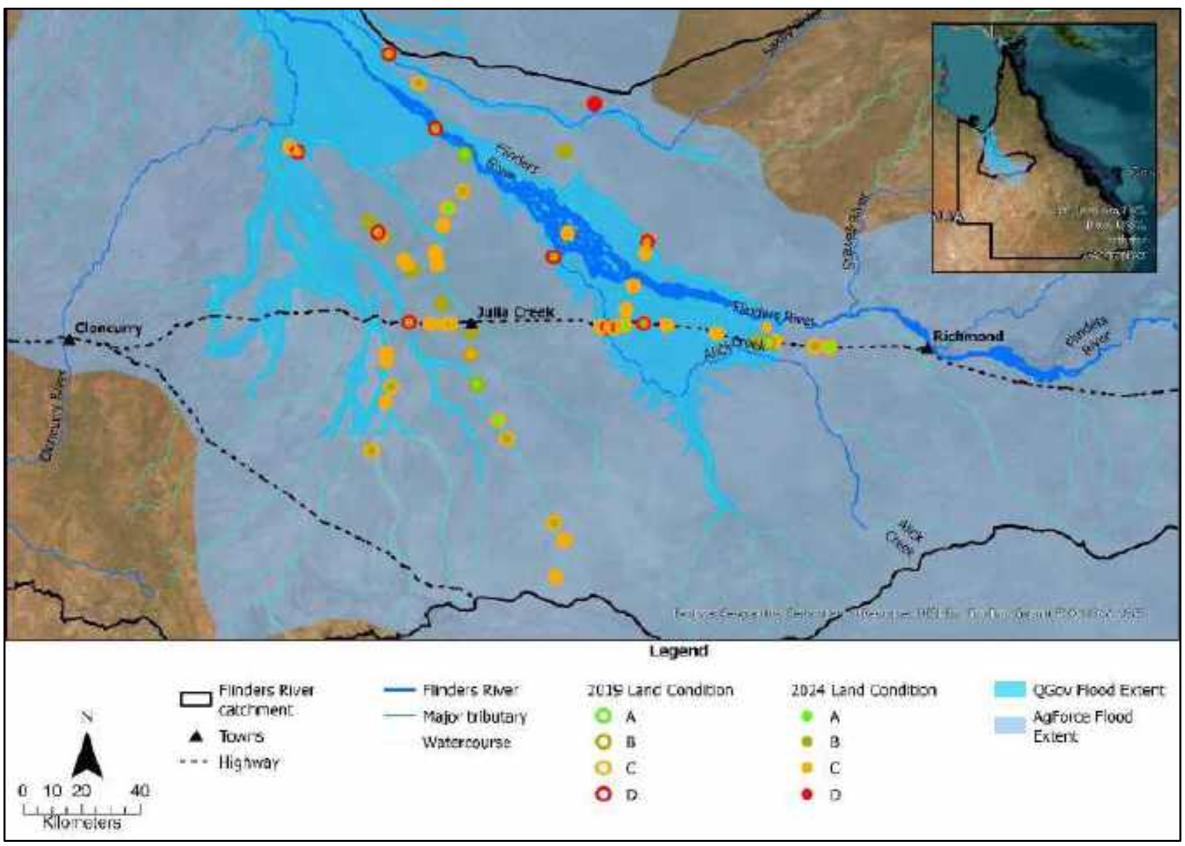

Figure 1. Map showing the change in land condition rating of sites surveyed in both 2019 and 2024, as well as extent of the flood zone as mapped by the State of Queensland (2019b) and AgForce Queensland (2019).

Rainfall across the study areas was average to below average in the six years prior to the late January/February 2019 flood and in the three years following the flood (Fig. 3). Well-above average rainfall occurred in 2022/23 and average rainfall occurred in 2023/24.

Table 1. Matrix showing the change in land condition rating of 62 sites assessed in 2019 and 2024.

	2024					
	Rating	**D**	**C**	**B**	**A**	**Total**
2019	**D**	1	3	7	0	11
	C	1	21	10	6	38
	B	0	2	7	4	13
	A	0	0	0	0	0
Total		2	26	24	10	62

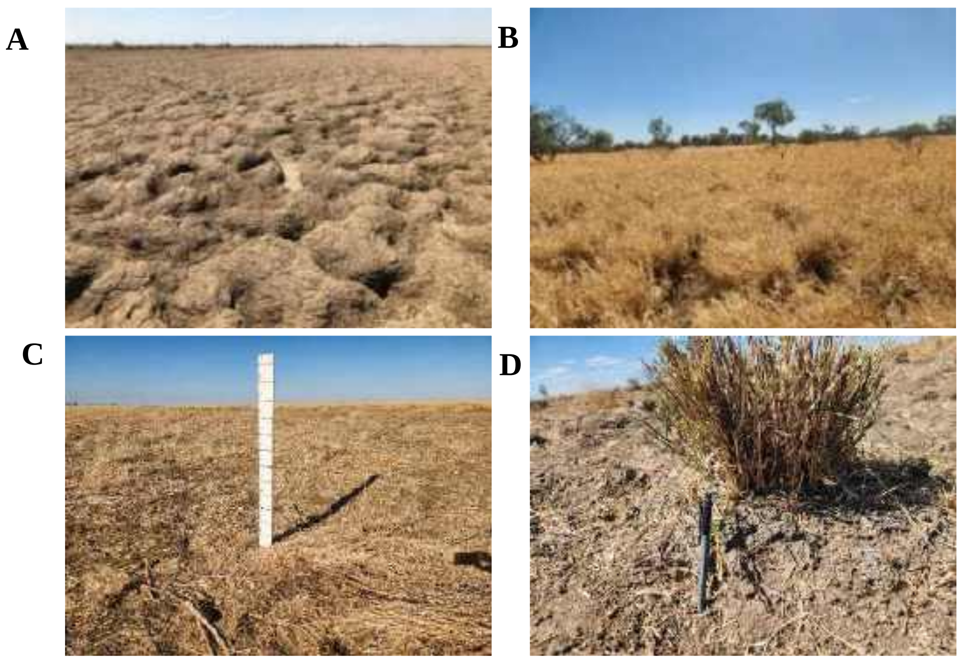

Figure 2. (A) Photo of a site that was in D condition in early March 2019 with complete loss of pasture cover and serious scouring. (B) Photo of the same site in September 2024. The site has recovered to B condition with high coverage of Mitchell grass. Note, the 2024 was taken closer to the treeline, visible in the 2019 photo. (C) Photo of a different site in 2024 that has remained in C- condition. (D) Photo of an exposed Mitchell Grass tussock in 2024.

Discussion

Across the Mitchell Grass Downs, a wide range of flood impact and recovery responses on land condition are evident. The variation in response can be linked to interactions among: (i) historical grazing management; (ii) the impact of the preceding long-term drought, combined with the grazing management imposed during this drought; (iii) the hydrodynamics (depth, velocity and duration of inundation) during the flood; (iv) grazing management following the flood; and (v) climate conditions following the flood. Overall, it is clear that land managed to remain in good condition (A or B), is much more resilient to severe impacts associated with extreme climate events (both drought and floods) and recovers more quickly. Continued monitoring at the assessed sites will enable long-term quantification of pasture recovery while accounting for seasonal climatic fluctuations. Further work is needed to better understand the role that soil type has in influencing flood impact and recovery. Further work is also needed to better model the hydrodynamics of floodwater in this low-gradient, multi-channel landscape.

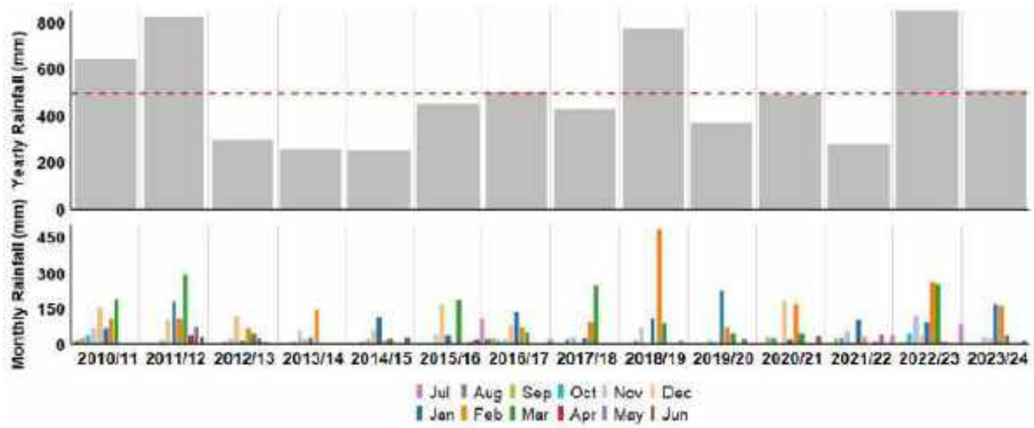

Figure 3. Monthly and yearly rainfall at Julia Creek. Annual rainfall is calculated as commencing on 1 July and ending on 30 June the following year to encapsulate a full wet season. The red dotted line shows the long-term (1888/89 – 2023/24) mean annual rainfall. Data source: State of Queensland (2024).

Acknowledgements
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Assessing the environmental footprint of grazing bison in the United States

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Key words: Bison; grazing; greenhouse gas; soil carbon

Abstract

The bison is a highly held species in the United States (U.S.) due to its historic and cultural significance along with its distinction as the national mammal. Despite a drastic decline in the 1800s, the U.S. bison population is rebounding with nearly 250,000 existing within private operations, federal, state and public herds, and public lands (U.S. Department of Agriculture 2024). A majority of this population is owned and raised privately as livestock. However, several herds also exist as conservation or Indigenous herds. As the bison production sector continues to grow, its impact on the climate is coming into question. Similar to other grazing ruminant livestock, bison emit greenhouse gases (GHG), which are often publicly associated with negative environmental impacts. However, bison can also positively impact the environment by contributing to healthy grasslands and carbon sequestration through grazing action. South Dakota State University (SDSU) was recently awarded a commodity development grant focused on grazing livestock producers, including bison producers. A primary goal of this project is to assess the environmental impacts of bison grazing systems and to encourage sustainable land management practices by providing producers with practice incentives and creating novel market opportunities. To accomplish this, SDSU is partnering with bison producers in the Northern Great Plains to implement sustainable grazing and land management practices and subsequently measure, monitor and verify associated GHG and carbon impacts. Measurements include soil carbon and GHG, along with estimates of bison GHG emissions measured using GreenFeed (C-Lock, Inc., Rapid City, SD, USA) technology. Data generated from this project will help establish baseline environmental impact estimates for grazing bison, which are needed to help inform producer management decisions and guide future market development opportunities.

Introduction

While tens of millions of Plains bison (*Bison bison bison*) once roamed the plains of North America, a sharp decline in bison numbers occurred in the 1800s, driven by a number of factors including commercial hunting, disease introduction, environmental conditions (e.g., drought), and division of the plains by railroad expansion (Boyd and Gates 2006). This drastic decline ultimately led to one of the first major conservation movements in North America, with numbers dwindling to a few hundred in the late 1880s. Conservation efforts were first led by private citizens, with government efforts later gaining momentum to reestablish the Plains bison population (Freese et al. 2007).

The Plains bison is unique in its multi-faceted significance as a production, conservation, and cultural species. Greater than 90% of today's bison are managed for commodity production purposes. However, bison are publicly recognized as culturally important because of their Indigenous culture status and their designation as the U.S. national mammal. As the commodity production sector continues to grow, the impact of bison production on the climate is being scrutinized. Bison are ruminants that generate and emit greenhouse gases (GHG) similarly to beef cattle (Stoy et al. 2021), and these GHG are frequently associated with negative impacts on the environment. However, these grazing ruminants also have potential to positively influence carbon sequestration and soil health in grasslands through changes in plant species composition and carbon distribution (Reeder and Schuman 2002). Additionally, intentional grazing management can result in more carbon sequestration than GHG emissions (Teague et al. 2016) and improved nitrogen cycling (Vega Anguiano et al. 2024), indicating that grazing livestock systems can support ecologically healthy grasslands and ecosystems and promote greater biodiversity (Ratajczak et al. 2022; Tielkes and Altmann 2021).

While bison reintroduction has been successful in growing the Plains bison population, the GHG impacts of such reintroductions are unknown. There have been limited attempts at understanding GHG emissions from bison, including using eddy covariance (Stoy et al. 2021) and gas chambers (Galbraith et al. 1998) to estimate GHG on enclosed bison along with employing known energy requirements to estimate historical herd emissions (Kelliher and Clark 2009). However, numerous factors can influence methanogenesis and subsequent measures of GHG, including (but not limited to) host genetics, age and diet along with seasonality and type of production system. The recent development of GreenFeed technology (C-Lock Inc., Rapid City, SD) has enabled GHG sampling on individual grazing livestock. This technology has been used to successfully collect GHG emissions data on both grazing (Husmann et al. 2024; Waghorn et al. 2016) and confined (Ryan et al. 2022) cattle. Use of GreenFeed technology to collect GHG measurements on grazing bison will help inform the environmental impact of bison production and reintroduction. Our objective is to collect GHG measurements on grazing bison along with relevant soil carbon, forage and climatic data to provide baseline knowledge for bison grazing systems in the Northern Great Plains of the U.S.

Methods

We are currently engaged in a large-scale, five-year study focused on bison and beef calves produced on operations in the Northern Great Plains that implement approved conservation practices, such as cover crop grazing, conservation cover and range plantings, and prescribed grazing. A critical component of this project is determination of GHG emissions and carbon sequestration associated with grazing bison and beef cattle. To accomplish this, we have established cooperative partnerships with three bison operations and four beef cattle operations located in South Dakota and Wyoming. GreenFeed units are deployed at each operation to collect GHG measures from grazing animals. Additionally, soil samples are actively being collected from each operation for determination of soil organic carbon and bulk density along with microbial community size and composition, which can be earlier indicators of changes in carbon sequestration potential. The goal of this initial report is to share preliminary results from the first year of GHG data collection on grazing bison.

Study Sites - Bison

South Dakota State University established cooperative partnerships with three bison operations to measure GHG emissions of grazing bison. These operations were selected because they are located in different geographic gradients across Wyoming and South Dakota and ultimately represent the greater study area of the Northern Great Plains. Historical grazing activity information is being collected for each site, but all sites have been grazed by bison in recent years. Site 1 is located near Custer, South Dakota, and consists of approximately 650 hectares at a mean elevation of 1,320 m. The dominant vegetation consists of western wheatgrass and green needlegrass, along with big bluestem and sideoats grama. The predominant soil type is silty clay loam. Ambient temperatures range annually from 2.2-13.3 °C and average precipitation is 551 mm. Site 2 is located near Gillette, Wyoming, and consists of approximately 20,900 hectares at a mean elevation of 1,524 meters. The dominant vegetation is Wyoming big sagebrush along with shrub needle and thread, western wheatgrass, crested wheatgrass and blue grama. The predominant soil type is loamy. Ambient temperatures range annually from 0.3-14.7 °C and average precipitation is 337 mm. Site 3 is located near Fort Pierre, South Dakota, and consists of >59,000 hectares at a mean elevation of 750 meters. The dominant vegetation is from the Western wheatgrass community. The predominant soil type is dense clay. Ambient temperatures range annually from 2.0-16.3 °C and average precipitation is 477 mm.

GreenFeeds

The GreenFeed pasture system from C-Lock (c-lockinc.com) collects gas flux measures of primarily methane (CH_4) and carbon dioxide (CO_2), with oxygen (O_2) and hydrogen (H_2) as additional options. The system reads the animal's electronic identification tag upon entry and dispenses a small amount of pelleted feed as an attractant. As the animal consumes the bait, a fan draws air at a continuous rate past the animal's mouth to enable the capture of eructation events. The animal must be within an approved head proximity for a minimum of 2 minutes with adequate airflow (> 29 L/s) for a measurement to be recorded. Animals can be measured multiple times each day and settings regarding the number of visits, number of bait drops per visit and timing of allowed visits can all be modified in the machine interface.

There is no standard adaptation procedure for bison on GreenFeed units. Therefore, the procedure for GreenFeed introduction and use varied by site due to differences in pasture size and herd management. At Site 1, a subset of bison heifers (n = 12) was initially adapted to the GreenFeed units during the Fall of 2023 before being combined with the main herd (n = 115) in 2024. At Site 2, the GreenFeed units were rotated alongside the yearling and 2-year-old bison (n = 618) as part of the rotational grazing plan. At Site 3, bison (n = 3,133) were placed into relatively smaller pastures of < 567 hectares to encourage initial use; however, average pasture size at Site 3 at the time of GreenFeed unit introduction was considerably larger than at Sites 1 and 2, ranging from 2,740-4,474 hectares.

Results

GreenFeed Use and GHG Emissions

GreenFeed adoption was unsuccessful at Site 3 with only two observations recorded. This was likely due, in part, to the substantially larger pasture size, machine movement restrictions and limited labour resources. The herd at Site 3 is also enrolled in a grass-fed program, restricting the type of bait used in the machine to alfalfa pellets. Site 1 also used alfalfa pellets but Site 2 used a textured sweet feed as bait. GreenFeed adoption success was much greater at Sites 1 and 2. The number of monthly GreenFeed observations at Sites 1 and 2 are shown in Table 1, along with monthly means for the two greenhouse gases of primary interest, CO_2 and CH_4. In total, 1,696 observations were recorded across Sites 1 and 2 in 2024 (to-date). No observations were recorded at Site 2 in April due to temporary bison relocation to another grazing allotment.

GHG Emissions

Averages and standard deviations for CO_2 (g/d) and CH_4 (g/d) for Sites 1 and 2 are also presented in Table 1; results from Site 3 are not shown due to the limited data collection from that herd. A simple t-test indicated no difference ($P > 0.10$) in either CO_2 or CH_4 across the two sites.

Table 1. GreenFeed observations and CO_2 and CH_4 emissions collected from grazing bison at Sites 1 and 2 in 2024.

Site	Month	GreenFeed Observations	[1] CO_2, g/d	[2] CH_4, g/d
1	January	243	6,047.37 (1,106.5)	146.34 (52.3)
1	February	159	5,791.64 (1,150.3)	127.45 (50.7)
1	March	238	5,809.51 (1,085.9)	134.91 (46.3)
1	April	306	5,410.92 (1,285.8)	120.64 (41.3)
1	May	87	6,931.43 (1,624.2)	196.69 (71.2)
1	June	52	7,687.42 (1,611.5)	194.80 (84.3)
1	July	70	8,421.40 (1,615.7)	222.98 (80.4)
1	August	59	6,654.10 (1,129.5)	190.7 (62.8)
2	March	9	6,125.75 (1,023.9)	144.89 (44.3)
2	May	9	5,754.40 (647.4)	153.96 (35.9)
2	June	140	6,623.39 (1,266.5)	157.66 (70.0)
2	July	183	6,887.39 (1,167.3)	165.98 (65.7)
2	August	122	6,469.23 (1,266.5)	157.96 (76.4)
2	September	19	6,217.32 (1658.8)	145.35 (74.3)

[1] CO_2 mean (CO_2 standard deviation), g/d

[2] CH_4 mean (CH_4 standard deviation), g/d

Discussion

Grazing lands account for 25% of the global sequestration potential of carbon storage (Follett and Reed 2010) and the role of grazing animals – including bison - is critical in the control of the carbon cycle (Schmitz et al 2023). There is limited GHG data on grazing bison, and data captured from this study over the next five years will be fundamental in documenting GHG emissions in foraging bison and furthermore understanding the role of bison grazing systems in net carbon sequestration on grasslands.

We have demonstrated that GreenFeed units can be successfully adapted for bison use. It does appear, however, that limiting pasture size may be critical for successful adoption by bison. A smaller pasture size may help to ensure closer proximity to a GreenFeed unit, which could be an important factor considering differences in grazing behaviour between bison and cattle. However, it is also worth considering that limiting pasture size may influence other effects associated with bison grazing and carbon cycling. Finally, limiting other supplement availability and/or choosing a more enticing bait may be critical in persuading bison to use the GreenFeed with only a small amount of pelleted feed bait.

While GHG estimates did not differ across the two bison sites included here, further analysis and data collection are needed to determine differences associated with season and forage type and availability. Forage samples were collected routinely at each site across the grazing seasons, and associated climate data has been archived. Additionally, soil samples were collected at each site and will be analysed for soil organic carbon and bulk density along with soil microbial communities. These data collectively will help establish the baselines for bison grazing systems in the Northern Great Plains.

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Testing virtual fencing for the sustainable management of north Australian rangelands: Impacts on beef cattle grazing behaviour, pasture resource, and cattle production.

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Key words: Adaptive grazing; grazing distributions; perennial pastures

Abstract

The selective grazing behaviours of cattle frequently lead to degradation of selected areas. Virtual fencing (VF) will be tested to control cattle spatial grazing distributions in extensively managed herds in northern Australia. If VF can successfully be used to change spatial grazing pressure, this would allow for increased rest for preferred areas and improved utilisation of less preferred areas that would otherwise have limited productive value. This will likely improve land condition, carrying capacity, and drought resilience. If successful, VF could be an important tool for management of grazing impacts to increase production and achieve a variety of environmental goals in the extensive systems of northern Australia.

Introduction

Cattle are highly selective grazers at the patch and landscape scale (e.g., Mott 1987; Senft et al. 1987), preferring specific areas, especially those close to water and on flatlands, while under-utilising other, less preferred areas within a paddock (Andrew 1988). This uneven spatial use is particularly problematic in the large heterogenous paddocks of northern Australia, even when stocking rates are appropriate (Hunt et al. 2007). Overutilisation of selected areas leads to negative changes in pasture and land condition such as loss of palatable perennial grasses, increased bare ground and risk of soil erosion, and weed invasion. Increased utilisation and thus productive use of previously underutilised areas may provide opportunity to incorporate rest in preferred areas.

While physical fencing may be implemented to increase the evenness of spatial grazing pressure (Bailey 2004), it is often cost prohibitive in the extensive rangelands of northern Australia. Virtual fencing (VF) has been demonstrated to be highly successful in managing cattle grazing distributions across pastures in intensively managed systems (e.g., Lomax et al. 2019). However, the use of VF in extensively managed north Australian herds, and the associated impacts on pasture and cattle production, are yet to be studied in detail.

In this four-year experiment, a virtual fencing system will be tested to investigate the following in extensively managed beef herds: 1) Can VF technology successfully be used to overcome preferential grazing and increase evenness of cattle grazing distribution across large, spatially variable paddocks? 2) Do VF-enabled changes in spatial grazing pressure result in improvements in pasture species composition and dry matter production? and 3) Do VF-enabled changes in spatial grazing distribution influence cattle production? In preparation for the experiment, initial work has been completed investigating cattle learning of the VF system and grazing preferences. This paper covers the experimental methods and preliminary results on cattle learning and grazing preferences.

Methods

The four-year grazing experiment will be conducted at the Spyglass Beef Research Facility (110 km north of Charters Towers, Queensland; 19°29'24.6"S 145°41'30.3"E), with an average rainfall of ~610 mm. Two treatments are to be compared: VF and Control. In the VF groups, VF collars will be used to control utilisation of different land types, allowing resting of areas as needed while excluding cattle from any scalded areas. The control herds will be managed conventionally, with free access to the whole of their paddocks. The VF and control herds will be managed in separate paddocks matched for similar watering circles, soil types, and topography. The VF and control paddocks will be replicated twice, with replicate 1 paddocks being approximately 790 ha each and replicate 2 paddocks being approximately 390 ha each. Paddocks will be stocked primarily with young cows (approx. 60 and 16 per paddock for replicates 1 and 2 respectively), with a small number of growing non-reproductive cattle (10 per paddock) for the monitoring of weight change without the confounding effects of lactation. Stocking rates will be adjusted mid-year annually based on forage availability (Department of Primary Industries 2018). Cattle movement planning will be done in consultation with the project's producer advisory group. All groups of cattle will be managed to meet their nutritional and welfare needs.

Pre-experimental work, including training cattle to use VF, investigation of grazing distributions and baseline pasture monitoring was conducted as follows.

Heifers (n=50) were trained to use VF in small paddocks. Several changes in the location of the VFs were made to investigate cattle behavioural responses, as seen in Figure 1B. Training began in a 24 ha paddock, with the VF first activated on the morning 17 November 2023. The VF was then shifted out approximately 50 m to allow an additional grazing area on the morning of the 20 November 2023. A week later, the gate into an adjacent 57 ha paddock was opened and the VF was moved to allow cattle into the adjacent paddock. On 30 November 2023, the VF shape in the new paddock was shifted to confine grazing to the north/northwestern side of the paddock. To investigate baseline grazing distributions, freely grazing heifers (n=227), including those in the initial training program, were allowed to graze across all replicate 2 paddocks during the month of August 2024. GPS co-ordinates were recorded at 10-minute intervals using the virtual fencing collars.

Animal behaviour data analysis was conducted as follows. The success of VF group cattle responding to the VF within the groups during and after training was quantified by a success ratio, i.e., the ratio of audio cues to electric pulses (Hamidi et al. 2024). GPS data for baseline grazing distributions were used to quantify cattle preference for topography types using Ivlev's index, where a value of -1, 0, and 1, respectively, indicate that a land class is never used, is used in proportion to its availability, or is exclusively used (Ivlev 1961). Topographical position class was mapped and analysed using Ivlev's index. Topographical position class is an index based on differences in elevation between different points at different scales and local slopes (Weiss et al. 2001).

Baseline measurements of land condition were taken at evenly spaced grid points at intervals of 325 m across the paddocks and will be resurveyed at the end of the grazing trial. A detailed soil survey conducted previously for Spyglass (Bryant and Harms 2016) was utilised to map the soil types in each paddock. Land condition was assessed using the ABCD framework (see Quirk and McIvor 2003; Karfs et al. 2009; State of Queensland 2015) which includes rating both pasture and soil condition. Other measures taken included the top three species contributing to yield, total standing dry matter, level of defoliation and tree basal area. Indian couch grass (*Bothriochloa pertusa*) occurrence is also being monitored as a proxy for disturbance (Spiegel 2023). Baseline mapping of degraded areas (scalds and gullies) will be conducted. Cover metrics (organic cover, green cover, biomass) will be collected annually. Preliminary findings reported herein are focussed on one replicate only, with a closer to complete data set.

Measurements

Live weight production of cattle will be calculated based on yarding weights collected at annual weaning musters (Fordyce 2023) with weekly weight change monitored using Optiweigh portable weighing platforms.

Seasonal pasture monitoring will use the BOTANAL methodology (Tothill et al. 1992) at the end of the wet and dry seasons. Average yields and defoliation scores will be used to develop pasture species selection indices (Andrew 1986; Hunt et al. 2013). Paddock site data will be pooled for soil type and related to animal distribution data. Pasture biomass and green cover will also be assessed at a paddock level using a combination of remote sensing methods, including CiboLabs remote sensing (Guerschman et al. 2023) and LongPaddock MyFORAGE (https://www.longpaddock.qld.gov.au/forage/myforage/).

Preliminary results

During the initial training of cattle to use the VF system, there were high incidences of both audio cues and electric pulses delivered on day one, which rapidly decreased by day two (Figure 1A). There was a rapid increase in success ratio from day one to day three (Figure 1A). The activation of a virtual fence in the second paddock (30 November, Figure 1B) was associated with a rapid increase in incidence of audio cues delivered with minimal electric pulses delivered.

Cattle preference, land condition and proportion of 3Ps (perennial, palatable, productive pasture species) are shown by topographical position class in Table 1. The only topography class with a positive Ivlev index value was the flat plains . The lowest proportion of 3P species also occurred on the flat plains (46% c.f. 62% for highlands). Overall mean land condition ratings ranged from B class (fair) for the open slopes and highlands, to C class (poor) for the flat plains and lowlands. The overall mean land condition across all topographies was a high C (C^{+}). The naturalised stoloniferous grass *Bothriochloa pertusa* was found across all topography classes with the exception of lowlands, with the highest occurrences on the flat plains and open slopes, and to a lesser extent on the highlands (data not shown).

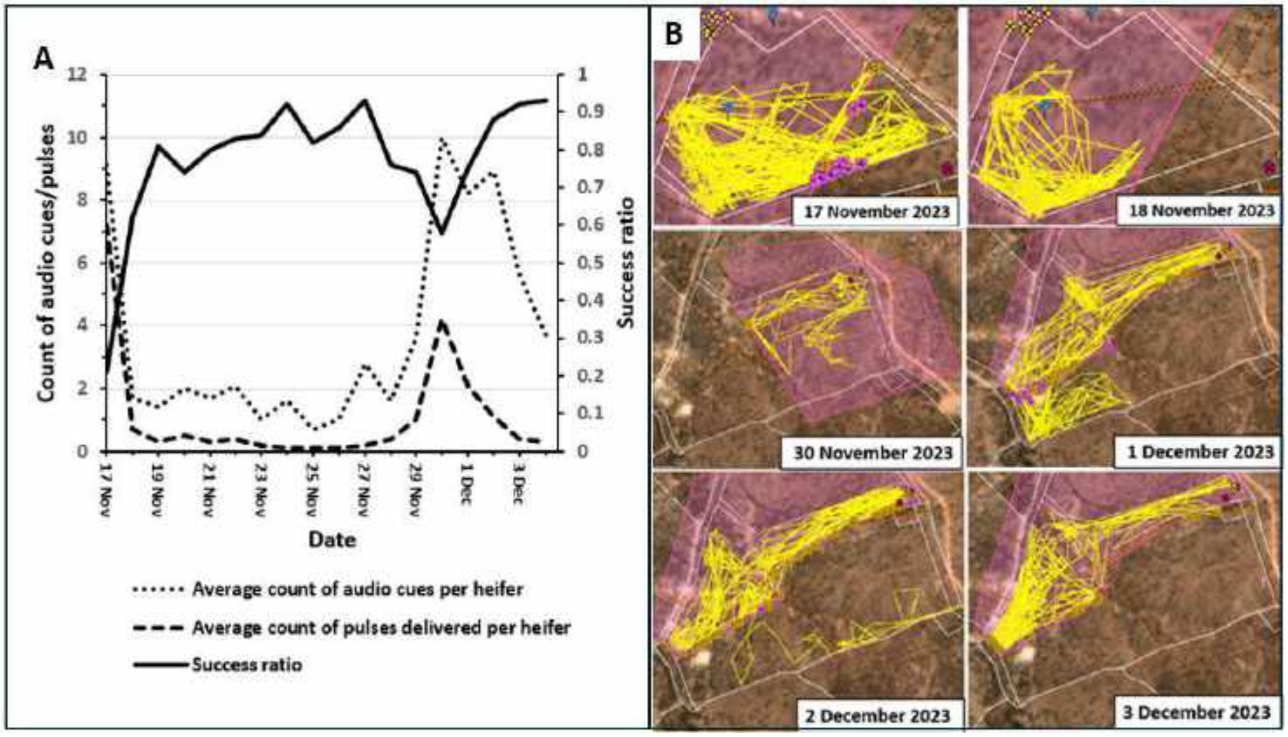

Figure 1. Audio and pulse cues delivered to heifers and success ratio throughout the training program from 17 November to 3 December 2023 (A), and cattle movement 'tracks' for 10 randomly selected heifers during the first 16 days of the training program. White line=physical fence, pink shaded area=virtual fencing inclusion zone, yellow= 'tracks' walked by cattle (B).

Table 1. Preliminary results for cattle preference, the contribution of 3P species to yield and average land condition by topography type for paddocks within replicate 2.

Topographical position class[A]	Ivlev's index value[B]	Proportion 3P species[C] (±SEM)	Average land condition[D]
Flat plains	0.13	46% (±5%)	C^+
Lowlands	-0.29	52% (±10%)	C
Open Slopes	-0.33	60% (±7%)	B^-
Highlands	-0.44	62% (±12%)	B^-
Other	-0.85	no data	no data

[A]The topographical position class is an index based on differences in elevation between different points at different scales and local slopes (Weiss et al. 2001).
[B]Ivlev's index is a common measure of food selection based on both the extent of selection and the relative abundances of the food types in the environment, in this case the relative abundance of land areas by topographical position class.
[C]3P stands for preferred grass species that are Perennial, Palatable and Productive. The proportion of 3P species was calculated from the top three pasture species contributing to yield.
[D]Land condition classes include A (good), B (fair), C (poor), D (very poor), with the possible range within each class including variants from high (plus), neutral, to low (negative).

Discussion

This study demonstrates that naive cattle can learn to respond to the VF audio cues within a day, as indicated by a rapid increase in success ratio after day one of training. When the animals were shifted to a second paddock and restricted to a portion of the paddock, they were able to be contained to the VF inclusion zone largely by responding to the audio cue with a minimal incidence of electric pulses. The success of cattle learning to respond to VF cues in this study is consistent with other studies investigating the learning of a VF system by dairy cattle (Lomax et al. 2019) and moving small herds of beef cattle (<13 cattle) short distances of <400 m (Campbell et al. 2021). While the functionality of VF does show promise on a small scale, no published studies to date have evaluated its capacity to hold and shift cattle in the extensive, variable landscapes of northern Australia.

The large paddocks and variable terrain in north Australian production systems present additional challenges for VF systems. These include obstacles (e.g., hills, gullies, and trees) for radio transmission between VF base stations and collars, the large proportion of herds that are predominately breeding females and the challenges associated with cow-calf movement patterns, predators, and multiple widely spaced watering points. Potential challenges to achieving full use of VF technology, yet to be investigated in this study, are likely to be associated with shifting cattle from one watering point to another and shifting cows during the calving period.

Preliminary results indicate that the topography type with the highest preference and therefore highest risk of overgrazing is the flat plains, with all other topography types being avoided by cattle. However, this result is based on cattle GPS data for the month of August 2024 only, and grazing distributions will likely change at other times and with varying seasonal conditions. The preference of cattle for flat plains (e.g. Raynor et al 2021) is consistent with the lower 3P abundance in the flat plains compared to other topography types.

Conclusion

This experiment aims to test the VF system for high level control over grazing distributions in extensively managed herds, while also monitoring impacts on land condition and cattle production. Our preliminary results show that it can be used at least on a small scale and provide data on cattle grazing behaviour and land type selection. Whether VF can be used to implement increased rest of pastures within large heterogenous paddocks and ultimately produce positive biological and economic outcomes in a northern production systems context is yet to be established.

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Evaluation of herd instinct tags on cattle behavior and spatial distribution

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Abstract

On expansive rangelands, a major alteration to the historic grazing patterns is the lack of herd instinct that increased animal density and supported nomadic behavior. It is thought that re-instilling herd instinct into domestic livestock may mitigate the overuse of specific areas on rangelands and improve profit per acre, while supporting more diverse plant communities and wildlife habitat. A new technology is the Herd Instinct Tag (HIT) that utilizes audio and electrical stimuli to maintain animals at a defined herd density. HIT does not define borders, but rather tags communicate with each other to maintain herd density based on animal proximity. To test the HIT, 41 Hereford-cross animals were divided into two groups, HIT and control (CON), and evaluated for 5 weeks on the Mimms Division of the Dixon Water Foundation in Marfa, TX. Animals were maintained in separate pastures and recorded weekly to evaluate behavioral changes over time. There were no significant differences between treatments for any animal behaviors. Spatial distribution differed between treatments with the average distance between HIT individuals being 18.3 m, whereas the CON averaged 258.4 m between individuals. Ultimately, there were no indications that HIT affected animal stress levels following the use of HIT for 5 weeks. Animals with HIT successfully maintained a higher herd density but the long-term impacts on animal and rangeland health and production still need to be evaluated.

Introduction

Over the last 100 years increased attention has been placed on the state and revival of rangeland health, resulting in significant emphasis on extensive grazing systems and sustainable grazing practices (Kothmann 1974). During the mid-1900s, the management of livestock and rangelands became particularly centered on the creation of grazing systems that relied on the idea of rest-rotations, as opposed to traditional continuous grazing. These grazing rotation systems have various forms, including deferred rotation, short duration grazing, high intensity-low frequency, and adaptive multi-paddock grazing, which involve different approaches to the timing and duration of rest periods (Teague et al. 2013). Nevertheless, these systems commonly aim to mimic, to some degree, historic, migratory grazing patterns of native grazers (Teague et al. 2013; Bamforth 1987; Guy et al. 1981) that consisted of resource use followed by a non-grazing period, generally supporting landscape heterogeneity and co-existence of livestock and wildlife on rangelands (Behnke 2021; Chen and Shi 2018).

Within extensive rangeland scenarios there is a market for livestock management systems that producers can maintain use to desired stock density and support migratory grazing patterns where animals move as a unified herd. Because of this, a new technology coined the Herd Instinct Tag (HIT; RanchCheck, Inc., Marfa, Texas, USA) has been developed that focuses on re-instilling herd instinct into domestic livestock to support migratory grazing. HIT is a solar powered ear tag that utilizes audio and electrical cues to maintain animals at a user defined proximity that translates to herd density, but it does not define borders. Instead, the tags communicate with each other to determine and maintain herd density based on animal proximity relative to the center of the group. The goal of HIT is to promote innate herd instinct and promote animal grazing as a unified herd with minimal human intervention. As with any new technology, evaluating its influence on animal behavior and performance is crucial for successful implementation and widespread adoption. Therefore, our study objective was to assess the impact of HIT on animal behavior and evaluate its ability to maintain herd formation relative to "free ranging" animals.

Methods

The animals used in this experiment were registered and cared for according to guidelines approved by the Institutional Animal Care and Use Committee (AUP 2022-1163) at Texas Tech University.

On the Mimms Division of the Dixon Water Foundation in Marfa, TX (30.3929 ° N, 104.0622 ° W: elevation 1,432 m), a total of 41 yearling Hereford heifers and steers (318 ± 23 kg) were used to evaluate HIT. A total of 19 HIT were placed on animals. However, during the first week of observation, two animals in the HIT group lost their tags, resulting in 17 total tags for the full observation period. Animals were divided into two groups, HIT (17 operational HIT (65 g; n = 17) and control (CON, conventional ID tag (10 g; n = 24), and evaluated over a four-week period (February 24 – March 24, 2024). Animals were stratified by sex, nine heifers and ten steers initially received HIT, with random tag assignment within groups being performed by alternating between HIT and CON tags for every animal that entered the chute. Tag placement was performed by removing the current ID tags and fitting the assigned tag (i.e., HIT or CON) by securing it through the pre-existing hole in the ear. Following tag application, HIT devices were activated and each group was released into separate pastures (HIT 55 ha; CON 457 ha) out of the eyesight of each other. The HIT device was set to maintain a maximum distance of approximately 30 m between individuals. Although not optimal, the CON group was placed in a larger pasture due to a lack of similar-sized paddocks not out of eyesight of the HIT group, as well as grounding issues with electric fences. Data logged by the HIT included the continuous periodical relative proximity between the devices and all audio or electric cues.

Animals were maintained in their separate pastures and monitored weekly to evaluate behavioral changes over time using a modified ethogram of behaviors (Ranches et al. 2021). Individual animal behaviors were recorded using focal-animal sampling (Altmann 1984) for five minutes using a spotting scope with a mounted GoPro camera (GoPro Hero10 Inc. San Mateo, California, USA). Animal behavior monitoring was performed two days per week over a four-week period on the following dates: February 24 and 25, March 3, 4, 10, 11, 17, and 18 of 2023. All videos were taken at the same relative time each week, between the times of 8:00 AM to 6:00 PM Central Standard Time (CST), alternating between the two focal groups to ensure equal time sets for both morning and afternoon evaluations (e.g., HIT monitored during the morning on day 1 and afternoon for day 2). Behavioral analyses were performed by evaluating every 30 seconds of the recording. All recordings of individual animals were analyzed into observations by recording the primary behavior during the 30 second period. Observations were removed from the dataset if the animal being evaluated was out of view at any point. To evaluate spatial distribution, drone aerial images were taken between 11:00 AM and 2:00 PM CST for both groups. GPS positions of the cattle were obtained by georeferencing (Syetiawan et al. 2020) aerial pictures taken with a drone at a height of 200 meters in ArcGIS pro (ESRI, California, USA) and proximal distance between all animals within a group were determined by calculating the distances between their GPS positions.

All statistical procedures were performed using the MIXED procedure of SAS software version 9.4 (SAS Institute Inc., Cary, NC). Behavioral data were evaluated for the 2×2 factorial arrangement, considering treatment and week as fixed factors, with animal within group considered a random intercept. Distance data was evaluated to assess the effect of treatment and week using a completely randomized model. Normality and homogeneous variances were checked using Kolmogorov-Smirnov and Levene's tests, respectively. Mean comparisons were performed using Least Square Means for all significant effects ($P \leq 0.05$) and tendencies assumed at ($0.05 < P \leq 0.10$).

Results

There was no difference in post-tagging behavioral scores between the CON and HIT ($P > 0.05$). There was no interaction or main effect differences for any animal behaviors, with both CON and HIT spending similar proportions of time within each behavior category ($P > 0.05$). However, the spatial distribution assessment indicated a significant interaction between treatment and week ($P < 0.001$). Because the interaction appeared to be a result of social and environmental stressors, we compared treatments by week. The control treatment demonstrated significantly greater spatial distribution for all weeks ($P < 0.01$)

Discussion

Overall, time spent in all behavioral groups was similar between treatments. Feeding comprised >60% of behaviors, followed by locomotion and cohesive behaviors. Agonistic and agitation behaviors were <1% for both groups, indicating animal discomfort due to HIT was not present. According to Kilgour 2012, animals exhibiting <5% of these behaviors are considered to be in a state of comfort. Confirming the previous observation, both groups demonstrated high levels of cohesive behavior, with 10 and 15% for CON and HIT, respectively. We found that the CON group had numerically greater locomotion than the HIT group, which was surprising initially; however, this was likely due to individual animal movement within HIT group being constrained by the herd relative to the CON group and the greater pasture size of CON. Generally, our results follow the same trend found in virtual fence studies where no negative behaviors are noted following use of the technology (Lee and Campbell 2021; Verdon et al. 2021; Campbell et al. 2019).

The assessment of spatial distribution indicated a significant interaction between treatment and week, but this interaction can be largely attributed to CON in response to social and environmental stressors. There was no difference in distribution over time for HIT, with the average distance between HIT individuals being 18.3 m. In contrast, CON averaged 258.4 m between individuals with large weekly variations. The greatest distance between individuals was observed in week three for CON group (550.3 m), while the greatest distance for HIT herd was in week 4 (23.9 m). The HIT group in week two had the least distance between individuals (8.4 m), whereas the least distances for CON were in weeks one and four, 125 and 105 m, respectively. Overall, the HIT group maintained a single herd within a radius of no greater than 30 m, while the CON group divided into subgroups spaced up to 920 m apart.

Throughout the trial the HIT herd remained clustered, demonstrating the HIT's potential to maintain group density. In contrast, the CON group's proximity varied with their activity. For example, the CON herd would form a single group near water or supplement but disperse into subgroups during grazing events. The HIT group, however, maintained close proximity during all activities, including grazing, watering, and resting. When most of the herd wanted to rest, HIT individuals who wanted to graze stayed adjacent to the herd to maintain formation. Although anecdotal, evidence that suggests herd instinct was improved is that animals #2 and #6 lost their HITs midway through week one but did not stray from the herd even though they were no longer receiving cues. Although receiving only a brief period of exposure to the tags, these animals demonstrated strong herding behaviors and had to be moved to another paddock by ranch personnel.

There were no differences in animal behavior between animals that received CON vs HIT. The primary stressors observed in this study were associated with altered herd dynamics from splitting one herd into two and environmental stressors (i.e., freezing temperature, snow, and high winds). Animals with HIT maintained a close cluster formation which translates to a higher herd density. The HIT appears to adequately maintain herd dynamics without compromising animal welfare, but tag weight likely needs to be reduced to mitigate ear damage. Greater evaluation of tag weights is a prerequisite for future technology applications. Next steps for HIT require longer term evaluation of the technology and how it influences animal performance and ecosystem health.

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Resilience and adaptation among pastoralists

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How rural Mongolians understand climate change: knowledge, attitude and practice survey

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Key words: climate change, resiliency, herders, knowledge, readiness

Abstract

Over the last 80 years, Mongolia's average annual temperature increased by 2.36°C. The population groups, in particular herder groups are likely to be disproportionately affected due to not only their exposure to shocks and stresses but also their limited capacity to withstand and respond to climate induced disasters and risks. Mongolia's Climate change mitigation and adaptation policy goals can succeed and can be sustainable if the public, key stakeholders and policymakers support effective action. The priorities of protecting vulnerable groups to climate change, empowering the public to respond to climate induced risks were also mentioned in the Nationally Determined Contributions. However, no studies have been conducted to identify what opportunities exist to increase knowledge and promote positive attitudes and practice among the rural population and vulnerable groups. This 'Climate Change Knowledge, Attitude and Practice Survey in Mongolia' was commissioned by the Global Green Growth Institute and the Ministry of Environment and Tourism. The purpose of the Survey was to assess awareness, knowledge, attitudes, practice and media consumption related to climate change among the population including the herder communities. The results of the study inform the development of a national awareness-raising campaign strategy to improve public awareness and capacity-building activities to mainstream climate change in national policies. The survey covers awareness, knowledge and attitudes of entire communities, namely their observations about weather, environmental and climate changes, understanding of causes and effects. The survey reveals capacity needs of stakeholders and priorities needed for mitigation and adaptation strategies at community and national levels. It focuses on rural community's access to information about CC and strategies for effective awareness campaigns.

Introduction

The Mongolian climate is harsh and continental due to its unique geographical location in the center of the Eurasian continent. It is at a high altitude above sea level, is surrounded by tall mountains, and is in a remote location far from the sea. Mongolia faces some of the most pronounced climate change risks of any country in the world. This includes rapid desertification, water scarcity, changing precipitation patterns, and seasonal intensification of extreme weather events[i]. The country has extreme weather conditions, fragile ecosystems, and prominent pastoral livestock and rain-fed agriculture sectors, making Mongolia vulnerable to climate change risks that affect the economy, livelihoods and traditional cultures.

High temperatures are likely to increase the frequency and severity of heatwaves and droughts, while *dzud* (extreme cold, harsh winter natural phenomenon unique to Mongolia) will become more frequent and fiercer. Extreme events such as landslides, flash floods and land erosion are highly likely to occur due to the increased intensity of extreme rainfall. More frequent and intense drought conditions will accelerate the rate of desertification of previously productive pasture and grazing land. The number of extreme weather events, including drought, *dzud* and flooding has doubled in the last 20 years and the devastating socio-economic impact caused across the country is well documented. In addition to these extreme events, the impacts of climate change affect public health and livelihoods – both directly and indirectly. The increase in respiratory illnesses (12%) and cardiovascular disease (8%) is highly common among the population depending on the regions and is expected to rise due to climate impacts.

Animal husbandry continues to play a vital role in Mongolia's economy, employment, and export earnings. However, with increasing livestock density and the impacts of climate change, approximately 70% of the country’s pastureland is now degraded. This degradation has led to a decline in the quality of livestock products, such as meat, dairy, wool, and cashmere, which are essential to the economy and account for over 80% of the food sector. Mongolia`s agriculture sector stakeholders claimed that agriculture is the most vulnerable to climate change impacts. They pointed out the need for sufficient regulation to balance the livestock population and better controls over meat, cashmere and dairy production. Moreover, the technical capacity of the sector, particularly at the academic and university levels, was considered sufficient by the availability of a large amount of research linking climate change to agriculture and livestock. However, on the overall issue of climate change, the national data reports about the lack of qualified and competent personnel or experts at the sectoral and organizational levels.

Methods

The survey assessed the general awareness, knowledge, and attitudes of rural Mongolians regarding climate change. It explored their observations of weather, environmental, and climate changes, their understanding of the causes and effects of climate change, and their concerns about its impacts.

The survey employed a mixed-method, non-experimental, and cross-sectional approach, with a sampling design aimed at capturing results at the national level and across all regions. Data collection took place between September and November 2022 through face-to-face interviews conducted in 13 *aimags* and Ulaanbaatar city. A total of 2,804 respondents participated, of whom 51.9% were female, 48.1% male, and 36% (1,009) from rural areas. The survey employed a stratified, multi-stage cluster sampling method to select sites and respondents. Additionally, 49 key informants were purposefully chosen from national and local government, non-governmental organizations (NGOs), academia, media, and the private sector. Among the respondents were 402 herders (14.3%) and 20 farmers (0.7%), alongside government officials, civil society organization (CSO) members, business representatives, and others.

The majority (89.8%) of 402 herders lived in rural areas, particularly in the steppe zone (42.5%). Regarding gender, 55.2% of herders were male, compared to 46.9% among non-herders. Over half (52.0%) of the herders were aged 35–59 years, and educational attainment among herders was significantly lower; 84.6% had completed secondary education. Furthermore, only one-third (34.1%) of herders had purchased private livestock insurance. The rural population includes herders and farmers and other groups whose lives are vulnerable to climate change impacts. Those that had lower levels of completed secondary education were more likely to live in rural areas. Within the rural population, a distinction should also be made by age as well as it has been found that knowledge, attitude and practice levels differ with age.

During the interviews, questions on climate change mainstreaming capacity factors were asked, including demand, leadership, resources, technical capacity and institutional arrangements. A total of nine focus group discussions were conducted which included community representatives - men and women, youth, older people, herders, farmers, ethnic minorities, communities in *ger* areas, mining-affected areas, and remote border areas. The Survey examined how socio-economic status can influence climate change awareness, information needs, and the processing of climate-related information. In doing so, the team constructed and used a simple vulnerability index that measured different characteristics of a person that places them at higher risk of economic deprivation, health issues and social isolation in relation to climate change. A total of 13 characteristics were used to construct the index including age, disability, chronic illness, income, levels of education, internal migration status, and those who engaged in livelihoods vulnerable to climate change impacts. Using the index, the respondents were divided into two groups - 'less vulnerable' and 'vulnerable' - to allow for disaggregated analyses by vulnerability status. The survey did not include a "not vulnerable" category in the vulnerability index because the primary focus was on assessing varying levels of vulnerability among respondents. By concentrating on the "vulnerable" and "less vulnerable" groups, the analysis could more effectively identify and compare disparities in climate change awareness, information needs, and information processing.

Results

Awareness, knowledge, attitudes and practices

Those that participated in the Survey possessed relatively good awareness about climate change. Over two-thirds of respondents (67.3%) said they had heard about climate change and nearly half of respondents (46.6%) stated that climate change had affected their lives and livelihoods in the last 10 years. Moreover, the majority of respondents (84.0%) agreed that human activity is the main cause of climate change. However, citizens in both rural and urban areas demonstrated poor knowledge, attitude and practice regarding climate change.

Rural respondents' (36% of the total survey participants) knowledge about the causes and effects of climate change was low; therefore, they are unlikely to believe that climate change is occurring globally and affects Mongolia. While they noticed more environmental changes and experienced natural disasters, they thought it frequently occurs in ten-year cycles and is natural. They were, however, more concerned with the negative effects of environmental changes, including seasonal changes, because it has the potential to affect their livelihoods. A high number of rural respondents were also willing to receive more information about climate change from the media.

The fact that many respondents thought they had a low understanding of climate change and awareness of the ways to cope with the effects of climate change should be taken as an opportunity for raising awareness. The Survey found that there was high demand for reliable and consistent information related to climate change. The majority of the respondents (85.4%) said they would like to receive more information related to the topic from the media. Key stakeholders - including local government officials, civil servants, journalists and others in the media sector - will play a crucial role in improving the public's understanding of climate change and their demand for climate change information. However, those who were in the position to inform and engage the public also had a low understanding of climate change and lacked resources.

Media consumption and communication

Television, or TV, (73.6%) and the internet (63.7%) were the primary sources respondents used to obtain information on important topics - such as politics, the economy, health, education and the environment. The mobile phone was the most accessible device to reach people from all segments. More than 99.1% of the respondents who used mobile phones said they use their mobile phone, or someone else's, 'everyday' or 'occasionally.' In terms of trustworthiness in sources of information, TV was the fourth most trusted source of information (67.5%) after trainings and meetings (87.3%), local authorities (83.6%), and family and friends (73.9%). Trust in internet was the lowest (29.8%)

Discussion, Conclusions, Implications

The research revealed that most Mongolians surveyed had observed changes in weather patterns during their lifetimes, such as an increase in extreme temperatures and weather events. However, public understanding of climate change was generally limited, particularly in rural areas, including among local government representatives. While 84% of respondents agreed that human activity is a cause of climate change, rural respondents—such as herders and farmers—primarily attributed climate change to common environmental issues like mining and livestock overgrazing. The survey also highlighted a strong demand for reliable and consistent information on climate change. Science-based, consistent awareness of climate change and its impacts can empower herders and farmers to strengthen their resilience, enhance their adaptation capacity, and better prepare for potential climate events.

One of the most significant barriers to improving the public's understanding of climate change has been a lack of leadership in communicating information about climate change in Mongolia. Although multiple government and non-governmental agencies could potentially take a leadership role on climate change awareness, they lack the resources to do so. They also have not prioritized information and communication as a response to climate change. There have been efforts to raise awareness on the topic through the media and press in the past. However, these efforts did not reach a broader audience and have not made an impact due to a lack of synergy and coordination. Capacity-building, raising awareness, information dissemination and coordination of responsibilities are mandated to government organizations. However, due to inconsistency and instability, the activities have been largely ineffective. The multi-stakeholder engagement approach in decision-making, policy development and implementation are currently insufficient and needs to be improved. Therefore, establishing a mechanism, and promoting leadership in communicating information about climate change, are the most crucial steps for effective awareness-raising in Mongolia. A pool of financial resources that donors can contribute to (and is specifically dedicated to climate change awareness) could be created. This would help the sustainability of the awareness-raising campaign, support future climate change and communication efforts, and improve coordination between stakeholders working in the field.

Given the limited finances allocated from the state budget, it will be crucial to utilize other available financial resources – such as foreign investments and donor support – that can help with climate change awareness-raising and capacity-building. Communication, information, and awareness-raising initiatives in particular, will be central to Mongolia's response to climate change.

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Attentive maintenance models of social-ecological pastoral systems

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Key words: Resilience; Social-Ecological; Adaptive; Sustainability; Complex

Abstract

Pastoral societies have developed sophisticated institutions for managing persistent, sustainable social-ecological systems in nonequilibrium environments. These institutions operate at different geographic scales in different years, depending on the climate. This paper generalizes a methodology for modelling groups of related pastoral institutions as complex adaptive systems. The methodology then draws on hierarchy theory to detect inter-system relationships that are characteristic of social-ecological panarchies. I applied this methodology in southeast Amdo, Tibet (part of western China), an area with highly differentiated cultural and linguistic pastoral institutions. The methodology generated three interdependent models, which I termed "Attentive Maintenance Models" and which each describes complex adaptive systems at a distinct social-ecological scale: livestock herd composition, livestock herd movements, and dairy product flows. Each attentive maintenance model further reveals 1) degrees of freedom for influencing pastoral systems at that scale and 2) which institutions play similar roles to one another in enabling systems at that scale to persist. Historical qualitative data, sourced through semi-structured interviews, supports my theory that completely removing any one type of institution in an attentive maintenance model (e.g. those linked to ecological cycles, stochastic social events, or personal sentiments) precipitates system collapse across all scales. Since attentive maintenance models reveal the degrees of freedom for helping a system adapt as well as which of its types of institutions are most vulnerable for a lack of redundancy, I recommend using this methodology to assess the adaptive capacity, resilience, and vulnerability of pastoral social-ecological systems prior to forecasted types of political and climatic change. This framework reveals opportunities to reinforce resilience, adaptive capacity, sustainability, and risk management in existing pastoral systems through the development of educational resources about pastoral system function and the protection of functionally redundant institutions.

Introduction

In southeast Amdo, Tibet in western China, overlapping southern Gansu Province and northern Sichuan Province and at an elevation between roughly 3000 and 4000 meters, nomads historically managed the compositions of herds and flocks, the locations of herds and flocks, and the production and distribution of dairy products (Burnett, in press). They were attentive to ecological, social, and sentimental cues to manage these resources in particular ways: ecological cues such as physical, phenological, and physiological changes encouraged partial resource turnover; social cues such as ceremonies, celebrations, and chance meetings encouraged partial resource recombination; and sentimental cues stemming from gratitude or long-term habits and relationships encouraged partial resource persistence (Burnett, in press). The combination of these types of resource management guided nomads in adapting their pastoral resources to the ever-changing environment.

Ellis and Swift (1988) theorized that pastoral ecosystems are often non-equilibrial: “strongly controlled by external forces rather than, or in addition to, internal biotic factors” (Ellis and Swift 1988:453). Yet, despite pastoral systems’ sensitivity to external influences, Ellis and Swift observed in the region they studied—Ngisonyoka Turkana in northern Kenya—that “[the] ecosystem and its pastoral inhabitants are relatively stable” (Ellis and Swift 1988:453). Fernandez-Gimenez and Le Febre (2006) described how pastoral institutions—"the formal and informal rules, norms, and repeated patterns of interaction among people that guide individuals’ behaviour with respect to the environment and other people” (Fernandez-Gimenez and Le Febre 2006:342)—support strategies of “flexibility, mobility, diversity, reserves and reciprocity” (Fernandez-Gimenez and Le Febre 2006:342) that enable pastoralists to persist in “patchy and unpredictable low-productivity environments” (Fernandez-Gimenez and Le Febre 2006:341). Burnett (2024a) demonstrated that such pastoral institutions in southeast Amdo, Tibet in western China are interdependent in a highly structured way, and Burnett (in press) modelled the structure of the interrelationships between pastoral institutions there, then used the resulting model to trace historical disturbances’ effects on social-ecological resources—the resources that pastoralists traditionally had managed in response to ecological, social, and sentimental cues.

This paper generalizes Burnett’s methodology of i) identifying social-ecological resources in a pastoral system, ii) identifying the pastoral institutions responsible for maintaining those social-ecological resources, iii) modelling the management of social-ecological resources using Attentive Maintenance Models (AMMs), and iv) embedding those AMMs into a Panarchical Model comprising nested sets of complex adaptive systems (Holling 2001; Gunderson and Holling 2002; Burnett 2024a; Burnett, in press). It then demonstrates that using Panarchical Models and AMMs can help people manage risk by predicting the combined effects of different policies and environmental changes on the resilience, adaptive capacity, and sustainability of a pastoral system.

Methodology for Modelling Pastoral Systems Using Attentive Maintenance Models

The first step in developing AMMs to include in a Panarchical Model of a pastoral system is to identify the system’s social-ecological resources, as follows (Burnett 2024a; Burnett, in press):

1. Record, then translate into a written language, semi-structured interviews with people in their native dialects talking about the natural resources they depend on.
2. With each successive interview, adapt the topics/questions to better align with what past interviewees seemed excited or enthusiastic to talk about, talked about at greater length, or chose to talk about (especially when their responses did not directly answer the questions you had thought you were asking). If there is a strong division of labour in the management of natural resources between the different demographics of people that you interview, then the topics and questions you focus on will need to be fine-tuned independently for each demographic.
3. From the transcripts, compile a list of all the actions that people described having taken alongside whatever particular observations they had made that precipitated those actions. Some examples from southeast Amdo include: “winter → slaughter yaks and sheep for food,” “livestock not happy → move the livestock,” “meet somebody with a good yak → try to exchange livestock for it,” “livestock fare poorly somewhere → avoid that location during that season in the future,” and “feel for your past livestock and have excess butter → offer religious butter lamps” (Burnett, in press).

4. Divide the resulting list into three separate parts, one each for observations related to: physical, physiological, and phenological cycles; social happenings or events; and internal personal sentiments.
5. Identify things, concrete or abstract, that are directly affected by actions taken in all three parts of the list. The things will likely be describable in two parts: i) an ecological resource and ii) what is being managed about that ecological resource (e.g. "livestock" and "herd composition," "livestock herds" and "location," and "dairy products" and "flows of production and distribution"). These things are likely to be critical social-ecological resources within the system that you are studying.

For each social-ecological resource identified, an AMM can then be constructed that describes important ways that pastoralists manage the related ecological resource. An AMM is constructed using the following steps:

1. Subset the list that you compiled of sequences of observations and actions to include only those that directly affect the social-ecological resource for which you are making the current model.
2. Place the three parts of the subsetted list side-by-side: place the sequences associated with ecological observations in the left-hand column, sequences triggered by social events or observations in the middle column, and sequences related to sentiment, accrual, or persistence in the right-hand column.
3. Rephrase each sequence's action component as a decision that affects the available set of a single ecological resource (e.g. livestock in a herd or flock, pastures to move to, or dairy product recipients).
4. Use arrows to represent observations and draw boxes to represent consequent decisions that are made.
5. To simplify the diagram, multiple arrows may be pointed to a single box wherever different observations can lead to the same decision state. The final AMM should resemble Figures 1 and 2.

In Figure 1, observations (arrows) lead to decisions (boxes) about Set A of an ecological resource. Observation-decision sequences in the left column are triggered regularly by ecological observations. Sequences in the middle column are triggered stochastically by social observations. Sequences in the right column are triggered by sentiment. An emergent attribute of Set A becomes a social-ecological resource that adapts based on the interplay of decisions being made at these three different frequencies.

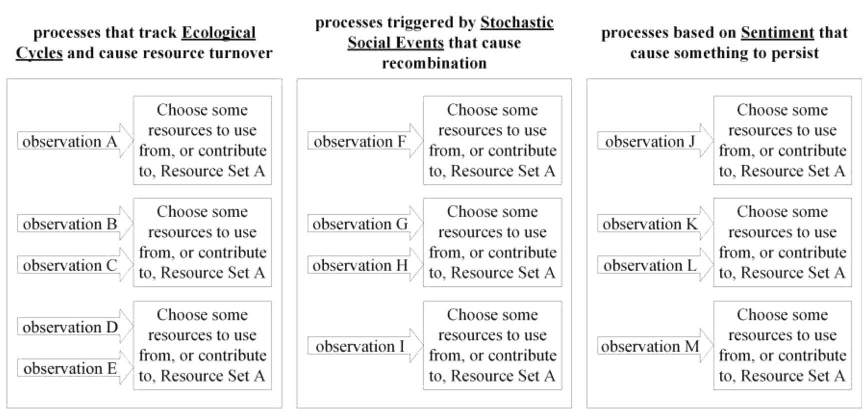
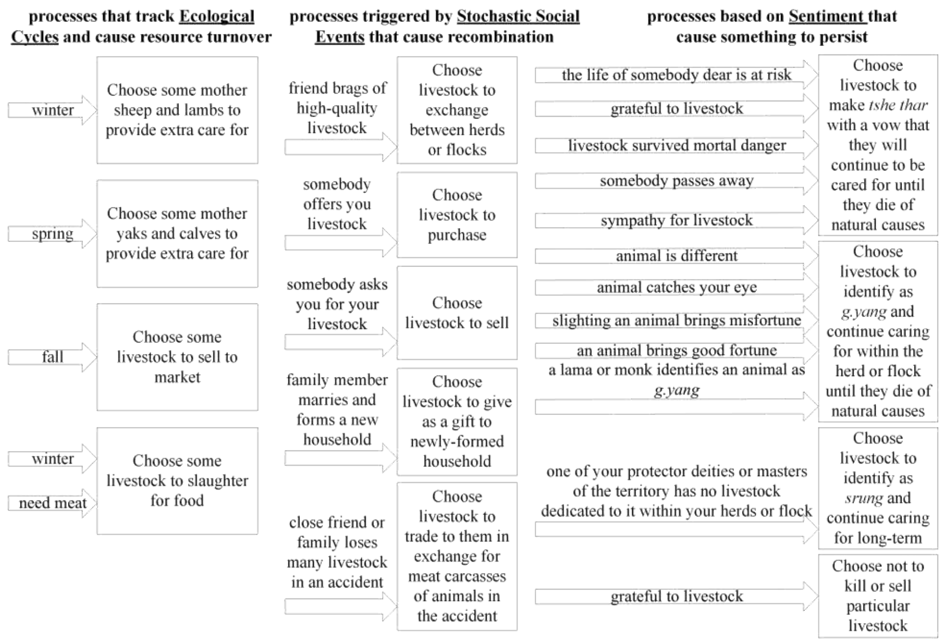


Figure 1: Schema of an Attentive Maintenance Model (Burnett 2024b)

Figure 2: Livestock Herd Composition Attentive Maintenance Model (Burnett 2024b)

Ecological, social, and sentimental observations prompt nomads to make decisions affecting the fates of individual livestock in southeast Amdo. These three different types of observations occur at different frequencies, and they prompt different types of decisions. Collectively, they cause livestock herd compositions to adapt to the ever-changing environment.

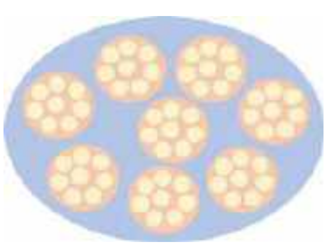


Modelling the Interdependence of Different Social-Ecological Resources in a Pastoral System

Different social-ecological resources in a pastoral system are managed in accordance with different AMMs, but they are also hierarchically interdependent (Burnett 2024a; Burnett, in press; cf. Holling 2001, Gunderson and Holling 2002). For example, in southeast Amdo, each household can manage its own herd's composition, but then to feed that herd the household must begin to move through rangeland. As households meet each other while moving through the common rangeland, they pool their labour to increase dairy production (Burnett, in press). These relationships are hierarchical because many herds must exist before they will develop patterns of sharing forage with one another, and many families must be keeping their herds and tents close to other families before noticeable increases in dairy production and distribution will arise due to shared labour. Each larger social-ecological resource management pattern is therefore sustained by many functionally redundant management patterns of a smaller-scale social-ecological resource: large regional flows of dairy are sustained by many sets of households internally sharing milking labour, and cooperation within each of those sets of households is sustained by the movement patterns of the many households' yak herds (see Figure 3).

The more types of hierarchically interdependent social-ecological resources exist in a pastoral system, the more resilient that pastoral system will be (Burnett 2024a). As different households exchange labour,

Figure 3: Hierarchical Structure of Panarchy (Burnett 2024b)



In Figure 3, using the example of southeast Amdo, each innermost yellow oval represents a herd of yaks maintained by one household, each intermediate orange oval represents the patterned movements of many herds of yaks, and the outermost blue oval represents the production and distribution of dairy products coming from the many sets of many households moving with their herds of yaks. Larger ovals are sustained by many functionally redundant smaller ovals and also provide a network of resource exchange for the smaller ovals that increases their adaptive capacity and resilience to disturbance.

livestock, and knowledge with one another in response to ecological, social, and sentimental cues (respectively), those exchanges enhance their guiding of the adaptation of their social-ecological resources, and they improve the odds that those social-ecological resources can recover from disturbances. Since the management of each different social-ecological resource generates a new social network, hierarchies that have more scales of social-ecological resources provide people with more social networks. The resultant increase in structured connectedness enhances pastoral system resilience (Walker and Salt 2012) by increasing in-network opportunities for people to share labour, livestock, and knowledge with one another. Figure 3 illustrates panarchy's nested hierarchical structure, which underlies the resilience in addition to the sustainability of pastoral systems.

Implications

The role that social-ecological resources play in structuring the social resource networks of pastoral systems has largely been overlooked in scientific literature. Studies of rangeland management and pastoral cultures usually measure ecological resources and social resources separately. Since ecological resources and social resources both fluctuate for pastoral societies, pastoralists create internal resource stability by developing dependable patterns of pastoral institution use that mediate their relationships with society and ecology. In this paper, I have shown how to detect those stabilizing patterns and communicate them using AMMs and a Panarchical Model, as in Figure 4. These models can be used for environmental education, to vet proposed policies, and to plan for climate change. They are useful because they clarify when seemingly irrelevant customs are critical to the resilience and sustainability of a pastoral system in practice and they reveal vulnerable institution types.

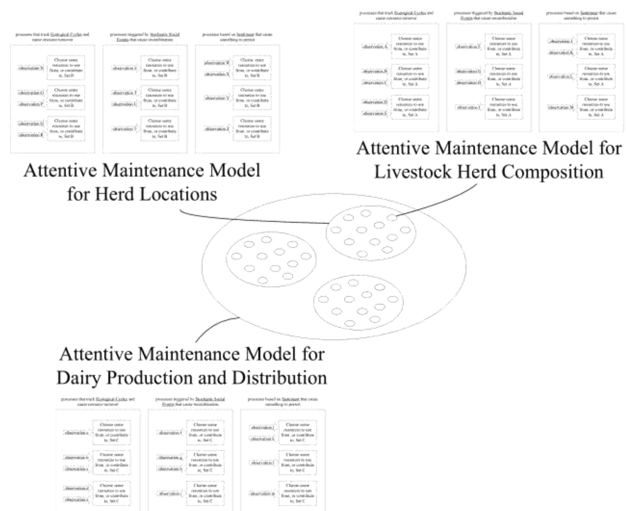


Figure 4: Scales of Panarchy and Attentive Maintenance (Burnett 2024b)

Attentive Maintenance Models can be used to describe the management of social-ecological resources at different scales within a panarchy. The three types of nested social-ecological resources in this sample Panarchical Model are managed in accordance with three respective Attentive Maintenance Models.

Every column in the AMMs of a pastoral panarchy is critical to pastoral resilience. Removing any one of them causes the loss of social networks at that scale and all larger scales of the pastoral panarchy, reducing the resilience of the pastoral system. In southeast Amdo, private leasing of rangelands once used in common now prevents pastoralists from moving their yak herds in response to social, ecological, or sentimental changes, amounting to the removal of three columns of attentive maintenance. Dairy production is no longer sustained by the social-ecological pattern of yak herd movements, which once led households to share milking labour. The larger two scales of social networks and resilience in the pastoral panarchy are thus fading, but assessment with a Panarchical Model reveals both the mechanisms underlying these changes and the potential to reverse them (Burnett, in press). Risk in a pastoral system can be mitigated by the restoration and support of all columns of attentive maintenance; in combination, the columns help a system adapt to its changing context, even when the columns' internal sequences change.

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De-risking, inclusion and value enhancement of pastoral economies (drive) project in Kenya

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Key words: De-risk; Rangelands; Pastoralists; Index-Based Livestock Insurance; Private sector.

Abstract

DRIVE is a regional financial intervention project being implemented in four Horn of Africa (HoA) countries as part of building resilience to climatic shocks, facilitating trade and supporting livestock value chains within the rangelands. The project objective is to protect pastoral economies against drought risk, increase financial inclusion of pastoralists and better connect them to markets and to facilitate livestock trade and upgrade livestock value chains by mobilizing private investments. The project has two components: one is to support the provision of an integrated package of financial services to build climate resilience including drought index insurance, savings incentives and manage digital payment, and the other is to better include pastoralists in the livestock value chains and facilitate trade and de-risk private investments in the livestock value chains. The project supports four priority areas including: pasture production and conservation, livestock breeding of cattle, sheep and goats, livestock finishing and value addition. To ensure sustainability, the project is private sector led, with regional implementation via local private sector players and international reinsurers, that are constituting pastoralist groups around economic activities to have access to products and services for ownership and alignment to the project objectives. Extensive lessons were learnt from current and previous drought schemes. So far, 186,903 small scale pastoralists have bought USD 4.08 million worth of insurance premiums covering 673,986 Tropical Livestock Units (TLUs), and fourteen private sector investments worth USD 8.9 million have been approved for financing. The project has made livestock insurance payouts of USD 4.94 million to the pastoralists via mobile money transfers.

Introduction

The Horn of Africa (HoA) includes the eight countries that are members of the Intergovernmental Authority on Development (IGAD) namely Djibouti, Eritrea, Ethiopia, Kenya, Somalia, South Sudan, Sudan and Uganda. Most of these countries are amongst the poorest and most fragile regions in the world, where one third of the population lives below 1.9 dollar a day (HOA REM, 2021). In the eight HoA countries, one fifth of the total population is made up of pastoralists or agro-pastoralists, i.e., around 50 million people. Their main source of livelihood is the rearing of livestock, mostly in open grazing rangelands in the semi-arid areas. Several countries have come together to strengthen regional cooperation and address global challenges within the "Horn of Africa Initiative". The region is exposed to disasters, amplified by climate change, and recurrent severe droughts are a key factor for poverty and conflicts in pastoral economies. Droughts degrade rangelands, deplete livestock, and lead to underinvestment. Underinvestment lowers pastoral productivity and holds pastoralists in a poverty trap. Pastoralists move across national and clan borders in search of greener pastures and the pressure on scarce resources exacerbates conflicts. About 29 percent of the total land area in Ethiopia and 40 percent in Kenya is classified as degraded. However, such degradation is caused by growing population numbers, land use for economic development, and climatic impacts.

The economies of countries in the HoA are highly dependent on pastoralism and livestock production as a source of livelihoods, income, and contribution to GDP. The impacts of the COVID-19 pandemic have been severe and compounded by other shocks. The regional livestock trade is significant but mainly unrecorded and focused on live animals. Livestock trade represents one of the few economic success stories in the Horn of Africa (Little, 2020).

The livestock value chains are dominated by traders, with limited benefits going to the pastoral producers. Livestock sales are often influenced by ethnic and family ties, due to the uncertain business environment, the absence of formal systems of credit enforcement, weak infrastructure, limited market support services and prevalent insecurity in pastoral areas (HoA REM, 2021). Women are highly engaged in the pastoral economy, as labourers, consumers, and producers, both for markets and their households. Access to formal financial services and credit for pastoral producers is limited

The project development objectives are to enhance pastoralists' access to financial services for drought risk mitigation, include them in the value chains, and facilitate the livestock trade in the Horn of Africa. Compagnie De Réassurance De La Zone Préférentielle (ZEP-RE), PTA Reinsurance Company and Kenya Development Corporation (KDC) are the project Implementing Partners for component 1 of De-risking pastoral production through a package of financial services and component 2 Part 1 of Promoting livestock value chains through trade facilitation and private sector support respectively while the State Department for Livestock Development is the Implementer of component 2 Part 2 which involves supporting management of the project and guiding day-to-day operations of DRIVE project. The project period is October 2022 to September 2027

Methods

In Kenya, the project targets 21 ASAL counties of Turkana, Marsabit, Isiolo, Laikipia Mandera, Wajir, Garissa, Tana River, Taita Taveta, Kilifi, Kwale, Lamu, Meru (Meru North sub county), Tharaka Nithi, Samburu, Baringo, West Pokot, Narok, Kajiado, Makueni and Kitui where pastoralism type of farming is done and drought Index based Livestock Insurance (IBLI) products are viable.

Training on the IBLI product has been conducted each season, equipping these stakeholders with essential knowledge on index-based insurance principles, premium structures, payout mechanisms. Specifically, promotional campaigns and outreach efforts are used to educate pastoralists how insurance could help them cope with drought by helping them purchase fodder, feed supplements, water, and vaccines during drought thus potentially keeping more animals alive and maintaining their livelihoods and leveraged community meetings, radio broadcasts, digital platforms, and printed materials to ensure that even

About 240,000 pastoralists from 21 project counties have been sensitised and registered in project financial digital inclusivity platform. Insurance companies assess livestock insurance payouts using Index-Based Livestock Insurance (IBLI) product that has been designed to protect against prolonged forage (pasture) scarcity. This index is typically derived from satellite data monitoring vegetation, and the pay-out is triggered when the index falls below 25th percentile of historical data indicating a potential livestock mortality risk due to drought.
Trade facilitation and private sector support is done competitively by KDC and awarded to successful implementers after thorough assessment of their business plans

Results
The project has conducted livestock insurance sales to pastoral beneficiaries in the 21 project counties and cumulatively under Component 1 on pastoralist access to financial package for drought resilience the following milestones have been achieved in the 21 counties where livestock insurance has been implemented in the four livestock insurance sales seasons:

Out of the 240,000 pastoralists registered, 186,903 agreed to buy livestock insurance which is a good response. For sustainability, the subsidy reduces annually so that by the end of the project the pastoralists can buy the insurance on their own
Since the project's inception, the financial package under Component 1 has been successfully delivered to pastoralist communities in the 21 counties for five consecutive seasons of OND 2022, MAM 2023, OND 2023, MAM 2024 and OND 2024. This initiative has played a crucial role in enhancing the financial resilience of pastoralists by providing them with essential support mechanisms such as insurance, savings, and market access. Over this period, the project has sold 186,903 policies with 673,986 Tropical Livestock Unit (TLU) Insured (TLU= Cow equivalent) insured in the process which have positively impacted approximately one million pastoralists and their families, improving their ability to manage financial risks, sustain their livelihoods, and adapt to climate-related challenges. The project has subsidized livestock insurance premium at a rate of 70% - 80% where pastoralist have benefited from a total subsidy of USD 13.9 million and to this end the pastoralist have paid their 20%-30% of the livestock insurance premium totalling USD 4.08 million. The pastoralists who have procured livestock insurance for 3 TLUs and above have benefited from a one-off enrolment saving bonus (USD 50 per beneficiary) totalling to USD 7.3 million and the project has made livestock insurance pay-outs of USD 4.94 million to the pastoralist. The total benefits in terms of livestock insurance premium subsidy, enrolment saving bonus and livestock insurance pay-outs pastoralist in the 21 counties added up to USD 26.2 million

As at 31st January 2025, KDC had already disbursed loans worth USD 2,558,057 to successful investors, while 62 projects are pipeline Investment projects totals to USD 51,614,137

The Project Implementation Unit (PIU) carried out its coordination role as well as capacity building in collaboration with counties and relevant stakeholders. The project will subsidize insurance premiums up to the end of the project in the year 2027. The provision of index drought insurance products is been done commercially by roping in private sector insurance providers who will be able to cover their cost of operations and run profitable business. The project supports the creation of necessary awareness on insurance and the number of pastoralists buying livestock insurance and thus the using of other financial services like savings and credit is expected to increase. A strategy has been put in place where supported pastoral households under livestock insurance are linked to better livestock markets which will provide them with an opportunity to sale their livestock for better prices, thus increasing their income. As household income increases, they can contribute more for insurance premium payment reducing the fiscal burden from the government. The demand for formal financial services among the pastoralist is expected to go up with increased awareness on the DRIVE project interventions.

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XII INTERNATIONAL RANGELAND CONGRESS
AUSTRALIA 2025

Strategies for building resilient pastoral and agropastoral systems in Africa

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Key words: climate risk; last mile delivery; climate services; resilience, decision support.

Abstract

In the drylands of Africa, low and variable rainfall and the increasing incidence of extreme weather events, leave poor communities, dependent on pastoral and agropastoral livelihood systems, highly vulnerable. Building resilience must consider the immediate 'tactical' approaches for managing climate risk (e.g. de-risking measures such as the index-based livestock insurance (IBLI) bundled with credit, inputs, climate information services) and 'strategic' approaches, where communities work together to reimagine sustainable land-use and resilient livelihoods (e.g. participatory rangeland management (PRM) supported through bylaws). Enhanced mobile network penetration also offers unprecedented opportunities for the dissemination of information to pastoralists and farmers through digital channels. Further, digital technologies enable new methods of acquiring and sharing data, ground truthing, and obtaining user feedback especially in data sparse environments (e.g. KAZNET, a citizen science innovation that crowdsources information on rangelands animals, markets, food security, conflict). Data collected through such innovations can contribute to the monitoring of shocks, improving product design, informing policies and institutional decision making. This paper gives examples of several tactical and strategic approaches to building resilience in pastoral and crop-livestock systems in Africa.

Introduction

Climate variability is a major source of risk in livelihood systems of the drylands, that are home to almost 3 billion people and cover some 46% of the globe's land area (IPCC 2022). In the drylands, pastoral livelihoods take place on the rangeland areas (some 25% of the total land area), and in crop-based farming systems (some 12% of the total land area) (FAO 2019). Increasingly, these livestock-based livelihood systems are in flux and are threatened. Along with other biophysical, socio-economic and political factors, climate risk contributes enormously to food insecurity, economic losses, and multi-dimensional poverty (Shiferaw et al. 2014). Research has also identified potential options that can contribute to improved management of agricultural systems under variable climatic conditions, and the perceptions and coping strategies being adopted by farmers. Resilience, agricultural productivity and profitability under these high climate risk environments are therefore dependent on: (i) the inherent resilience of the livestock and farming enterprises which is a function of landscape and farm design within the context of the agricultural innovation system (strategic); and (ii) how well the livestock and farm management are planned and executed in the context of the risk (tactical). How this applies to agropastoral and pastoral systems in Africa is presented in a series of examples of on-going work that ILRI and its partners are undertaking in West, East and Southern Africa.

Tools and methodologies

Examples of strategic approaches to build agricultural system resilience include:

- Working with communities and government to co-design more sustainable land-use, for example the joint village level land use planning coupled with PRM and supported with bylaws (ICPALD 2024).
- Co-design climate information services with community of practice (CoP) for livestock farmers with digital technologies (mobile phones and radio program dissemination) (Houessionon et al. 2023, Diallo et al.2024).
- Influencing the decisions of pastoralists regarding routes and movements of livestock to access fodder and water (IGAD 2024).
- The use of model-based approaches to underpin the farm/landscape co-design process or to influence policymakers and development practitioners understand the farming systems' sensitivities and the potential benefits of climate change adaptation to current and future climate scenarios (AGMIP 2024; Whitbread et al. 2021)

Examples of tactical management of climate risk include:

- Innovative insurance schemes for livestock producers (i.e. IBLI) (Banerjee et al. 2019).
- The intelligent Systems Advisory Tool (iSAT) (Ramaraj et al. 2023)
- KAZNET as a data collection and dissemination approach based on citizen science principles to crowdsource data on rangeland condition, animal numbers, markets, conflict, household food security etc (Chalenga et al. 2022; Alulu et al. 2024).
- Web-based platforms like (WENDOU 2024) in Ferlo, Senegal for assessing water availability in ponds, thus facilitating stock drinking water management in arid areas.

Discussion

Strategic approaches for building resilient livelihood systems

The longer-term perspective, where an agricultural system is redesigned to be more resilient to the current and future climate patterns, can be termed 'strategic' planning. The design of the agricultural systems should consider what mix of management, enterprises and farming systems are most resilient to current and future climate also considering market and cultural factors. This requires analytics to understand the historical and projected climate scenarios, model-based scenario analysis, and co-design of farming systems that are more resilient to extreme events and reduce the damage of such events on the natural resource base. In some landscapes and environments, transformational changes in landscape design might be urgently needed (Whitbread et al. 2021).

In agropastoral systems, climate induced risk associated with season-to-season variability of rainfall is one of the major challenges to achieving food security across large parts of semi-arid Africa. Since season outcomes are uncertain, even with the best climate information, farmers have limited flexibility in applying management with confidence. In fact, in risky environments, farmers most often respond by adapting a risk averse strategy and are reluctant to invest in even risk reducing measures (Leathers and Quiggin 1991). In most agropastoral systems, there are a limited range of enterprise or crop options to consider. The options may be further restricted by cultural traditions, food preferences, market opportunities or simply a lack of access to inputs such as seed and fertiliser or knowledge. New thinking on crop-livestock integration is needed to bring the climate risk lens to the design and management of such systems. Examples include: Using diversification such as multi-species crop-tree-livestock (forage) farm systems (e.g. for the West African Sahel, millet-cowpea-ziziphus agroforestry-based systems show great promise according to Bado et al. (2021)); building soil fertility management and restoring soils to overcome nutrient limitations and avoid water stress (Bado et al. 2022); more broadly using crop breeding programs to enhance the use of multi-purpose traits in cereal germplasm (e.g. Blummel et al. 2020).

In pastoral systems, mobility has been the core adaptation mechanism in pastoral systems for generations. Restrictions on the mobility of pastoral communities and their livestock, conflicts and stricter cross-border control and defective tenure policies pose threats to the sustainability of pastoral livelihoods (IGAD 2024). While well managed rangelands may store carbon in soils and vegetation, and provide a range of ecosystem services, the management of rangeland systems in Africa are increasingly contested as populations grow, government policies tend to aim at settling pastoral populations, and the resource base becomes degraded (Nori and Scoones 2024). Recognizing that pastoral communities remain central to finding solutions, empowering communities to design and manage landscapes with good governance, resolving and preventing conflicts between land users, employing early warning systems (i.e. drought, extreme events) and other methods to manage livestock and rangeland resources are key. Methods such as participatory land use planning or participatory rangeland management (PRM) have been successfully piloted across several East African countries (Waweru et al. 2021). In West, Central and East Africa where transhumance is common, seasonal variations drive transhumant migrations over vast distances between wet and dry zones, providing pastoralists with access to stock feed, and farmers with improved soil fertility via manure, leading to co-benefits and efficient land use. According to Wane et al. (2023) climate change has become a direct and aggravating factor of other shocks (i.e. animal health, markets, conflicts) that result in considerable quantitative, qualitative and economic losses. Development bodies such as IGAD play a key role in building an understanding of the role of pastoralism in managing landscapes and livelihoods and engaging communities and government to agree on movement between countries, on cross border animal health, mapping of transhumance routes, and early warning systems for drought and extreme weather events. Additionally, linking the design, management and restoration of rangelands to the issues of climate risk management, mitigation and carbon sequestration, may be a way to drive much needed innovation in these long-neglected systems.

Tactical approaches for building resilient livelihood systems

Adopting a flexible risk management strategy informed by multiple information sources to make decisions allows a pastoralist, livestock keeper or farmer to develop tactical management approaches. Such strategies may include pre-season planning guided by seasonal climate forecasts, a set of criteria or 'triggers' for sowing, variety selection, livestock life cycle planning, and a range of in-season responses to the prevailing weather, market signals or other factors. Recent advances in climate science have led to significant improvements in the predictability of climate and weather at scales that are useful in planning and managing agricultural systems. These predictions, when linked to systems information and scenario analyses through simulation models, provide an opportunity to critically evaluate and identify alternative soil, crop and management options that minimize risk and improve productivity and profitability. While pilot studies have established the usefulness of climate information for decision-making, operational delivery 'at scale' of actionable information products requires context-specific granularity, timeliness, formatting and feedback loops for continuous learning (Ramaraj et al. 2023).

While agropastoral systems remain important in the developing world and potentially support more equitable, resilient, and sustainable agriculture than other food systems, climate risk has remained a major disincentive to sustainable intensification. Exacerbating the challenge has been the expansion of cereal farming, especially maize, into the semi-arid regions, leading to a risky food security situation (Tesfaye et al. 2015). Further, the role and potential productive capacity of livestock in agropastoral systems are generally undervalued compared with the farmers' desire for the grain staples. At the farm level, area planned deployment of annual crops (cereals and legumes) within rotations and planning arrangements (e.g. intercropping) must consider temporal (historical and forecasted climate) and spatial (soil fertility, soil moisture conditions) to allow more optimal land use considering risk. The role of dual-purpose germplasm can be made more central for its provision of multiple products options and the end-use decisions that can be made tactically within the season. In crop-based systems, a decision support tool called 'iSAT', which built on earlier work in commercial cropping systems in Australia (see Hochman et al. 2009), defines a process to create context specific climate informed agro-advisories for use in tactical agronomic decisions making at the farm level. In these examples, models have been used in a participatory mode to develop scenarios that farmers face in their day-to-day management and are linked to ICT methods of deployment through a range of public and private dissemination efforts.

For livestock keepers in pastoral or mixed crop-livestock systems, advisory services are much less developed than those developed for agronomic decision making and rarely linked to climate drivers. This represents a significant area for research, by considering the life cycle of fodder or animal components linked to climate information to develop actionable management strategies similar to the agronomic examples of iSAT. For example, the timing of reproduction, management of the herd, timing of marketing or stock movements, prediction of rangeland feed resources could all be linked to climate information. In transhumance systems, Wane et al. (2020) show that the probability of transhumance increases under rainfall delay, drought or with changes in cattle prices. In such systems, livestock itineraries involve detailed planning, adjusting for water conditions and fodder constraints and may be influenced by information coming from a range of sources, for example a multi-stakeholder platform or community of practice (COP). Houessionon et al. (2023) documented a COP in Senegal that made use of decision support tools, market price forecast tools, indigenous and expert knowledge of its members to reach >78,000 herders using various communication channels (e.g. interactive voice response IVR, rural radio). The need for bundled socio-technical innovation bundles comprising of risk financing mechanisms and other services (e.g. inputs, climate information services) is increasingly important for building resilience in the pastoral areas. Research is needed to understand the socially differentiated preferences of pastoralists for such bundled innovations and evaluate their effectiveness ex-ante and ex-post.

Conclusions

The pastoral and agropastoral systems in Africa remain central to the livelihoods and farming systems of millions, but are often highly vulnerable to extreme weather events and affected by land degradation, contested government policies and conflicts. Developing solutions must be considered through a climate lens, with farming system or landscape design co-developed considering future climates. Participatory processes embedded in community dialogue and consultation ultimately supported by government policy, bylaws or customary processes, have been shown to be scalable and sustainable. To maintain livelihoods and food security, farmers and livestock keepers must consider climate risk in their management decisions, especially through the use of advisory and extension information that are linked to climate and indigenous knowledge. Enhanced co-operation of the national agriculture research and extension services, the national meteorological agencies, farmer facing organisations and private sector players (e.g. agri-tech), are needed to develop the digital public infrastructure that support the creation and dissemination of innovations.

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Mucuna pruriens-based feeds that improve sustainability of communal goat farming during the dry season in semi-arid savannah of southern Africa

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Key words: *Mucuna pruriens*, drought, supplementary feed, home-mixed rations.

Abstract

The International Livestock Research Institute is promoting cultivation and processing of *Mucuna pruriens* as a climate-smart fodder which can produce cost-effective feed supplements for livestock on communal rangelands in semi-arid Zimbabwe, to de-risk and improve sustainability of livestock production during droughts. Commercial supplements are generally expensive and not readily accessible to agro-pastoralists. Home-mixed Mucuna-based supplements can be nutrient-dense and effective. In a seven-week on-farm trial, Mucuna hay (MH) reduced weight loss in mature Matebele goats, though its effectiveness was inferior to Bambara nut hay and dried groundnut haulms ($P<0.05$). Goats averaging 28.2kg body weight (BW) and grazing solely on rangeland lost -66g head^{-1} day^{-1}, while those fed 1:2 MH: maize stover (MS), 1:2 Bambara nut hay: MS and 1:2 groundnut haulm: MS at 1% body weight during evenings only achieved -5g, 54g and 63g head^{-1} day^{-1} average daily weight gain (ADWG), respectively at the peak of 2022 dry season. This showed that farmers can maintain goats on MH. East Africa-type does (±25kg BW) supplemented with 45g head^{-1} day^{-1} of coarsely ground Mucuna pods (shell + kennel) at night-time during the 2021 dry season gained even more (150-270g head^{-1} day^{-1}), proving that pods are a richer supplement. Efforts were made to combine Mucuna with other local nutrient-dense feeds and forages to diversify the range of supplementary feeds and so improve accessibility. On-farm demonstrations conducted over a six-week period in 2022 showed that home-mixed rations (21.9 and 21.4% CP) of (i) *Mucuna* grain (MG) + *Lablab purpureus* hay (LpH) and (ii) MG + LpH + *Sorghum vulgare* grain fed to Matebele goats at 1% of body weight increased ADWG to 50g and 70g head^{-1} day^{-1}, respectively. These results led ILRI and national partners to officially register three marketable supplements for goats and sheep in April 2024.

Introduction

Maize-mixed farming occupies 32 million hectares (or 19%) of the total cultivated land in East and Southern Africa (ESA) region (Garrity et al. 2012). Maize is a staple crop in ESA and an important source of livelihood. Farmers usually add diversity to maize through cultivation of grain legumes to reduce the risk of total agricultural failure in the event of droughts and other calamities (Sumberg 1998). Legumes normally sown in rotation or through intercropping with maize were listed by Garrity et al. (2012). Grain and residues from these legumes and from tropical forage legumes can be incorporated in supplementary diets of large and small ruminants. Home-mixed supplements containing non-conventional legumes are cost-effective compared to commercial supplements which are formulated using oil-seed cake (Chakoma *et al*. 2016). Feeding non-conventional supplements to livestock grazing communal rangelands can increase productivity and farmers income.

The International Livestock Research Institute (ILRI) is conducting various studies to mitigate drought and de-risk maize-mixed farming systems in ESA. Several on-farm experiments conducted in Zimbabwe during the past two decades demonstrated that it is possible to sustainably integrate livestock production with maize-groundnut and other maize-legume rotations (Chakoma et al. 2016; Gwiriri et al. 2016). In the Ukama Ustawi (U2) and the EU-Funded LIPS-Zim Projects ILRI is promoting ley farming using two climate-smart forage legumes (*Mucuna pruriens* and *Lablab purpureus*) to diversify and sustainably intensify traditional cropping patterns towards livestock production (Matebesi 2024; Siyamachira 2022). As ESA is predicted to be a climate hotspot (Lugoi *et al*. 2023) there is need to promote resilient climate-smart farming practices, which include goat rearing.

The objective of this paper is to show how farmers practising integrated crop-livestock farming can formulate home-mixed feeds to de-risk and sustainably improve goat production on Savanah rangelands.

2. Materials and Methods

2.1 Study sites

Three participatory on-farm experiments were conducted in villages of Buhera (Ward 15) and Beitbridge (Ward 11) districts during the 2021 dry season and Gwanda district (Ward 24), during the 2022 dry season. All districts are in the semi-arid regions (agro-ecological IV and V) where the dry season normally extends from May-November. At all sites host farmer selection was based on (1) willingness (2) availability of goats for the experiments and (3) availability of planted fodders.

2.2 Dietary treatments

In *Experiment 1 (Beitbridge, Fula ward)* 20 Matebele goats at one homestead were randomly assigned to four treatments diets namely, (T_1) rangeland grazing only (i.e. farmer practice); T_2 comprised of velvet bean hay and maize stover (1:2 ratio); T_3 groundnut haulms and maize stover (1:2 ratio); T_4 Bambaranut (Vigna subterranea (L.) Verdc) haulms and maize stover (1:2 ratio). Five goats were assigned to each treatment. All goats grazed Acacia thornveld during daytime. During the evening, those on supplementary feeding were separated, individually penned and fed different supplementary feeds at the rate of 1% body weight. Water was provided *ad-libitum*. The experiment ran for 49 days from October to November 2021.

In *Experiment 2 (Buhera - Mutunha Vidco)* 30 East Africa-type goats from two villages (15 from each village) were assigned to three supplementary diets namely, (Ti) rangeland grazing only, (T_2) 75 grams of crushed velvet pods (unshelled); (T_3) 280g of a velvet bean-based ration. Five goats from each village were assigned to each treatment. Feeding management was the same as in *Experiment 1*. The experiment ran for 42 days from September to October 2021.

In *Experiment 3 (Gwanda, Ward 24*) 15 Matebele goats were used in the trial. Five goats were allocated to each treatment. Goats across all treatments grazed Acacia thornveld during daytime. Supplementary feed was only provided to goats in Treatment 2 and 3 at the rate of 1% of BW, during the evening. Composition of feed supplements for Treatments 2 and 3 is shown in Table 1.

Table 1: Composition of treatment diets for the goat feeding experiment conducted in Gwanda during the 2022 dry season.

Diet ingredient	Proportion (%) in diet on DM basis	
	Diet 2	Diet 3
Lablab purpureus hay	25.80	25.80
Mucunapruriens grain	58.70	48.30
Molasses	12.10	12.10
Sorghum grain (crushed)	0	10.30
Monocalcium phosphate	0.61	0.65
Limestone flour	1.31	1.36
Coarse salt	1.08	1.05
Ammonium Chloride	0.22	0.22
Vitamin-Mineral Premix	0.21	0.21

Feeding management was the same as in *Experiment 1*. The experiment ran for 41 days from October to November 2022.

2.3 Preparation of experimental animals

All experiments were set out to determine voluntary feed intake (VFI) and live weight changes of goats fed different diets. Goats with average live weights of 26 kg - 32 kg were used in *Experiment 1 and 3* and average ± 25 kg in *Experiment 2*. Experimental animals were vaccinated for Pulpy Kidney (PK), dipped and dewormed (i.e for ecto and endo parasites) prior to trials. Goats were ear-tagged for identification and initial weights were recorded. Fourteen days were permitted for feed induction in all experiments. Animals were weighed once a week. The amount of feed supplied to the goats was adjusted weekly on the basis of their body weight changes. Animal husbandry practices were similar across all treatment groups.

2.5. Laboratory analyses.

Samples of all supplementary feeds were ground through a 1mm screen and dry matter (DM) was determined by oven drying at 70^0C for 48 hrs. Crude protein was determined following the standard Kjeldhal method (AOAC, 1991), ether extract was determined using the Soxhlet apparatus while neutral detergent fibre (NDF) and acid detergent fibre (ADF) were assessed using the methods proposed by Van Soest et al. (1991).

2.6. Statistical design and analysis

In Experiment 1 and 3 dietary treatments were tested using a randomized complete block design (RCBD) with initial weights and sex used as blocking factors. Statistical analyses were conducted using the General Statistical Package software (Genstat 14th Edition, 2017). Data were tested for normality using the Shapiro-Wilk. Daily weight gain and VFI were analysed following a General linear model procedure (GLM). Data were fitted to test the effect of feeding regimes on daily weight gain and feed intake. Differences of means were tested using Least Significant Difference (LSD) *post hoc* test at 5 % level of significance.

In Experiment 2 a RCBD was used to test three dietary treatments with age and breed as blocking factors. Collected data was tested for normality using the Kolmogorov-Smirnov test in SPSS software. PROC GLM procedure of SAS was used to analyse treatments effects on dependent variables.

3. Results

3.1 Experiment 1

Daily liveweight gains were significantly ($P<0.05$) higher in goats fed supplements containing Bambara nut haulms (BNH) and groundnut haulms (GNH) compared to Mucuna hay (MH), even though MH had relatively higher crude protein (CP) content (Table 2). There were no significant differences on NDF content. Heaviest losses (-66g head^{-1} day^{-1}) were observed in unsupplemented goats while MH caused lower weight losses (-5g head^{-1} day^{-1}).

3.2 Experiment 2

There were no significant differences ($P<0.05$) between does on supplements derived from unshelled Mucuna pods (UMP) and the Mucuna-based supplement (MBS). These East Africa-type does gained live weight at 42.9 and 28.6 g $^{-1}$ day^{-1}, respectively during the dry season, whereas those on rangeland grazing only lost weight at -95.2 g $^{-1}$ day^{-1} ($P<0.05$).

3.3 Experiment 3

Efforts were made to incorporate local nutrient-dense feeds and forages to diversify the range ingredients and so improve accessibility (Table 1). Results showed that home-mixed rations (21.9 and 21.4% CP) of (i) *Mucuna* grain (MG) + *Lablab purpureus* hay (LpH) and (ii) MG + LpH + *Sorghum vulgare* increased ADWG to 50g and 70g head^{-1} day^{-1}, respectively in Matebele goats (Fig. 1).

4 Discussion

Traditional dry season goat management practices in Buhera, Beitbridge and Gwanda consist largely of semi-extensive rangeland grazing during the day and overnight penning with limited supplementation. Results from all experiments show that rangeland grazing alone is not sufficient to meet nutritional needs of all classes of goats and may culminate in poverty deaths. This resonates with Charambira *et al*. (2021) who indicated that smallholder farmers ought to adopt practices such as forage conservation, utilization of crop residue and use of cultivated fodder crops.

Supplementary feeds based on MG and GNH or BNH could be a powerful alternative to conventional feeds, judging from the higher levels of live weight gains (54.5 – 71g^{-1} day^{-1}) recorded in Experiments 1 and 3. This collaborates findings by Chakoma *et al*. (2016) and Gwiriri *et al*. (2016) who recommended the same for beef and dairy cattle, respectively. These results led ILRI and national partners to officially register three marketable supplements for goats and sheep in April 2024 under the Ukama Ustawi Project.

Experiment 3 findings suggest that increasing energy to legume-only supplements improves gut fermentation, evidenced by an increase in liveweight gains from 40 g^{-1}day^{-1} on T_2 to 69 g^{-1}day^{-1} on T_3, turning them into effective supplements for maintenance or grower rations. Farmers could feed up to 1.5% of body weight before goats start suffering from antinutritional or depressants factors.

Performance variations in Experiments 1 and 3 are attributable to breed factor (Matebele vs East Africa type) and nature of biomes. Rate of weight loss in unsupplemented goats from Buhera seemed to be higher (-95.2 $g^{-1}day^{-1}$) compared to Gwanda (66.4 $g^{-1}day^{-1}$), during October and November. The nutritive quality of rangelands deteriorates more in sour veld of Buhera compared to the sweet veld of Beitbridge. Therefore, it is more imperative for Buhera farmers to provide supplementary feeding to goats. It would also be even more beneficial is the feeding starts in July or August, especially for young goats.

Fig 1: Average daily weight gain Gwanda district

5 Conclusion

It is not sufficient for ESA farmers to rely on communal rangeland grazing only for subsistence or commercial goat production. These farmers can improve their livelihoods and incomes through goat farming by diversifying and de-risking maize-mixed farming systems through incorporation of *M. pruriens* and *L. purpureus* leys to supply grain and hay, respectively which will be mixed with residues of common grain legumes to improve quality and cost-effectiveness of dry season feeds. Adoption of this technology will be easier when farmers can access appropriate machinery to process the ingredients.

Table 2: Performance of goats fed different types of forage-based supplements and nutritional composition of the formulated supplements.

District	Treatment	Average daily gain (g/day)	[#]Daily suppleme nt-ary feed intake (g/day)	CP (%)	ADF (%)	NDF (%)	DM (%)
Experiment 1							
Beitbridge	T1 (*Farmer practice*)	-66.4^{a}	0	n/a	-	n/a	n/a
	T2 (*VBH + MS*)	-4.9^{b}	280	10.76	-	33.79	91.60
	T3 (*GNH + MS*)	54.5^{bc}	280	7.98	-	33.48	91.32
	T4 (*BNH + MS*)	63.2^{c}	280	7.78	-	33.74	91.49
Experiment 2							
Buhera	T1 (Farmer practice)	-95.2^{c}	0				
	T2 (MBS)	42.9^{a}	280^{a}	21.86	33.35	48.02	92.42
	T3 (UMP)	28.6^{b}	75^{b}	21.14	37.63	65.58	92.90
Experiment 3							
Gwanda	T1 (Farmer Practice)	-8.0^{b}	0				
	T2 (MG + LpH)	40.0^{ab}	280	21.86	33.35	48.02	92.42
	T3 (MG + LpH + SGM)	69.0^{a}	240	21.14	37.63	65.58	92.90

[#]DFI refers to daily intake of supplementary feed.

Experiment 1: VBH = Velvet bean hay, GNH = Groundnut haulms BNH =Bambaranut haulms.

Experiment 2: MBS = Mucuna-based supplement, UMP = Unshelled Mucuna pods)

Experiment 3: MG = Mucuna Grain, LpH = Lablab hay, SG = Sorghum grain meal

*Within an Experiment site, the same superscripts in same column denote no significant differences between treatments at P<0.05

[1] Experiment 3 Gwanda ADG statistics: P-value = 0.037 and s.e.d = 0.026 and Beitbridge ADG statistics: P-value 0.005 and s.e.d. = 0.024.

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Poster presentation – Theme 5

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Climate-smart legume-grass system can reduce greenhouse gas emissions and net SOC

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Keywords: Soil organic carbon; legume-native grasses; global warming; soil restoration; climate adaptation

Abstract: Improving forage productivity with lower greenhouse gas (GHG) emissions from limited grassland has been a hotspot of interest in global agricultural production. In this study, we analysed the effects of native grass species (*Artemisia capillaris* L.; *Lespedeza daurica* L. & *Stipa bungeana* L.), with legumes (alfalfa; M-vetch & Pea-shrub), and native grasses+legumes mistures (*artemisia capillaris* + alfalfa; *Lespedeza daurica* + pea shrub; and M-vetch + *Stipa bungeana*) overseeded mixtures were tested to quantify on GHG emissions, net soil organic carbon potential (Net SOC). Fodder forage yield-based greenhouse gas intensity (GHGI), soil chemical properties and forage quality and productivity in Typical Steppe grassland in Gansu province of China during the cropping season on 2023 and 2024. The research results demonstrated that high seeded intensity alfalfa + native grass significantly improved forage production. The maximum total dry matter yield (DMY) during 2023 and 2024 was attained from legumes+native grass at optimum seeding (9,317 and 10,461 kg ha^{-1}), and legumes mixtures vs native grass mixtures (8,513 and 9,892 kg ha^{-1}) at higher seeding rates. The yearly collective GHG emissions from legume + native grass mixtures were lower than alfalfa sole-culture. Alfalfa with native grass mixtures significantly reduced greenhouse gas intensity (GHGI) compared with the native grasses and sole alfalfa planting system. Moreover, experiment outcomes showed that native grass, alfalfa and alfalfa- native grass mixtures differentially affected on chemical properties of soil. Lower soil pH and C/N ratio were documented in higher planting density of alfalfa when grown under sole system, whereas legumes and native grasses mixtures significantly (17%) increased soil organic carbon (SOC) and soil total nitrogen (STN) contents up to 11.2% respectively. Notably, alfalfa maximum planting density with native grasses combinations are essential for improving fodder/forage quality, productivity by mitigating the GHG emissions from the highly-productive agroecosystems. In conclusion, the Legumes+Native grass mixture enhanced Net-SOC and GHGI in Typical Steppe grassland systems, whereas restoring soil nitrogen and ecosystem functioning with high quality forage yield. These climate-smart agricultural practices could contribute to the development of sustainable grassland production in China under extreme weather conditions by investing minimum input resources.

1. Introduction: The Chinese grasslands ecosystem is greatly affected by climate change and human activity via land use and cover change, direct grazing, mowing, infrastructure and recent development. Grasslands of China are vast (approximately 400 Mha), and some 90% are overgrazed and considered degraded, although only 10%

have become so badly degraded and decertified (Kemp, 2019). One of the key challenges is degradation of grasslands in China as about 40% of all agricultural and natural land is occupied by rangelands (Ge et al., 2022; Chang et al., 2024). These grasslands have gone through severe degradation over time under extensive anthropological disturbance and drastic climate change (Arshad et al., 2020; Zhang et al., 2022). Among the complex causes of grassland degradation, overgrazing is considered a major driver (Maestre et al., 2022) leads to poor soil fertility. The growing demand on ruminant-sourced food gives pressure on the natural ecosystems, including the Typical Steppe agroecosystem in Gansu province. Moreover, degradation of rangelands proceeds at a rate of 2 Mha yr^{-1} which is equivalent to an annual loss of 1.5% of the grassland biome area in China. In China, nearly 61% of grasslands suffer from degradation due to intensive grazing (Hou et al., 2021). Degraded grasslands not only fail to provide subsistence for the local people (Zhao et al., 2017; Bardgett et al., 2021), but also fail to mitigate climate change, negative impact on greenhouse gas emissions (GHG) and C-stocks (Wang et al., 2016; Deng and Shangguan, 2021).

Grasslands are among the most important terrestrial carbon pools in China, storing approximately 3.06 Pg of vegetation carbon and 41.03 Pg of soil carbon (Ni 2002). Degradation intensity significantly affects below-ground C and N cycling in grasslands system. Heavy grazing decreases soil C and N pool sizes which critically important ecological and economic values while from various degrees of biodiversity degradation in China (Hou et al., 2021), and left with zero seed bank and facing feed shortage, soil erosion in coming future. Previous studies indicate that pre-season climatic elements such as temperature, precipitation, sunshine and thermal conditions play a dominant role in influencing the phenological period (Gastaldi et al., 2020). For example, increasing precipitation can extend the growing season in Canadian and Ethiopian grasslands, and precipitation in the previous autumn and winter have led to an earlier vegetation SOC in the Tibetan Plateau (Workie and Debella, 2018). Grasslands are sensitive to climate change, and the carbon sequestration ability is closely related to water availability. Increasing temperature followed by prolong-droughts is impacting on different growth stages, thereby reducing the fertility input from grasses to soil (Derner et al. 2006; Zuo et al. 2018). Multiple studies worldwide reported the optimization of seeding rates with changing environmental condition is essential (Li-li et al. 2019; Workie and Debella, 2018) to recover the grasslands productivity, nutritional values of herbage in parallel richness of soil fertility. There is dire need to test combination climate-smart grassland management practices such as high planting density of perennial native grasslands and multiple legumes species. Introduction to conservative agroecosystem including year-around soil mulching followed by no-tillage to reduced emission. Our research aims those changes in land-use management might positively impact on yield and agroecosystem. The key scientific problems to be solved under long-term field experiment: a) How does the area-specific planting density of legume grasses vs native grasses to impact forage productivity, quality and SOC? b) Also quantify the response of grasslands under native + legumes system to current climate variations and ecosystem services? c) Best climate-smart grasslands practices adaptive to the local environmental conditions to promote forage productivity by canceling greenhouse gases emissions?

2.Methods

2.1. Study site: The research area is located in the Huanxian county and typical steppe grassland/agricultural trial station in Gansu province, China (37.12°N, 106.84°E, 1700 m a.s.l), which is the largest inter and intra-annual precipitation variability in the world (Huang et al., 2022). The mean annual temperature is 7.8 °C and the mean annual precipitation is 289.8 mm, occurring mainly (>70%) from April to September (the growing season). The typical soil type is classified as loessal soils with sand texture.

2.2. Experimental design: The field experiment will be carried out in a typical steppe (slope≈5°) with combination of multis-legume species composition and soil conditions under the randomized complete block design (RCBD) followed by No-tillage (mentioned in schematic I & II). The project interventions will be carried out in Huanxian Grassland areas of Gansu Province by integration of three legume grasses Alfalfa (*Medicago sativa* L.); Milkvetch (*Astragalus laxmannii* L.); Pea-shrub (*Caragana korshinskii* L.) of optimum, high, very high seeding rates (15, 20 & 25 kg ha-1); followed by zero-tillage.

2.3. Compute soil organic carbon (SOC): Methods include Walkley and Black and Photometric methods, while dry combustion includes ignition tests (SoilOptix®). Walkley and Black Method relies on the oxidation of potassium dichromate ($K_2Cr_2O_7$) that is acid catalyzed as shown in Fig. 1. The heat from the dilution raises the temperature to induce substantial oxidation of carbon-to-carbon dioxide. A modified Walkey and Black Method called Meibus uses the same procedure but includes sulphuric acid with $K_2Cr_2O_7$ (Usman, et al., 2022). Also applied the IPCC Tier > 1 methodology assumes that the SOC in a specific situation is given by:

SOC = SOCREF * FLU * FMG * FI

where SOCREF is the SOC under native vegetation (assumed to be native grass species), and FLU, FMG and FI are factors dependent on land use by legume crops species, management practices and inputs material.

Figure 1. A graphic representation of the different SOC stock baselines and the associated changes that were sampled and measured under the legumes + native grass species seeding proportion% (optimum>high) production systems.

3. Results & discussions

3.1. Agrometeorology and SOC at a landscape scale: Pastures are particularly important to the global carbon cycle because of their size and relatively high SOC reserves as compared to equivalent croplands in temperate climates. Large portions of the world's grasslands are under intense environmental pressure as a result of deterioration caused by overgrazing, which could affect SOC stocks. At the landscape scale, however, changes in SOC stocks are caused by complicated interactions between various variables, including climate, land management, and inherent soil biophysical characteristics, such as soil texture and/or chemical qualities. The connection between precipitation (mm) and soil organic carbon (g C m^{-2}) at a landscape measurement level. Thus, to quantify management effects on SOC stocks from 2001 to 2022 we compared the effects of abiotic site conditions, long-term plot experiments showed that areas with higher annual rainfall (>300 mm) exhibited greater SOC levels compared to regions with lower precipitation levels (<250 mm). Moreover, at a landscape scale, SOC content was positively correlated (>22.5%) with the amount and distribution of rainfall (> 300mm). Areas experiencing more consistent and higher rainfall showed higher SOC concentrations above 2214 g C m^{-2}) in the topsoil layers from 20-30cm soil pool. Long-term data analysis discovered a significant positive connection among yearly rainfall changeability (250-300mm) and SOC accumulation (~17.3-21.5%) mentioned in table 1, demonstrating the role of rainfall patterns in shaping SOC dynamics over time.

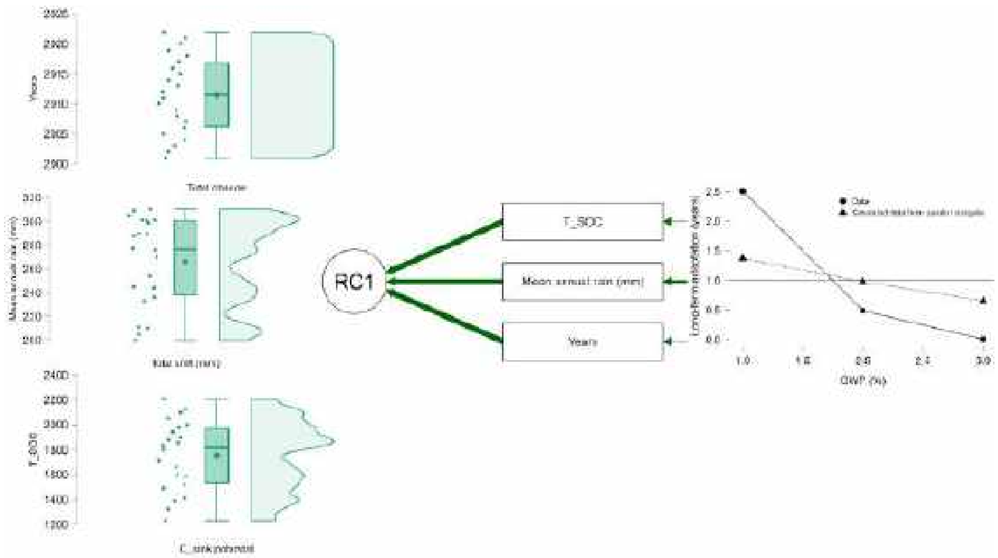

Figure 2. Yearly contribution mechanism determination on the bases of observed field data (RC1) total SOC, rainfall and mean annual shift (mm) at typical steppe, Gansu province of China.

3.2. Legumes vs. native grass species in typical steppe:

When legumes grass species grown with native grasses at optimum seeding (O.S) and high seeding (H.S) rates plots found to significantly ($P < 0.05$) reduced ST (soil temperature) by 3.72% and 5.71%, soil pH by 1.37% and 2.18%, and C:NC/N ratio by 10.03% and 11.18% shown in Fig. 2. Equally, improved SM (soil moisture) content (%) by 2.81% and 3.61%, SOC (soil organic carbon) up-to 2.96% and 3.56%, and soil total nitrogen (STN) by 12.58% and 17.37%, linked to native grass and legumes species sole-cultures in 2024, respectively. Furthermore, winter-cuttings increased soil temperature (2.24% and 2.38%) and CO_2 in Fig. 3, while decreased soil moisture (1.18% and 1.47%) compared to spring-cuttings. Additionally, the initial results indicated that legumes overseed (O.S) with native grasses significantly ($P < 0.05$) increased the forage yield by 51.48% and 39.65%, crude protein (CP) content by 19.86% and 24.13%, ash content by 12.45% and 26.89%, and relative feed values (RFV) by 4.78% and 7.13%.

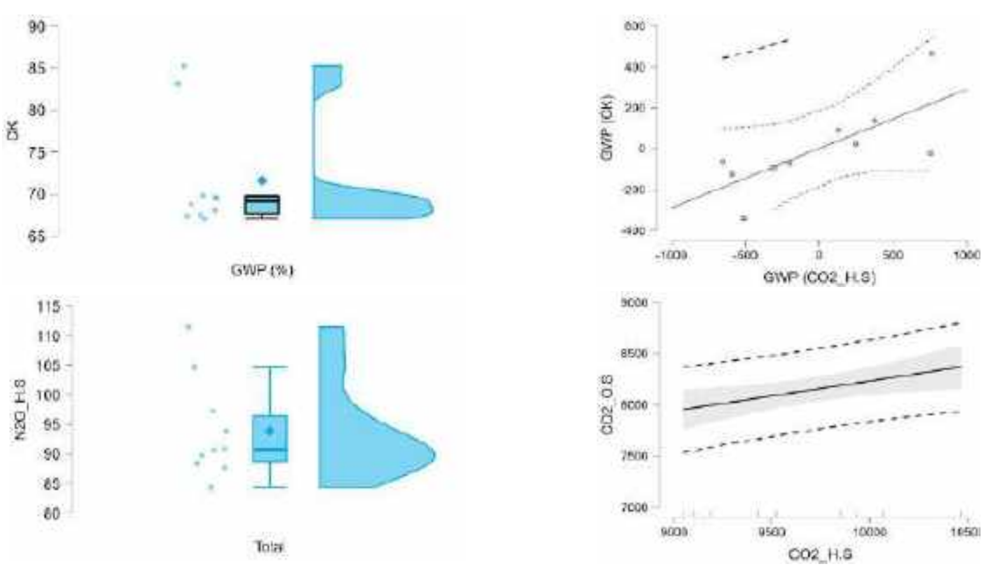

Figure. 3. Accumulated contribution of legume + native grass species production for quality and yield to GHG global warming potential of typical stepper of Gansu province in China.

Cultivating forage crops is crucial to improve feed quality, production, and grazing is an important utilisation method to improve SOC. Improving soil organic carbon (SOC) content and reducing carbon dioxide (CO_2) emission through planting legumes species at different planting proportions with existing native grass species. Soil is the major carbon pool of grassland ecology and stores 26–36% of the carbon in the terrestrial ecosystem (Zhang et al. 2018; Pourshirazi et al. 2022).

4. Conclusion

The increase of storage or SOC sequestration of content is significant to improve crop productivity and soil fertility as well. Conceivable trends in soil organic carbon (SOC) stocks in agroecosystem sequestration scenarios and subsequent implementation of soil carbon sequestration trials. (i) Soil organic carbon (SOC) shares are assumed to be in steady pool/conversion with zero-change in changing climate scenario, (ii) SOC stocks are projected to increase even without C-sequestration measures in the warming potential-as-usual scenario, (iii) Stocks of SOC are expected to decline in the SOC despite the implementation of C-sequestration actions, and (iv) SOC stocks are expected to decline if no C-sequestration measures are implemented under legumes planting proportions.

5. Supplementary material:

Table 1. Parametrization of soil properties under legume + native grass species at optimum seeding and high seeding rates in typical steppe growing system of Gansu province, China.

O.seeding	Soil parameters				
(%)	PH	NH4+N	NO3-N	TON	TOC
C.vetch	8 (0.04)b	3.03 (0.04)a	18 (0.05)a	0.75 (0.02)a	10.96 (0.08)a
Alfalfa	8.15 (0.05)a	2.91 (0.04)ab	17.77 (0.05)b	0.72 (0.01)ab	10.83 (0.08)a
N.grasses	8.15 (0.06)a	2.84 (0.05)b	17.62 (0.06)b	0.69 (0.01)b	10.89 (0.07)a
F	2.93	4.45	12.98	4.01	0.63
P	0.06	0.02	0.00	0.02	0.54

H.seeding	Plant parameters				
(%)	PH	NH4+N	NO3-N	TON	TOC
C.vetch	7.96 (0.03)c	3.21 (0.03)a	18.15 (0.04)a	0.78 (0.01)a	11.32 (0.04)a
Alfalfa	7.93 (0.05)c	2.94 (0.04)b	17.82 (0.05)b	0.73 (0.02)b	10.92 (0.04)b
N.grasses	8.34 (0.04)a	2.83 (0.03)c	17.61 (0.04)c	0.71 (0.01)b	10.98 (0.04)b
CONTROL	8.18 (0.04)b	2.73 (0.04)d	17.6 (0.06)c	0.65 (0.02)c	10.36 (0.04)c
F	19.12	33.73	26.40	14.54	94.12
P	0.000	0.000	0.000	0.000	0.000

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Business planning for drought preparedness and resilience in the variable climate of Northern Australia

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Key words: drought; livestock resilience; climate variability

ABSTRACT:
Northern Australia typically experiences an annual wet season (November to April) and dry season (May to October). However, it is common for wet seasons to fail, or be reduced, and dry periods to extend into drought. To survive the highly variable conditions that are predicted to increase with climate change, northern cattle producers are encouraged to implement management strategies for drought preparedness and resilience. Due to extensive land areas and high costs, most properties have limited fencing and water infrastructure which constrains best practice grazing land management.

The GrazingFutures Livestock Business Resilience project (GFLBR) is designed to enable a collaboration of livestock extension agencies to support Queensland cattle producers to analyse their business through the development of Farm Business Resilience Plans. Through the project, producers are supported to develop goals for their business and develop a plan to achieve these goals. Key business risks and challenges are also identified and strategies for risk reduction incorporated into the plan. A developed business plan also enables producers to apply for Queensland Government drought preparedness grants and low interest loans for improving capital infrastructure on their properties.

Kevin and Shelly Taylor on Ooralat Station, near Mt Surprise, Queensland, provide an outstanding case study of the benefits of using drought preparedness grants for improving capital infrastructure. The Taylor's used the grants to fence 11 additional paddocks and improve water distribution. This work increased their ability to rest pastures over the wet season and thereby improve pasture composition and land condition. More water points for livestock have improved pasture utilisation across paddocks and property carrying capacity from 800 to 1,200 breeders. Irrigating pasture for hay production in one of the paddocks, has facilitated feed storage for managing future droughts.

The GrazingFutures Livestock Business Resilience project enables northern beef producers to be better prepared for climate variability, improve productivity and profitability, and landscape resilience.

Introduction
The highly variable climate of Northern Australia is difficult for northern cattle producers to manage, especially with the increasing variability predicted with climate change (CSIRO, 2024). This region typically experiences a

wet season from November to April and a dry season from May to October. Producers rely on a successful wet season for forage production and feed supply over the dry season, however it is common for wet seasons to fail, or be reduced, and dry periods to extend into drought.

Northern beef producers face a variety of challenges in maintaining a successful business. Properties are typically large, family run enterprises and adoption of best management practice is often limited due to the resistance of the older generation to change. It is very difficult to maintain a reliable workforce in these regional areas, resulting in managers that are time poor and incapable of further extending themselves for educational activities such as workshops.

The rising cost of production across agriculture has minimised profit margins and is forcing producers to become more efficient across their business (Rolfe et al., 2016). Despite this, many producers are resistant to adopting known best management practices to improve their grazing and herd efficiency, such as wet season spelling, matching stocking rate to carrying capacity, feeding phosphorous in deficient country, culling unproductive animals, pregnancy testing and keeping records.

Droughts are a common part of managing an agricultural enterprise in Australia. Governments have historically approached drought support for producers in a reactive manner, such as through providing freight subsidies for drought feeding or restocking, as has occurred previously in Queensland. It has been suggested that in-drought freight subsidies legitimise overstocking practices and limit potential beneficial practice change (McCartney, 2017). Reactive approaches are seen as less effective at minimising the impacts of drought and have led to a policy change by governments towards incentivising proactive climate risk management. The GrazingFutures Livestock Business Resilience project was created to enable producers to become better prepared for, and resilient to, drought through developing a business plan to guide implementation of drought management strategies.

Methods

GrazingFutures began in 2015 in western Queensland to 'increase and better align inter-agency extension support through the grazing land management (GLM), animal production and people–business pillars of the livestock operation. The four objectives of GrazingFutures include: (1) *partnering* (government and non-government); (2) *staff training*; (3) *service delivery to* graziers; and (4) assembling project and industry *legacy* (*information*) *products* (Fig. 1) (Rolfe et al., 2021b)'.

Figure 1. The GrazingFutures operating environment, project cycle and objectives. (Rolfe et al., 2021b)

The initial success of the project led to progression to the GrazingFutures Livestock Business Resilience project (GFLBR) which expanded to include the entire state and increased the number of delivery partners. It was developed to enable a collaboration of livestock extension agencies to support Queensland extensive livestock producers to analyse their whole of business through the completion of a Farm Business Resilience Plan. The extension providers include the Queensland Department of Primary Industries, Natural Resource Management groups, Rural Financial Counselling Services and various private consultants (Rolfe et al., 2021a). GFLBR is jointly funded by the Australian Government's Future Drought Fund and the Queensland Government's Drought and Climate Adaptation Program.

Producers undertake a self-assessment checklist Through the planning process that clearly identifies priority areas of focus enabling the development of goals and actions in relation to production, people and family, business, natural resources and climate (Queensland Government, 2022). These goals are developed to consider risk across these four areas and outline actions to build drought preparedness and business resilience. In addition, a Farm Business Resilience Plan (or equivalent farm business plan) also enables producers to apply for Queensland Government funded drought preparedness grant and concessional loans for improving capital infrastructure on their properties (QRIDA, 2024). Common activities are paddock subdivision, water infrastructure installation, dam construction, bore drilling, irrigation equipment and fodder storage sheds (QRIDA, 2024). Once the application to the Queensland Rural and Industry Development Authority (QRIDA) has been approved, applicants have 6 months in which to complete the project outlined in their business plan.

GFLBR also provides extension services to fast-track practice improvements through using a range of methodologies including educational workshops, industry forums, neighbour days, newsletters, case studies, property demonstrations, eExtension and one-on-one support. It also includes the capacity building of staff and producers through training, and the creation of legacy documents (Rolfe et al., 2021). GFLBR funds also contribute to Advancing Beef Leaders (ABL) a capacity building program that develops producer and community leaders to enact change in the industry (Rolfe et al., 2021). In addition to this, staff funded through GFLBR provide support during disaster response situations, such as flooding and fires.

Results

The GFLBR program has enabled many producers to implement planned strategies for drought preparedness and resilience. Ooralat Station, owned by Kevin and Shelly Taylor near Mt Surprise, Queensland, provides an outstanding case study of the transformational change benefits of using drought preparedness grants for improving capital infrastructure (Pickering & Buchanan, 2024).

When the Taylors purchased Ooralat in 2017 there were only four paddocks, one set of cattle handling yards and limited watering points across the 14,500-hectare property. When Ooralat was drought-declared shortly after purchase in 2018 the Taylors found themselves underprepared and set about implementing several drought preparedness strategies. With the support of a Rural Financial Counsellor these strategies were formalised in a Farm Business Resilience Plan, enabling them to apply for a drought preparedness grant (Pickering & Buchanan 2024).

The first action was to subdivide paddocks and increase water infrastructure for improved pasture utilisation and carrying capacity. Ooralat was further fenced into nine breeding paddocks, one bull paddock, three holding paddocks, two weaner paddocks and a few horse paddocks. Water troughs were installed in all paddocks across the property. Another two sets of yards were also built to reduce the stress from walking stock long distances during mustering. In conjunction with best practice management strategies, such as matching stocking rate to carrying capacity and appropriate supplementation programs, the Taylors were able to improve their pasture utilisation and increase their carrying capacity from 800 to 1,200 breeding cows (Pickering & Buchanan, 2024).

The second action was to build a dam and install irrigation infrastructure for hay production, to reduce the cost of drought feeding. A 32 ha hay paddock was developed with irrigation for half of the paddock and dryland for the remaining half. This has enabled the Taylors to have low-cost and weed free hay for dry times, as well as allowing the flexibility to retain stock and sell at an optimum market price (Pickering & Buchanan, 2024).

In conjunction with good grazing land management (GLM) and breeder management, implementing the drought preparedness strategies outlined in their Farm Business Resilience Plan have improved weaning rates from 50% to 80%. This is significantly higher than the average weaning rate of 56% for the region (Rolfe et al, (2016) Weed infestations have also been reduced and the proportion of the property with greater than '70% ground cover' has increased from 32% to 89% in 7 years (Pickering & Buchanan, 2024).

The most recent progress report for the program stated 8,433 producers have participated in GFLBR activities since project commencement in 2021 (Smith & Long, 2024). This is more than double the project target of 4,000. Further success has been achieved in providing individual support services to 3,075 producers which is also double the 1,500-project target (Smith & Long, 2024). A producer survey record 63% of grazing businesses rating GFLBR activities they engaged in at 7 or more out of 10 for enabling them to be more prepared for drought; of these producers surveyed, 79% made at least one business change from being involved in the program (GR Consulting, 2024).

Discussion

The goal of GFLBR is to enable a collaboration of livestock extension agencies to support extensive livestock producers to adopt management strategies that will increase their drought preparedness and resilience, including tailored support to develop holistic farm business plans. The move to increasing privatisation of extension in the 1990s has unsuccessful and reduced the available extension resources for beef producers. (Rolfe et al., 2021a; Bommel et al., 2023). The collaborative industry partnerships developed through this project have now enhanced capabilities across the region to facilitate practice change (Rolfe et al., 2021a). This has been shown through the doubling of extension services in western Queensland from 2015 to 2021 and an estimated gross benefit of $28M from a $6M investment (Rolfe et al., 2021a). Therefore, through its collaborative partnerships the GFLBR model has been effective in improving capacity for facilitating change towards drought preparedness and resilience across Queensland.

GFLBR utilises a holistic 'whole of business' approach that enables producers to identify their specific needs and tailor their actions to these needs. To achieve practice change, support needs to be individually tailored and take a whole of business approach incorporating production, land management, financial and personal dynamics (Larard, 2022; Broad 2016).

Despite success, having the capacity and strategies for effectively facilitating the adoption of best management practice continues to be a challenge across grazing industry extension professionals. Due to the regional locations and time constraints of most producers in the north, workshops are often cancelled or not well attended in northern Queensland. While the program has improved this, staff capacity limits the ability to provide one-to-one follow-up. Specialised and individually-focused support from extension staff located regionally and integrated into the community is deemed most effective in achieving practice change (McCartney, 2017). An increase in extension services and other independent service providers was seen as an opportunity for improving drought management in Queensland grazing enterprises. Producers interviewed for the report noted that, although there was plenty of training and information available there is a shortage of extension staff available to provide this individually-focused supported (McCartney, 2017). Staff need to understand the complex nature of the family livestock business they are working with, and success within the program is typically seen where support staff are familiar with the intricacies of these business (Rolfe et al., 2021b). Therefore, although GFLBR has improved the capacity of extension services since 2015 there is still an opportunity to extend the capabilities of these services through increased staff and capacity building in the regional areas.

Producers typically only engage in the business planning process because it is required to apply for a drought preparedness grant. Nevertheless, producers generally find completing the business plan useful in other ways, such as beginning the conversation about succession, and identifying areas for improvement they hadn't considered. Producers who did not apply for a drought preparedness grant still rated themselves an 8 out of 10 for being better prepared for drought following a business planning workshop (GR Consulting 2024). Nevertheless, it is a genuine concern that if the funding for the drought preparedness grant ceases it will become more difficult for extension staff to engage producers on business planning, potentially limiting improvements in drought preparedness and resilience across the industry. The project needs to improve uptake of the planning by creating an attractive value proposition so that people want to do the planning to improve their business, not just to receive the grant.

Currently the drought preparedness grant can only be used for new permanent capital infrastructure, however there is the opportunity for further management strategies to be incentivised to support greater drought preparedness and resilience (QRIDA, 2024). GR Consulting's (2024) report recommended including strong elements of grazing land management (GLM) practices that improve land condition due to these practices being necessary to build pastures resilient to drought. There has consistently been a low level of GLM changes reported across annual producer surveys from the past 6 years (GR Consulting, 2024). If GLM practices such as wet season spelling, establishing improved pastures and improving land condition were incentivised, a significant change to the drought preparedness capabilities and profitability of these businesses could be made. This incentive also has the potential to be used in conjunction with government policy to improve land condition.

The GFLBR project has vastly enhanced the capabilities of extension staff to facilitate drought preparedness and resilience across Queensland. There is an opportunity for further capacity building through investment in greater numbers of staff that are based in, and integrated into, the regional communities that beef producers are a part of. Continued funding for drought preparedness grants and concessional loans from the Queensland Rural and Industry Development Authority (QRIDA) would support ongoing engagement of producers in the program, noting other motivations for participation could be promoted. There is also an opportunity to expand these incentives to include grazing land management practices for further development towards a drought prepared and resilient Queensland.

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The immediate and long-term effects of aridification in a developing country context: The Karoo, South Africa

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Key words: drought; climate; grazing capacity; financial resilience; southern Africa

Abstract

In January 2017 the Karoo entered a 58-month drought that destroyed 30% of livestock in the region. Grazing declined by 40-60%, but recovered within two years after the rains returned. Feeding costs ate into profits and real net farm income tracked SPI-12 closely on the way down. While grazing capacity recovered, livestock numbers have not, and financial data must still be collected before financial recovery can be assessed. The government provided adequate drought relief but too little technical support, and limited data collection undermines our ability to evaluate and improve adaptation going forward.

Introduction

Wool provided the foundation for commercial agriculture in the Cape Colony in the 19th century. The Colony's 12 million sheep of 1904 doubled to 25.6 million by 1935, where it remained until 1965 (Department of Agricultural Economics and Marketing 1962; Republic of South Africa Department of Statistics 1964/65). Much of this was in the Karoo, the arid hinterland to Cape Town. After 1965 official sources show the Cape Province[9] losing sheep at a rate of 2.83% per annum (pa) due to drought and other factors (Statistics South Africa 2002, 2017).

The Karoo is an open landscape loosely bounded by the 400 mm isohyet and is spread across the Northern, Eastern and Western Cape Provinces. The winter-rainfall Succulent Karoo transitions into a summer-rainfall Nama Karoo biome (Mucina and Rutherford 2006). The matrix of dwarf shrubs is interspersed with mesembs in the former and grasses in the latter. Despite two centuries of commercial exploitation, farmland supports as much mammal diversity as protected areas (Drouilly et al. 2019). Freehold is the dominant tenure system. Fencing began in the 19th century and paddocks are still being improved. Modern animal husbandry sits along transhumance enabled by proximity to the rainfall divide, although selective purchases by lifestyle investors is disruptive (Reed and Kleynhans 2009) and damaging to the vegetation (Milton et al. 2023).

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[9] The Cape Colony, Natal and the Boer Republics unified in 1910. The Cape became a province in the Republic of South Africa after 1961 and divided into three provinces in (Northern, Western and Eastern Cape) in 1998. The switch from singular to plural in the text below is therefore deliberate.

It is difficult to determine the contribution of climate to developments in this rapidly changing landscape (Kiem and Austin 2013). This study brings together weather data, data from ongoing vegetation monitoring and one community's farm management data to assess the extent and impact of the 2017 drought.

Methods

A standard precipitation index (SPI-12) measures the severity and duration of the drought. It was fitted to a rainfall series that dates to 1927. Droughts are defined as beginning with SPI-12 < -0.5 and ending with SPI-12 > 0 for a sustained period. Vegetation monitoring commenced in 2017. Line point surveys are conducted at 500 points taken along a 900 m transect running from watering points towards paddock boundaries to capture local grazing gradients. The precise transect is resurveyed every three years and grazing capacity is calculated from a species list according to the method described in du Toit (1998).

The Karoo Management Panel (2012 – 2021) represents a convenience sample of 86 family farms (Conradie et al. 2019). It covers 420 000 ha. This study limits analysis to units whose wool and mutton income exceeds 67% of gross farm income. The observations were partitioned into baseline (control) and drought (treatment) groups whose means were compared using t-tests. There were n = 249 farm-years in the control group and n = 337 farm-years in the treatment group. Five variables were analysed including farm and flock size, stocking density, real feed cost and net farm income. Stocking density is measured in large stock units (LSU) per hectare, with an LSU defined in terms of the energy requirement of a growing ox. Meissner et al. (1983) tabulated LSU coefficients for a range of livestock types from which standard stocking units can be compiled to feed into stocking density calculations. Feed cost and farm income is expressed in ZAR (USD = ZAR 14.50 in December 2020) with a CPI deflator converting nominal to real values. Net farm income was computed in the usual way; gross income minus enterprise-specific costs gives gross margin and net farm income is obtained by subtracting overheads such as labour and machinery cost from total gross margin. Revenues include livestock, crops, farm-based tourism and light manufacturing but ignores salaries and investments. Land is owned and rented, with quality unadjusted.

Results

SPI-12 identifies January 2017 as the beginning of the drought which lasted until October 2021. The index averaged at -1.46 ± 0.67, hovering around -2 from July 2019 to February 2021. The lowest value of -2.56 was recorded 42 months into the drought. Table 1 relates grazing capacity to rainfall and temperature. Long-term grazing capacity equals the legal limit (RSA 2018), while observations for 2018-20 coincide with the drought and the period 2021-23 reflects the degree of recovery. At baseline, site A was 12% below its long-term average capacity with the other sites 22% above capacity. The drought destroyed 30% of measured capacity at sites C and D and twice as much at sites A and B. During the driest periods (2015-2020) all four sites also experienced the most extreme warm days that intensify the impact of the drought. Twenty-four months after the rains returned, grazing capacity was back at 98% of its long-term level at site A and more than 10% above at the other sites. Crown cover, the most important contributor to grazing capacity, improved more quickly than species richness (Table 1).

Table 1: Rainfall, temperature, grazing capacity, species richness, and % perennial crown cover at four Karoo sites before during and after the drought.

	Period	Site A	Site B	Site C	Site D
Rainfall	Long-term	120	230	230	270
mm per annum	2015 – 2017	84	224	248	284
	2018 – 2020	47	198	229	229
	2021 – 2023	148	343	360	299
Temperature	Long-term	149	77	126	87
Days >30℃	2015 – 2017	151	86	134	91
	2018 – 2020	160	86	132	109
	2021 – 2023	145	69	110	96
Grazing capacity	Long-term	42	28	24	22
ha/LSU	2015 – 2017	47	23	18	17
	2018 – 2020	101	69	34	31
	2021 – 2023	43	25	25	18
Species richness	2015 – 2017	13	24	20	26
(perennial plants)	2018 – 2020	10	15	14	19
	2021 – 2023	15	22	13	21
% crown cover	2015 – 2017	15.4	36.8	59.2	70.6
(perennial plants)	2018 – 2020	9.0	17.4	92.6	81.6
	2021 – 2023	19.8	43.6	89.8	70.4

The 2017 drought is one of four major events recorded in the Karoo since 1927 (Table 2). The first drought lasted for most of the 1940s at a low intensity. It reduced Karoo flocks by 14%. Drought relief, if any, was not recorded in the sources we had. The second drought was shorter but more intense. The Cape Province entered it with 21.3 million sheep in April 1968 and lost 3.8 million sheep over the following 35 months. The government spent the current equivalent of ZAR1.7 billion on feed subsidies and railway transport rebates to mitigate its effects, approximately 40% of the value of the national wool crop in 1970. The third major drought occurred in the early 1990s. Conditions deteriorated quickly from February 1991, with the lowest index value reached five months later (SPI-12 = -2.36). The Cape Provinces entered this drought with a third fewer sheep than it had at the beginning of the previous drought but lost the same percentage as in the 1960s. The Cape Provinces entered the 2017 drought with 6.6 million sheep. There is no official record of how many survived, but the Karoo Management Panel can provide anecdotal evidence of how one community was affected by the drought. This panel dates to 2012, with the most recent wave coinciding with the end of the drought. At baseline (2012 – 2016) farms typically ran flocks of 1200 stock sheep on 10 000 ha, stocking at 11% above the legal limit. As rental contracts were abandoned farm size decreased by 12.8% during the drought (t-stat = 2.118). Flocks shrank by 30% (t-stat = 3.761) and consequently stocking density fell to 79.5% of the legal limit (t-stat = 8.526). Feed cost increased threefold, from ZAR430/LSU to ZAR1198/LSU (t-stat = -6.106), rendering many profitable farms unviable. Net farm income dropped from ZAR30/ha to ZAR-1.11/ha (t-stat = 5.457).

Table 2: Four historical Karoo droughts

Period	Drought index SPI-12	Cape Provinces' sheep numbers in each drought Beginning	End	Drought relief ZAR million (2020)
Aug 1940 – Oct 1949	-0.55 ± 0.82	24	20.6	
Apr 1968 – Jan 1971	-1.37 ± 1.12	21.3	17.5	1703
Feb 1991 – Apr 1995	-0.47 ± 0.79	13.8	11.9	1677
Jan 2017 – Oct 2021	-1.46 ± 0.64	6.6		521

In Figure 1 the available farm income data overlay the SPI-12 index for the period 2010 to the present. Single variable analysis of variance indicates year-on-year differences in profitability (F = 4.59) with Bonferroni correlations confirming a structural break in 2017, which supports the SPI-12 data. The break in feed cost is in 2018 while stocking densities were adjusted in 2016 in anticipation of the drought. We are still awaiting the data with which to analyse possible financial recovery.

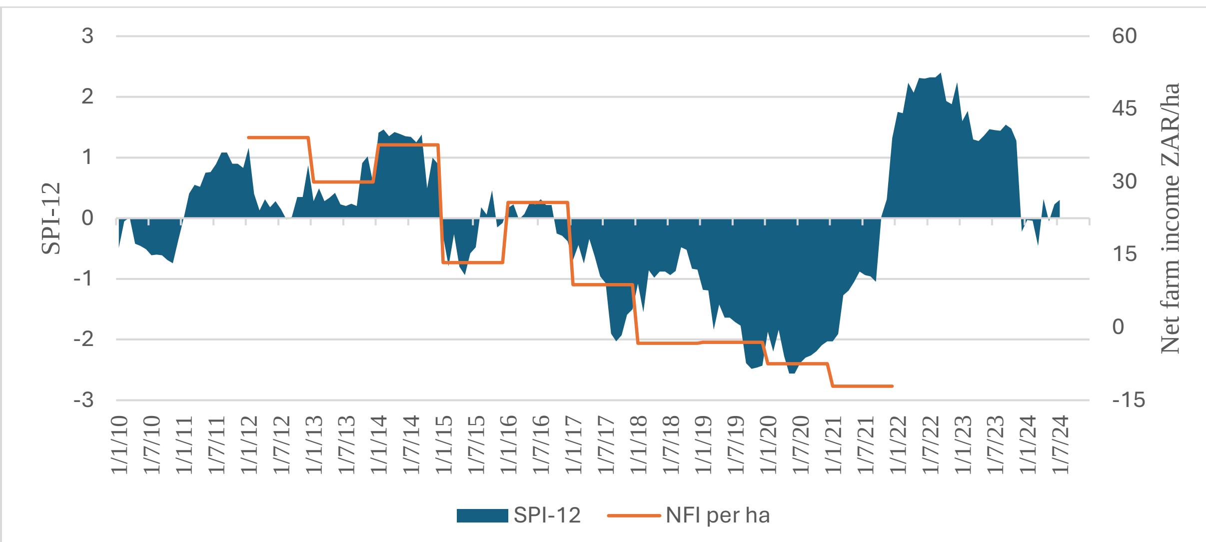

Fig. 1: Correspondence of SPI-12 drought index with net farm income (NFI) per hectare from survey data.

Discussion

The recovery of grazing capacity after the 2017 drought reported in Table 1 is different from how most rangeland ecologists see the effects of drought in the Karoo. In the Succulent Karoo mortality rates varied by species from 9-82% after the 2017 drought (Milton et al. 2023). Expected recovery is predicated on a "recruitment event", i.e. sustained rainfall over several months for shrub seedlings to become established. Excluding all herbivores would be ideal at this time (Milton and Wiegand 2001), but for game farmers it is technically infeasible and for sheep farmers it is unwise to give up the benefits of years of genetic selection even if other investment opportunities existed. Experience suggests that conditions for recruitment were poor at the end of the 1990s drought, which might explain the sharp decline in flock size since, although this is still an open question. Continuous grazing decreases palatability and, in a drought, lowers the perennial fraction of the vegetation (Milton et al. 2024; Wiegand

and Milton 1996). With more short-lived species in the mix, the rangeland becomes less productive and less resilient (Milton et al. 2023).

The 2017 drought was long and intense. It hit an industry that had become a shadow of its former self. The losses suffered remain uncertain as there has not been a census since 2017. Disaster relief decreased drastically in absolute terms, returning to a rate of support provided during the 1960s drought. This has implications for the number of livelihoods the Karoo can support. As the number of livelihoods decline, farm size must rise (Asghari et al. 2021). There are already farms of >20 000 ha spread over several cadastres, units that are rapidly becoming too expensive and time-consuming to operate. Moreover, drought relief was actively biased against large operators (Conradie 2019) which hindered the adaptation needed to bring management systems in line with the expected ecological changes.

Conclusion

The priors for this study were that the 2017 drought was the worst on record, that it permanently damaged the rangeland and that farmers were severely compromised by a lack of drought relief. The analysis showed that 2017 was just one of several serious droughts, that the rangeland recovered quickly and that farmers received the same level of support as before. But we do not know what contributed to the collapse of the industry before 1990, if changes in the weather accelerated the collapse since, or how farmers are faring now. We cannot act on the sound advice to prepare for the next drought now because we missed the opportunity to collect the data for a proper postmortem of the 2017 event. While South Africa's climate change adaptation efforts could benefit from technical assistance to our institutions, we remain the most technically proficient in the region. Colleagues in Namibia, Botswana, Zambia, and Zimbabwe likely face similar technical challenges as we do and almost certainly must contend with more serious funding problems than us. However, funds without proper implementation will achieve little.

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Spatial distribution, habitat use, and conservation implications of Himalayan brown bears in Deosai National Park, Pakistan

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Key Words: Extreme climate, anthropogenic challenges, extinction, movement patterns, grazing pressure

Introduction

The Himalayan brown bear (*Ursus arctos isabellinus*) is a critically endangered species, with its primary habitat in the Deosai National Park of Pakistan as their last stronghold for survival. This high-altitude plateau, situated between 4,000 and 6,000 meters above sea level, is crucial for the persistence of the species. The park lies within the Himalayan, Karakoram, and Hindu Kush ranges, bordering Afghanistan, China, and India, where political and environmental challenges complicate conservation efforts. The harsh conditions in Deosai, such as extreme cold temperatures reaching -20°C, thick snow and reduced oxygen levels (30% less than sea level), make it a challenging environment for both the bears and the researchers observing them. GPS collaring is an effective method to track these bears' movements and provide valuable data on their behavior and habitat use. The grazing impact and pressure is predominantly from livestock that should not be there. This study aims to understand the movement patterns of the Himalayan brown bear in the face of mounting threats, including habitat degradation, climate change, and human-wildlife conflict.

Methods

Study Area

Deosai National Park, located at the heart of the Deosai Plateau, is the last stronghold of the Himalayan brown bear. The park spans over 3,000 square kilometres (Chaudhary et al. 2019). The habitat is rich with key species such as the Machor (*Capra falconeri*), Himalayan ibex (*Capra ibex*), snow leopard (*Panthera uncia*), and Tibetan wolf (*Canis lupus chanco*). Rangers and veterinarians face considerable challenges due to the terrain, altitude, and climate.

Darting and Collar Fitting

The process of darting (theoretically using a Pneudart dartgun with a 3cc dart, loaded with Fentanyl (10-20 µg/kg) and Medetomidine, aiming for the shoulder for immobilization) involves immobilizing the bear using a tranquilizer dart fired from a distance (no more than 30m) to minimize human-wildlife conflict risks. The tranquilizer is specifically tailored to the bear's body size and weight. Once the bear is sedated, a Africa-Wildlife Tracking device and GPS collar is fitted around the neck, ensuring that it does not interfere with the bear's movements. The collar is designed to remain on the bear throughout the study period, transmitting location data whenever the animal moves and varies between 10min intervals or usually set at 1 hour intervals (Bauer et al. 2020).

Data Collection

Location data was obtained using GPS collars, and additional environmental data such as altitude, aspect, and slope were derived from Sentinel 2 imagery and Shuttle Radar Topography Mission (SRTM) data. These data were used to calculate NDVI (Normalized Difference Vegetation Index) and NDMI (Normalized Difference Moisture Index), both of which provide insights into vegetation density and moisture content, respectively.

Results

Spatial Distribution of Collared Bears

The map in Figure 1 presents the spatial distribution of collared bears in Deosai National Park, with the locations of Bears 7400 and 7401 (male and young male) indicated in the field. The distribution of these bears is shown in relation to various grazing pressure zones: high pressure (red), medium pressure (yellow), and low pressure (green).

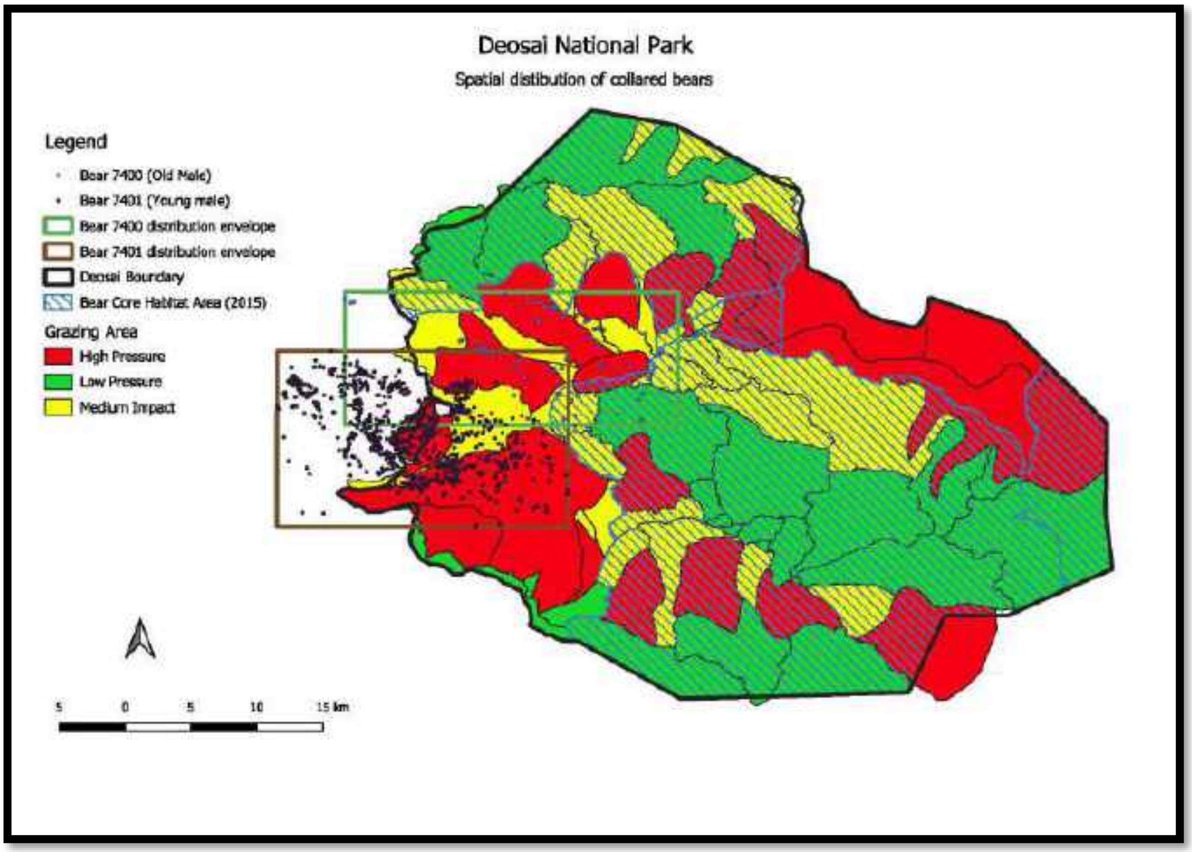

Fig 1 Illustration of the spatial distribution of the collared bears in Deosai National Park

- Bear 7400 (Old Male): The older male bear's distribution envelope overlaps significantly with areas of low to medium grazing pressure. This suggests a preference for less disturbed areas with abundant vegetation and fewer human-induced threats.
- Bear 7401 (Young Male): The young male bear also favours areas with low grazing pressure but appears to have a broader range, possibly indicative of its exploratory behaviour as it establishes its own home range.

This map also highlights the Bear Core Habitat Area and shows that the bears' preferred locations are predominantly within this core area, which is critical for their survival.

Correlation between NDVI and NDMI
Preliminary analysis of NDVI and NDMI values from Sentinel 2 data revealed a strong positive correlation, indicating that areas with higher vegetation density also exhibited higher moisture content. This correlation is critical in understanding the bears' habitat preferences for forage and shelter.

Impact of Environmental Factors
Aspect was found to have a significant effect on both NDVI and NDMI, with north-facing slopes showing greater vegetation and moisture content. However, temperature was not found to be significantly sensitive to aspect, suggesting that other factors such as solar exposure and wind play a role in vegetation growth. No significant correlation was found between altitude and temperature, further suggesting that climate factors are less influential in the selection of habitat.

Discussion
The results indicate that Himalayan brown bears use specific areas within Deosai National Park based on vegetation density and moisture levels, both of which are influenced by the park's aspect. These findings are consistent with studies on other bear species, such as the Grizzly bear (*Ursus arctos horribilis*) in North America, where aspect also influences habitat selection (Miller et al. 2017). The fact that temperature did not significantly affect vegetation or bear movements may suggest that, in Deosai, other environmental variables such as altitude, vegetation, and moisture are more important factors in the bears' habitat use. This is crucial for management, as it highlights the need to protect the most critical vegetation-rich areas, regardless of temperature fluctuations.

Additionally, with the help of the GPS location data, it was surprising to find that the bears do not descend to lower altitudes during hibernation, as was previously expected. Instead, they remain on the plateau, utilizing marmot burrows for shelter under deep snow (confirmed by the park manager and ranger team on site), which could have implications for their survival in the face of warming temperatures and loss of snow cover (Johnson et al. 2016). The results also highlight significant correlations between the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Moisture Index (NDMI), both of which are indicators of vegetation health and moisture content. Our data shows a strong correlation between these indices, particularly in areas with high vegetation coverage, where the bears tend to spend the majority of their time. This suggests that vegetation health is a primary factor influencing bear movement patterns, as also observed in studies on other bear species (Sawyer et al., 2017; Derocher et al., 2018). Moreover, aspect—the direction of slope—was found to influence both NDVI and NDMI, with north-facing slopes showing higher vegetation productivity compared to south-facing slopes. This is likely due to differences in sunlight exposure, which affects the growing conditions for vegetation. Interestingly, temperature showed little sensitivity to aspect, with minimal differences in temperature across the landscape, but the overall temperature range was not a strong determinant of bear movement. It is apparent that both bears tend to utilize areas with relatively low grazing pressure, which is likely indicative of their preference for undisturbed habitats where vegetation can thrive.

Other important findings include Aspect vs. Altitude: A significant correlation was observed, with altitude generally increasing in areas with a particular aspect (i.e., north-facing slopes at higher altitudes). Aspect vs. Slope: No significant correlation was found, suggesting that slope direction did not greatly impact the bears' movements or habitat selection. Temperature and Vegetation Indices (NDVI/NDMI): No significant correlation was found between temperature and the vegetation indices, indicating that the bears do not rely on temperature fluctuations to dictate their habitat use.

The presence of collared bears in areas of low grazing pressure indicates that these zones provide a more favourable environment for the bears, with better access to vegetation and fewer disturbances from livestock. In contrast, high pressure grazing zones are typically avoided, as these areas likely suffer from overgrazing and a reduction in natural vegetation, leading to lower food availability for the bears. Understanding these distribution patterns is critical for management efforts, as it can guide the identification of areas that need to be protected or restored to support the bears' long-term survival.

Additionally, the Bear Core Habitat Area in the map is a zone that should be prioritized for conservation, as it provides the most consistent resources for the bears, and further encroachment or disturbances in this area should be minimized.

Conclusions & Implications

The use of GPS collars to track the Himalayan brown bear provides critical insights into their spatial ecology. These collars have revealed new information about their habitat preferences, hibernation behavior, and the challenges they face due to habitat degradation and human activity. The data supports the need for improved conservation strategies that include better management of high-pressure grazing areas and protection of the bears' core habitat on the plateau. The new understanding of the bears' hibernation patterns, staying on the plateau and utilizing marmot burrows, challenges previous assumptions about their seasonal behavior and suggests a more adaptable strategy for winter survival. This information will guide future management decisions, ensuring that both the bears and their habitat are adequately protected. As the species is critically endangered, continued monitoring through GPS collaring will be essential for understanding their movements, estimating population densities, and making informed management decisions to ensure their survival.

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Include funding source and animal ethics approvals here.

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Implementing social-ecological resilience principles in the Australian government's future drought fund program: opportunities, challenges and lessons learned

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Key words: Future Drought Fund; Social-Ecological Systems; Resilience; Transformation

Abstract

Climate change impacts are increasing, leading to more frequent, longer and more severe droughts and other climatic events. The complexity of these issues requires proportional systems-based adaptation and transformation approaches to build resilience and achieve sustainability. The Australian and State and Territories governments commit to sustainability, adaptation and resilience to a changing climate in the National Statement on Climate Change and Agriculture. These commitments are reflected in multiple governmental initiatives and programs, one of which is the Department of Agriculture, Fisheries and Forestry's Future Drought Fund (FDF). The FDF offers a unique pathway to achieving sustainability through building drought and climate resilience, founded on robust scientific principles of social-ecological resilience. The FDF supports farmers and communities to learn about, be prepared for, and have the capacity and options to respond to drought and other climatic shocks, including through transformational change. The FDF programs fund projects, including in the rangelands, to achieve its objectives. This paper discusses how the FDF implements resilience principles and fosters collaboration and collective adaptive learning and action to achieve shared resilience and sustainability outcomes. Progress to date is presented and links to case studies of successful and impactful FDF-funded projects are provided. Lessons learned, opportunities and challenges facing FDF highlight the important role it can play in supporting resilient social-ecological systems in Australia.

Introduction

Drought is a recurring feature of Australia (DAFF 2024). Climate change is increasing the frequency, duration and severity of inter-connected climatic events, including drought (DAFF 2024; ABARES 2022; DAFF 2025b). The complexity of this issue requires proportional systems-based adaptation and transformation approaches to build resilience and achieve sustainability (IPCC 2023). The Australian and States and Territories governments commit to sustainability, adaptation and resilience to a changing climate in the National Statement on Climate Change and Agriculture (DAFF 2023a). It has several initiatives that aim to address sustainability and resilience to climate change, including the Climate Smart Sustainable Agriculture Package, National Soil Action Plan, Carbon Farming Outreach Program and the

Future Drought Fund (FDF) (DAFF 2025b). The FDF is aimed at achieving public good through building resilience to drought and broader climate impacts (DAFF 2025a). This work is uniquely underpinned by the systems-based social-ecological resilience theory (Folke 2016). Since its inception, the FDF has progressively improved the implementation of this theory, including through communicating and engaging with its stakeholders and supporting projects on the ground.

This paper provides an overview of the FDF and explores how it implements resilience principles. Quotes and examples from program guidelines and other key FDF documents are provided, as well as links to successful case studies. Lessons learned, opportunities and challenges are briefly discussed.

The Future Drought Fund: an overview

The FDF is a $5 billion initiative that was set up in 2019 under the *FDF Act 2019* (DAFF 2025a). $100 million is available each year to fund programs aimed at supporting farmers and regional communities to build social, economic and environmental resilience, through learning about, being prepared for, and having the capacity and options to respond to drought and other climatic shocks (DAFF 2025b). The FDF constitutes a unique and distinct pathway to sustainability, through a focus on building whole-of-system resilience to achieve sustainability. This approach includes innovative and, where needed, transformative management of natural capital that underpins landscape function and ecosystem goods and services, agricultural businesses and agriculture-dependent communities. Delivery of FDF programs is governed by 4-yearly Drought Resilience Funding Plans (FP) that set FDF objectives and aims (DAFF 2025a). Under the new 2024-28 FP and supporting Investment Strategy (IS) 10 programs will be delivered over the next 8 years. In addition, funding will be available for monitoring, evaluation and learning (MEL) activities and knowledge sharing, to share and facilitate learning from FDF outcomes (DAFF 2025b).

Social-Ecological resilience theory: FDF as an implementation pathway

Social-ecological resilience theory defines resilience as "*the capacity of a system to absorb disturbance and reorganise so as to retain essentially the same function, structure and feedbacks";* in other words, *"the ability to cope with shocks and keep functioning in much the same kind of way*" (Walker and Salt 2012) – where a system is *"an interconnected set of elements that are coherently organized in a way that achieves something*" (Meadows 2008), and social-ecological system (SES) as a linked system of humans and nature (Folke 2016). The FDF adapted this definition in its FP by stating that "*a key aspect of drought resilience is the ability to adapt, reorganise or transform in response to changing temperature, increasing variability, and scarcity or changed seasonality of rainfall, for improved economic, environmental and social resilience*" (DAFF 2025a,b), and looking at landscapes as complex and adaptive SES and farmers and regional communities are actors in, or part of these systems (DAFF 2025b). The FDF supports both adaptation and transformation, taking into account the adaptability and transformability of a system as defined by Walker and Salt (2012).

The FDF enables building specified resilience of landscapes, farmers and communities to drought, focussing on activities that help ensuring that SES avoid crossing critical social, economic or ecological thresholds into undesirable regimes, sometimes irreversibly (Walker and Salt 2012) – which makes these SES untenable: "*Increased adoption of whole-of-system thinking approaches to manage landscapes, including knowledge of and capacity to define and act on critical tipping points or thresholds, and contributing to connectivity across broad landscapes"* (Resilient Landscapes Program). In addition, FDF programs promote and support building general resilience to drought and broader climate impacts (DAFF 2025b), including the principles of complex adaptive systems thinking, safe-fail experimentation, broad participation, diversification, networks and connectedness, and adaptive learning (Carpenter et al. 2012; Biggs et al. 2015). Examples are provided below.

As outlined in the FP and IS, the FDF has 3 inter-connected strategic objectives of building social, economic and environmental resilience to drought, an approach that recognises the complexity of SES and maximises the impact of FDF investments (DAFF 2025b): *"In line with whole-of-system thinking, feedbacks and interactions between components of complex systems (in this case the land, people, industry, governance and so on.) lead to non-linear changes that are not necessarily the sum of the characteristics or dynamics of components, or any pair of interactions between these components. The whole system is therefore often more than the sum of its parts* (Drought Resilience Soils and Landscapes Program).

The FDF supports safe-fail experimentation with, and adoption of all forms of change, i.e. incremental, adaptive, transitional and, especially, transformational when the system becomes untenable (DAFF 2025b): "*The program allows for 'safe-fails', which will help participants learn from the experience, and assist primary producers and rural communities to adopt innovative, diverse, adaptive and/or transformative approaches to build drought resilience in agricultural landscapes"* (NRM Drought Resilience). The FDF also promotes diversification: *Increased diversification in land use and management, so that multiple options and pathways are available to farmers to prepare, respond, and recover from drought* (Resilient Landscapes Program).

The FDF values networks and connectedness, and the diversity they bring. It collaborates and partners with diverse stakeholders to design and deliver programs. It seeks opportunities to enact community-led, co-design, and / or end-user approaches, in collaboration with existing community networks, Indigenous organisations and communities, natural resource management organisations, businesses, industry and farmer groups (DAFF 2025b). Our delivery partners are similarly encouraged to form and maintain networks: "*Networks are established or strengthened between stakeholders who partner and share responsibility for managing natural resources (including public and private land managers), which improves connectedness and diversity of approaches across the landscape*" (NRM Drought Resilience Program). One program – Networks to Build Drought Resilience – is dedicated to that (DAFF 2025a). We support consortia of partners to deliver projects under other programs: *"[the program] fosters collaboration, in the form of consortia of partners and stakeholders collectively working on shared issues and outcomes to improve integration, coordination, communication, planning and implementation of drought resilience activities, and avoid unnecessary duplication"* (Resilient Landscapes Program). This approach enables learning as a tool to build resilience: *Collective adaptive learning and capacity building through stronger collaborative networks between farmers and other land managers, including First Nations land managers, in support of increased adoption of drought resilient practices, technologies or approaches* (Resilient Landscapes Program). To further support learning, successful case studies continue to be built and published (DAFF 2023a).

Opportunities and Challenges

Since its inception, the FDF has been communicating with its stakeholders and delivery partners how it's aiming to support building resilience and the principles and theories underpinning its work. This includes

FP and IS, program guidelines, meetings and workshops, and general communication material. The FDF stresses that resilience is about embracing change, particularly transformational where needed, and that to be resilient does not mean 'not to change' (Walker and Salt 2012). This engagement has been an iterative process. We realised the need to sensibly and progressively utilize and promote the adoption of technical concepts, as our experience and that of our delivery partners matured. As programs were rolled over the last 5 years, the FDF re-focussed its messages.

One of the unique aspects of FDF is its proactive support for transformation, especially through safe-fail experimentation. Transformability of a system is underpinned by 3 determinants: preparedness to change, capacity to change and options for change (Walker and Salt 2012). The FDF supports all three, by helping in changing paradigms towards accepting the need for transformation where needed, and providing funding for experimentation with transformative practices and approaches that go beyond current best practice. One of the most important lessons we learned is that change, especially transformative, takes time, hence the new suite of longer and larger programs (DAFF 2025b).

As mentioned above, the FDF recognises and focusses on fostering networking and collective adaptive learning and action to achieve shared resilience and sustainability outcomes (DAFF 2025b). In addition to the approaches mentioned above, and as part of its new suite of programs, the FDF provides funding for a strong MEL strategy. Having a robust MEL system enables both learning and sharing knowledge. Evaluation of earlier FDF program, currently underway, will help us determine and share how and to what extent FDF is succeeding and contributing to the broader resilience and sustainability ecosystem. We also created a MEL Community of Practice (COP) where our staff, stakeholders and external experts exchange ideas and share insights and lessons learned. We equally participate in other government COPs and working groups, and have an ongoing collaborative engagement with industry and research. All this work allows FDF to contribute to breaking silos.

The FDF recognizes that dealing with complex systems is itself a complex task. Behaviors, beliefs, world views, values and knowledge that influence actions and attitudes of people need to be taken into account to build trust and openness and achieve change (Dyball and Newell 2015). Policies that do that probably work best, and this has been our experience. Giving our delivery partners ownership of program design and outcomes is proving to be empowering and motivating. This is helping FDF to facilitate changing behaviors and promoting adoption of resilience practices, approaches and systems at scale. Delivery of various programs by consortia of partners further enables that, by aiming to collectively achieve change beyond projects' life and scope (DAFF 2025a).

Conclusion

There is a current momentum to build resilience to drought and broader climate risks. FDF is a key player in that, given the nature of its activities, robust theoretical foundations, and the perpetuity of its funding. Implementing its various approaches puts the FDF in a unique position to contribute to policy, on one hand, and academic deliberations of social-ecological resilience theory on the other. The more the FDF evolves and learns, the better it will get at that. This is a remarkable opportunity that needs to be leveraged and supported, and it is. FDF is effectively an enabler of systemic and transformational change, through continued experimentation, learning and sharing knowledge with its networks of stakeholders and partners. As Walker (2020) states, transformational change "*is and will always be an ongoing process of exploring, learning and keeping options open*".

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Heritage beef cattle genetics: A climate adaptation tool in desert rangelands

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Key words: Criollo**;** ranching; cow-calf; resilience

Abstract

Climate trends are exacerbating the challenges associated with raising beef cattle in desert rangelands. In the North American Southwest, where longer heat spells and extended drought periods are becoming more common, increasing levels of costly external inputs are required to wean a crop of marketable calves every year. A group of scientists at the United States Department of Agriculture Agricultural Research Service Jornada Experimental Range provided leadership for an international team of researchers who examined the feasibility of using heritage Criollo cattle as a climate adaptation tool in desert ranching systems. Criollo cattle exhibit phenotypes thought to be largely shaped by natural selection which is known to favor rusticity traits at the expense of rapid growth rates and offspring weight. Over the past 20 years, the team studied grazing behavior, animal production (including meat quality and yield), and the economics of raising Criollo cattle. A recent special issue of Journal of Arid Environments titled '*Heritage cattle genetics as a potential climate adaptation strategy for producers in arid regions*' compiled 12 articles that report results from this large research effort. Fifteen years of research results largely confirmed anecdotal accounts regarding the desirable grazing traits present in Criollo cattle. Our data strongly suggest that Criollo heritage genetics could be an important adaptation tool for desert cow-calf systems. Raising Criollo cattle could be a means of strengthening the economic sustainability of desert beef cattle ranching systems

Introduction

Ensuring food and nutrition security in a hotter world with more frequent extreme weather events will require developing resilient crop and livestock genetics (Mbow et al. 2019). Modern high-producing crops and livestock have been selected for enhanced production in high-input systems. Over the past six decades, per capita food production worldwide increased 30% subsidized by a 100% and 800% increase in irrigation water and nitrogen fertilizer use, respectively (Mbow et al. 2019). The long-term sustainability of such approaches to agriculture and food production are increasingly uncertain.

Frequently overlooked indigenous and heritage crops and livestock possess remarkable drought and heat tolerance traits shaped by centuries of close-to-natural selection (Mbow et al. 2019). The value of natural vs. artificial selection was perhaps most eloquently articulated by Charles Darwin (1872) over a century ago. In 'The Origin of Species by Means of Natural Selection', Darwin frequently drew parallels between natural and human-driven selection of organisms (wild vs. domestic). He argued that 'Man selects only for his own good: Nature only for that of the being which she tends' (p.65). This powerful idea, which Darwin would likely word somewhat differently today, captures the essence of differences in climate adaptation potential of commercial vs. heritage crop varieties and livestock breeds. There is growing consensus nowadays about the urgent need to recuperate indigenous and heritage genetic material and assess its potential to contribute to climate adaptation and mitigation of global agricultural systems (IPCC 2019).

In this context, an international team of researchers in North and South America came together to summarize research findings from 15 years of studies comparing aspects of rangeland cow-calf systems that raise commercial (British) vs. heritage (Criollo) cattle. Criollo, also referred to as Creole cattle, are a heritage type of livestock brought to the Americas by conquistadors more than five centuries ago (Anderson et al. 2015; Armstrong et al. 2022). Spanish, Portuguese, and African breeds provided the genetic basis for these cattle that spread rapidly throughout the Americas. By the end of the 19th Century, commercial breeds had mostly displaced Criollos to marginal regions unsuitable for specialized beef and dairy newcomers (Armstrong et al. 2022). Anecdotal accounts of ranchers from South to North America who raise these cattle consistently point to their ability to thrive under harsh conditions. The objective of this paper is to summarize research published recently in a special issue of Journal of Arid Environments that focused on the use of heritage cattle genetics as a potential climate adaptation strategy for producers in arid regions (https://www.sciencedirect.com/special-issue/103WLV70KVZ). Much of this research was both motivated by and co-produced with ranchers seeking novel climate adaptation solutions.

Methods Overview

Foraging patterns and thermotolerance of Criollo vs. British beef cows

Grazing behavior results summarized here are from studies ranging from one to three years in duration conducted between 2005 and 2021 at sites in the Chihuahuan Desert, New Mexico, USA (Nyamuryekung'e et al. 2022; Roacho Estrada et al. 2023), Colorado Plateau, Utah, USA (Duni et al. 2023), California Chaparral, California, USA (Duni et al. 2023), Sierra Madre Foothills, Chihuahua, Mexico (Roacho Estrada, et al. 2023) and Arid Chaco, La Rioja, Argentina (Herrera Conegliano et al. 2022). Mean annual precipitation at research sites ranged from 600 mm at the California site to 207 mm in Utah.

Raramuri Criollo was the heritage breed used at the four North American sites, and Argentine Criollo was used at the South American site. Phenotypic characteristics, origin, and ancestry of each of these biotypes are discussed in detail by Armstrong et al. (2022). Commercial beef breeds included Black Angus (California, Chihuahua, and La Rioja), Red Angus (Utah), Hereford (Chihuahua) and Black Angus x Hereford crossbred cattle (Chihuahua and New Mexico). At each site cattle grazed undisturbed in extensive rangeland pastures.

In all cases, study protocols were approved by the corresponding Animal Care and Use Committees. Raramuri Criollo cows used at the North American sites were on average 179 kg lighter than their commercial breed counterparts (388 vs. 564 kg for R. Criollo vs. beef breeds), whereas Argentine Criollo cows weighed roughly the same as their Angus counterparts (400 vs. 420 kg, for A. Criollo vs. beef breed). Five to eleven cows of each breed were fitted with GPS collars at each site. GPS data were used to calculate movement, activity, habitat use, and social cohesion metrics.

One of the Chihuahuan Desert studies included fecal sample collection for diet analysis (Estell et al. 2022). DNA metabarcoding was used to determine the proportion of plant species in fecal samples collected from 10 cows of each breed during the growing and dormant seasons for three consecutive years. DNA metabarcoding with chloroplast gene trnL primers were used. Plant taxa were identified using the global and locally developed reference libraries (Estell et al. 2022).

Body temperatures were measured in another of the Chihuahuan Desert studies using temperature loggers affixed to a blank CIDR (Controlled Internal Drug Release device) devoid of hormones inserted intravaginally and set to record body temperature at 10 min intervals (Nyamuyekung'e et al. 2022). Temperature loggers were deployed on 6 to 11 cows fitted with GPS collars with temperature sensors in summer and winter during two consecutive years. Logger data were compared with GPS collar and weather station temperature sensor readings. Soil surface temperature was mapped via a 30 x 30 m pixel raster file derived from the thermal infrared band 10 of the Landsat 8 satellite.

Economics of raising Criollo vs. British cattle in the Chihuahuan Desert

The profitability of raising Criollo cattle in an alternative production system (grass finishing) in the Chihuahuan Desert was investigated by producing enterprise budgets for a herd of Raramuri Criollo cattle at the USDA ARS Jornada Experimental Range (Chihuahuan Desert Research site; Torell et al. 2023). Costs, returns, and beef production rates and practices for the typical commercial breed ranch (4662 ha; 150 Animal Unit Year) were defined from published budgets and summary statistics. Property and livestock taxes were defined using mill rates ($1 in taxes per $1,000 in taxable value) for Southwest New Mexico counties. Revenues for the herd were calculated based on expected sale weight and price for the year 2013, considering steers and heifers sold and retained, as well as cull animals (Torell et al. 2023).

Results

Foraging patterns and thermotolerance

Across all sites and seasons, compared to commercial cows, Criollo cattle traveled on average 2 additional km each day, explored twice the area (206 vs 110 ha/day for Criollo and British cows, respectively), grazed about the same amount of time (~ 9 h/day), and showed more dispersed foraging tactics by traveling greater distances and covering larger areas for every hour they spent grazing (see data summary in Cibils et al. 2023). Breed differences were typically greatest in the dormant season. Criollo cattle showed significantly greater ability than British breeds to make seasonal (dormant vs. growing) and annual (dry vs. wet) adjustments in foraging behavior (Cibils et al. 2023). Criollo and Criollo crossbred steers finished on grass in the Chihuahuan Desert showed grazing patterns similar to those of Criollo cows (McIntosh et al. 2021).

At the Chihuahuan Desert site, Criollo cows showed less herd cohesion, spent less time in each landscape pixel and revisited previously grazed sites less often (Nyamuryekung'e et al. 2022 and Spiegal et al. 2019) than their British counterparts. Criollo cows also spent less time grazing patches dominated by black grama (*Bouteloua eriopoda*), a palatable Chihuahuan Desert grass of high conservation value, and tended to include less of this species in their diets compared to commercial beef cows (Nyamuryekung'e et al. 2022, Estell et al. 2022). Criollo cattle diets tended to include more mesquite (*Prosopis glandulosa*) and Yucca (*Yucca spp.*) than diets of their British peers. At the Utah and California sites, Criollo cattle were more likely to forage in shrub dominated areas and tended to spend less time in sensitive riparian lowlands (Duni et al., 2023) compared to their Red and Black Angus counterparts.

Criollo cattle were better able to cope with Chihuahuan Desert summer heat relative to British cows; they exhibited lower body temperature and higher collar temperature (ambient heat in the proximity of the animal) during the hottest hours of the day. Breed differences in activity (Criollo > British) were greatest during the hottest hours of the early afternoon (Nyamuryekung'e et al. 2021).

Economics

Criollo cattle in the Chihuahuan Desert had lower operating and overhead costs when compared to British beef cattle. This reduction in costs allowed the Criollo cattle operation modeled in this study to have greater net returns to land and risk when compared to a typical desert beef cattle operation. Importantly, grass-finished Criollo steers in the Chihuahuan Desert exhibited excellent meat quality parameters (McIntosh et al. 2021), a finding that is consistent with earlier South American research (Anderson et al. 2015; Armstrong et al. 2022).

Discussion and conclusions

Fifteen years of research results largely confirmed anecdotal accounts regarding the desirable grazing traits present in Criollo cattle. These characteristics, which are thought to favor overall animal fitness, likely evolved through centuries of close-to-natural selection. Our data strongly suggest that Criollo heritage genetics could be an important climate adaptation tool for desert cow-calf systems. Raising Criollo cattle could be a means of strengthening the economic sustainability of desert beef cattle ranching systems. Research addressing the environmental, economic, and social sustainability (including tradeoffs) of raising heritage beef in desert ranching systems is currently underway (Spiegal et al. 2023).

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Balancing challenges and benefits: climate change impacts and microclimatic regulation by *Macrochloa tenacissima* in north African arid steppe

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Key words: *Macrochloa tenacissima*; Temperature; Precipitation; Moisture; Bare soil; climate change.

Abstract

Macrochloa tenacissima steppes in Tunisia are facing significant challenges due to the effects of climate change, which exacerbate the problem of desertification. *Macrochloa tenacissima* L. play a critical role in regulating microclimatic conditions and it is considered as a nurse species. An urgent need for sustainable land management and conservation strategies of *M. tenacissima* to mitigate the adverse effects of climate change and desertification on arid steppes. This study examines both the impacts of climate change on these steppes and the beneficial effects of *M. tenacissima* tussocks on microclimate regulation. Historical trends and future climate projections in Tunisia were studied in relation with the distribution of *M. tenacissima* steppes. Furthermore, microclimatic stations with temperature and moisture sensors were used to explore microclimate conditions under tussocks and in bare soil. Our findings reveal that rising temperatures and altered precipitation patterns are reducing the extent of *M. tenacissima* habitats, affecting biodiversity and ecosystem services. Concurrently, *M. tenacissima* tussocks create microhabitats with lower soil temperatures and higher moisture levels, enhancing water infiltration and reducing evaporation rates. These microclimatic modifications are essential for maintaining soil health and supporting biodiversity. This dual role underscores the importance of *M. tenacissima* in both mitigating adverse climate impacts and promoting ecosystem resilience. Effective conservation and sustainable management practices are essential to leverage these benefits, ensuring the stability and productivity of Tunisia's arid landscapes in the face of ongoing climate change.

Introduction

Climate change is a major issue impacting species distribution across ecosystems, community dynamics, and ecosystem functioning (Weiskopf et al. 2020). Endemic species are the most susceptible to climate change, which are plants that only exist in restricted distribution regions with distinct ecological characteristics (Refaat et al. 2024). Variations in temperature and precipitation patterns cause spatial and temporal species distribution change, often leading to biodiversity loss and alteration of ecological interactions. Changes are most evident in arid and semi-arid areas, such the steppes of *Macrochloa tenacissima*. In these ecosystems, microclimatic conditions, temperature and humidity variations, play a crucial role in species' responses to climatic changes (Tan et al. 2023). Macro- and micro-climate heterogeneity exposes populations to mosaics of resource availability, varying abiotic conditions, and influencing biotic interactions (Denney et al. 2020). Tussocks *M. tenacissima*, a dominant perennial grass in Mediterranean steppes, exemplify such microhabitats. Acting as nurse plants, these tussocks modify the surrounding microenvironment by reducing soil erosion, enhancing soil fertility, and regulating temperature and humidity (Navarro et al. 2008). These facilitative interactions are essential for seedling establishment, community stability, and ecosystem resilience. Understanding the interplay between climate change, and microclimatic conditions is crucial for predicting species distribution patterns and managing fragile ecosystems like *M. tenacissima* steppes. This study explores the critical role of microclimatic conditions and the current and future species distribution patterns in responses to climate change in arid and semi-arid ecosystems in order to establish a rescue program for *Macrochloa tenacissima* to ensure its survival and to maintain the health of arid ecosystems.

Methods

Study Area and Microclimatic Data Collection

The study was conducted in Tunisia, covering its diverse climatic and ecological zones. Microclimatic conditions were monitored over one year using sensors installed at a height of 2 m above ground to measure air temperature (°C) and humidity (%), and at soil level to record soil temperature (°C) and soil moisture (%) in bare soil and under tussocks in Kasserine region. Measurements were recorded at hourly intervals. Occurrence data for the target species (*Macrochloa tenacissima*) were obtained from field surveys. These data were used to model habitat suitability under current and future climatic conditions.

Environmental Variables

Climatic variables for the current period were sourced from WorldClim at a spatial resolution of 30 arc-seconds (~1 km^2) representing the historical climate data (1970-2000). Future projections were based on the HadGEM3 climate model for the SSP5-8.5 scenario, representing the years 2081-2100. Five bioclimatic variables (e.g., maximum, mean, and minimum annual temperature and mean annual precipitation) were selected based on ecological relevance. Elevation data were included to test topographic influences.

Habitat Suitability Modeling

MaxEnt (Maximum Entropy Modeling) was used to predict habitat suitability under both current and future conditions. The model was trained using occurrence data and current environmental layers. Predicted suitability maps were generated for both scenarios and classified into binary maps using a threshold value of 0.5, representing areas of suitable habitat. The total area of suitable habitat was calculated by summing the pixels with values exceeding the threshold and converting this to square kilometers.

Statistical Analysis

Different statistical analyses, models and Maps of current and future suitability were analysed and fitted using R software. A post hoc Tukey test at $p < 0.05$ determined differences among microclimatic conditions.

Results

Microclimatic conditions

The soil temperature and humidity under *M. tenacissima* tussocks were lower than bare soil (Fig. 1). Air and bare soil temperature almost displayed the same value. The temperature under tussocks is 1.61°C lower compared to bare soil. The mean air temperature was 25.4°C. The soil moisture showed a better response under tussocks, with a mean humidity difference of 2.26%. The mean air humidity was 52.7°C. The mean soil humidity is 10% lower than air humidity.

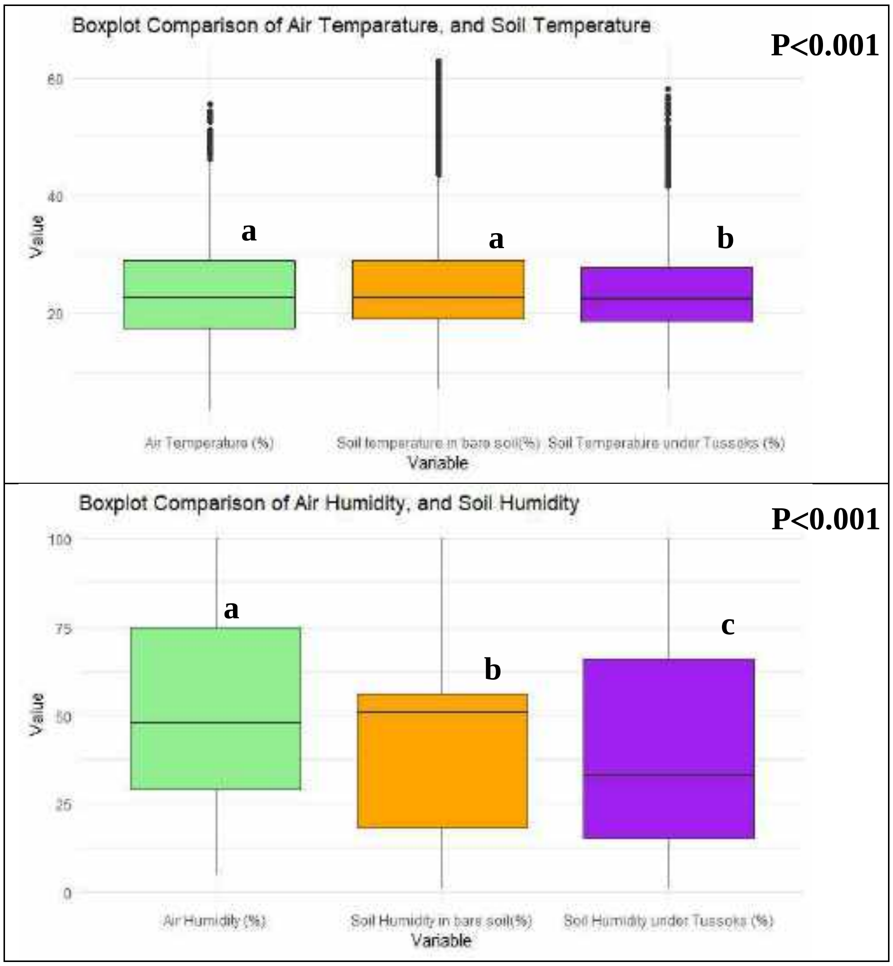

Fig.1. Boxplot comparison of air and soil temperatures and humidity under tussocks and bare soil.

Species distribution model

The binary maps indicate a clear reduction in suitable areas under future climate conditions of *Macrochloa tenacissima*, particularly in Kasserine region (Fig. 2.). The total suitable area decreases from 6735 km² to 4290 km², resulting in a net loss of -2445 km². Some areas, like Matmata mountain (Gabes) show new suitability under future conditions, but these gains do not offset the losses.

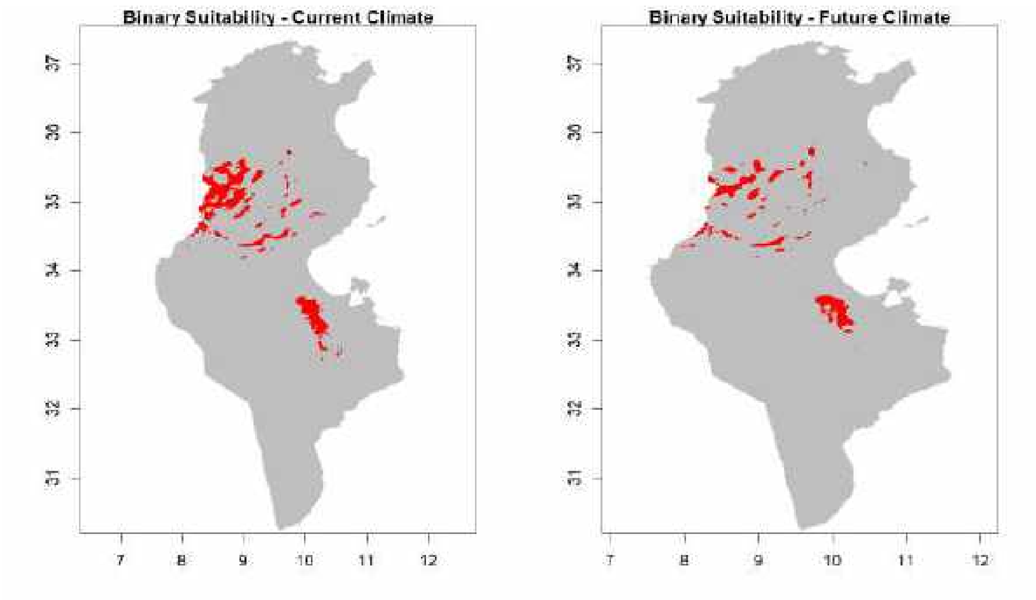

Fig. 2. Binary Suitability Maps for Current and Future Climate at 0.5 thresholds, with suitable region shown in red and non-suitable region in white.

Discussion [Conclusions/Implications]

The nurse and microclimate enhancer effects of *Macrochloa tenacissima* have been documented in several scientific studies (Navarro et al. 2008; Saiz and Alados 2011). Our study gives a precise projection by providing microclimatic conditions in each minute under the tussocks and in bare soil associated with atmospheric temperature and humidity. The presence of *M. tenacissima* moderates' temperatures and retains moisture, leading to better micro-environment conditions compared to bare soil. The Shade soil reduces direct solar radiation, preventing soil evaporation quickly which helps to retain moisture and regulate temperature fluctuations (Navarro et al. 2008). Under *M. tenacissima* tussock the temperature is decreased by about 2°C and the humidity is enhanced by 2%. The amelioration of arid microclimatic conditions facilitates co-occurring conditions for other species (Saiz and Alados 2011). The soil temperature under the tussocks is generally lower than that of bare soil, especially during the hottest parts of the day. Navarro et al. (2008) found higher K+, organic carbon, carbon:nitrogen ratio, and available water content inside and below the tussocks. In *M. tenacissima* steppe, under harsh climatic conditions, adaptation of co-occurring species results in facilitation by the amelioration of arid microclimatic conditions (Navarro et al. 2008; Saiz and Alados 2011).

The analysis of the species distribution model proved that *M. tenacissima* steppe occurred in Kasserine region and Matmata Gabes. It is generally related to the Tunisian Dorsal mountains chain, Matmata Mountains and steppes ecosystems characteristic of central Tunisia. The results showed that climate changes will significantly affect *M. tenacissima* suitability. According to the Maxent model maps, the suitable area will differ between current and future, the current distribution will decrease considerably. Ben Mariem and Chaieb (2017) found the same tendency of the decline of *M. tenacissima*. However, these authors found that *M. tenacissima* current cover (2000) was about *19304* Km^2 which could be very high in relation to the field observation. In this regards, Le Houérou (1995) estimates the *M. tenacissima* steppes cover to 32,000 km^2 in the western Mediterranean Basin. This finding confirms our estimation and reflects the significant habitat loss that *M. tenacissima* has experienced in Tunisia over recent decades due to climate change, land degradation, and changes in land use (e.g., overgrazing, agricultural expansion, and urbanization).

In conclusion, *Macrochloa tenacissima* is an important species to combat desertification, especially in arid areas. It plays a protective role by creating a microclimate that favors the growth of other plants and participates in the ecosystems' functioning. Since the species' suitable habitat is expected to decline in the future, there is a pressing need for a conservation program for *M. tenacissima*. Conservation in such areas is important to protect this species and the associated ecosystem services.

Acknowledgements
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‘Place-based’ planning and governance for drought resilience - Southern Queensland, Australia.

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Key words: drought; resilience; preparedness; planning

Abstract
The Australian Government launched the Future Drought Fund (FDF) in 2019 with an initial investment of $3.9 billion and $100 million per annum for program costs (Australian Government, 2024). Under the FDF’s core Regional Drought Resilience Planning (RDRP) program, regional communities across Australia have been supported to develop RDRPs including initiatives to build drought resilience through: better planning and preparedness; more effective responses during drought; and actions to build future resilience. In southern Queensland, the program has been jointly funded by the Australian Government and the Queensland Government, and delivered by UniSQ’s Institute for Resilient Regions (IRR) using their participatory planning model that was:

- 'Placed-Based' - involving three levels of government, NGOs, civil society, business sector and individuals.
- 'Holistic' - addressing impacts and proposing actions for: people & communities; regional economy; landscape & natural environment; and infrastructure & built environment.
- 'Co-Designed' - both the process and outputs have been created with local stakeholders.
- 'Locally-Voiced': the RDRPs capture the vital stories and knowledge of people in the region as well as data, science and advice from outside ‘experts’.

This paper describes the key learnings from IRR’s development of RDRPs in southern Queensland. It outlines: the model; the challenges encountered; and the solutions generated to meet these challenges. Lessons from this work should inform future drought resilience initiatives and governance arrangements.

Introduction
The Australian Government launched the Future Drought Fund (FDF) in 2019 with the aim to “…boost drought and climate resilience” by helping: “…farmers and producers to plan, access climate tools, and share resilient farming practices” and “…communities to plan, and fosters rural and regional leaders and networks” (Australian Government, 2024). The core RDRP program aims to move the management of drought from being reactive to proactive. The Institute for Resilient Regions at University of Southern Queensland (IRR) is a consortium member of the Regional Economies Centre of Excellence (RECoE) and is responsible for the design of the state-wide

RDRP program and the delivery across southern Queensland. Thus far, IRR has completed 5 Regional Drought Plans in southern Queensland that include practical and achievable actions to build drought resilience.

Methods

The Queensland Government replicated the regional boundaries of the Regional Resilience Strategies (QRA, 2020) for the RDRP program – 14 regions across the state. Whilst guided by broad instructions from government, IRR developed a co-design model (Mellor, 2022) that actualised the government goals of 'locally-owned, locally-led and co-designed'. The model (see Figure 1.) was highly participatory and included key elements of 'Collective Impact' (e.g. Kania and Kramer, 2011), 'Ethno-Narrative' research (Mellor, 2009) and 'Deliberative Decision-making' (e.g. Fishkin, 2009). Work with regional stakeholders was undertaken by multi-skilled and multi-disciplinary teams and the reiterative co-design process took between 12-18 months per region.

IRR chose to organise the examination of drought under four 'themes' (see Figure 2.): People, Culture & Community; Economy; Landscape & Natural Environment, Infrastructure & Built Environment. After testing with focus groups, a modified versions of Crossman's D-RAMP model (2018) was used to develop actions to: Plan/Prepare for Drought; Respond to Drought; and Build Resilience to Future Droughts (see figure 3.)

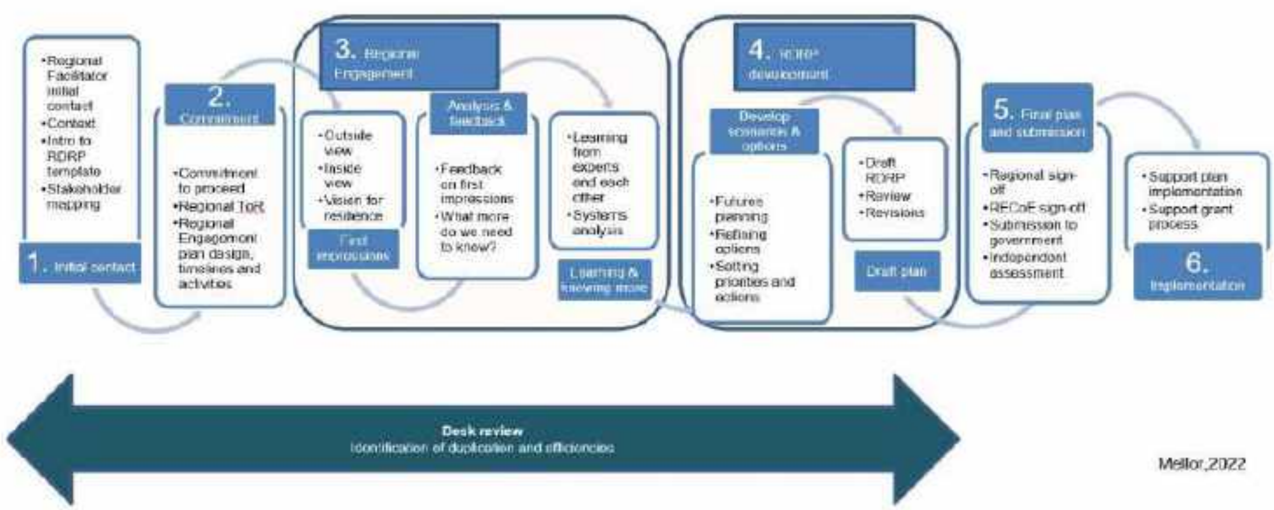

Fig. 1. IRR's participatory and deliberative model of engagement

Fig. 2. Queensland RDRP elements of drought resilience. Source: IRR

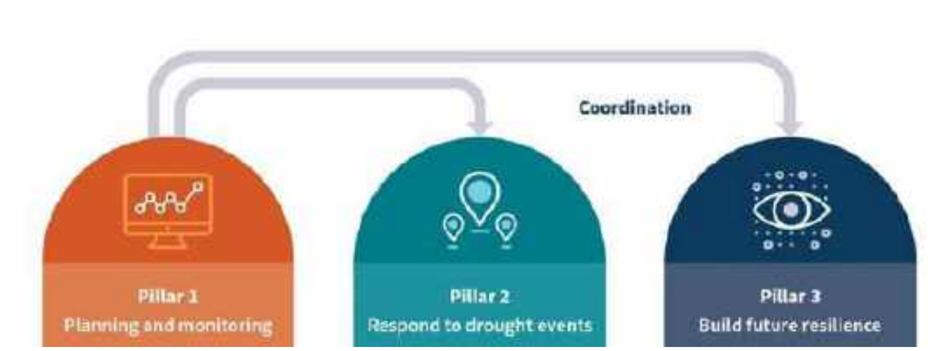

Figure 3. Modified D-RAMP Model. (Adapted from Crossman,2018)

Results

There are currently five completed Regional Drought Resilience Plans (RDRPs) for southern Queensland – some awaiting Ministerial approval. The RDRPs are documented 'Plans of Action' and are intended for use by the regions themselves as well as by government decision-makers and potential funders/investors. Our research and involvement in the RDRP project thus far has revealed a number of critical lessons, outlined below.

Drought Resilience Planning is more than just the Plan... it's the Process.

The process of engagement and co-design is a critical factor that: identifies community champions; brings together key stakeholders; provides 'backbone' support; and helps people in regions develop practical actions that meet their priorities. It involves important aspects of 'ethno-narrative' work as people are encouraged to tell stories of drought from their own perspectives and in their own words. They are also supported to explore possible scenarios and 'story-build' their agreed actions for future drought resilience. It requires a reiterative and deliberative process.

Hence, it takes time, it takes patience, and adequate scheduling must allow people 'pauses' and breaks to reflect, consider and learn more in order to make informed decisions.

Every region has its own unique 'Drought Personality' …so drought resilience planning has to be 'place-based'.

This work has revealed that the typography, impacts, and narratives of drought vary significantly from region to region. Climates, topography, hydrology, history as well as the past and present human interactions with the land, combine to create very different 'stories' of drought in different places. Drought amplifies existing place-based issues related to: community health and wellbeing; agricultural and business practices; remoteness; access and infrastructure; competitive (dis)advantage and the capacity of local communities to adapt and innovate. This complexity makes each region unique and requires a place-based approach to drought planning and governance. As noted by one participant, this requires "…*viewing the world from inside out*".

Place-based approaches require multi-disciplinary perspectives and multi-skilled teams.

Drought is not just about water, rainfall or climate. It is not just about the natural environment or human practices on that land. Drought is most beneficially viewed, concurrently, from multiple perspectives – we summarised them into four themes and that model proved practical and appropriate for working with regional stakeholders. This requires that the planning approach draws on a wide range of skills and perspectives. This can often be a challenge for government agencies that are typically organised around a single perspective or function.

Utilising many kinds of knowledge and information to make informed decisions.

Critical to our success has been a commitment to using (and respecting) many sources of knowledge to inform the process and assist communities to make better decisions. We have brought data, science, 'innovations' and so-called 'outside knowledge' into the regions we work with, but also valued the tremendous wealth of 'local knowledge'. Local knowledge has often been 'historical', 'traditional' or 'cultural', and in some cases we have been granted access to knowledge from traditional owners or First Nations people. It is critical to often 'triangulate' pieces of knowledge – in some cases they confirm the local stories, and in others they challenge historical tropes or offer new insights or possibilities. The challenge for scientists, academics, and 'experts' is to be able to communicate or 'package' their knowledge in such a way that it can be a valuable asset to a wide range of people and contribute to better local outcomes.

'Resilience' is hard to define…but that doesn't matter

The World Bank defined resilience as: "…the ability to anticipate, absorb, accommodate or recover from the effects of a hazardous event in a timely and efficient manner" (World Bank, 2019). However, in practice, resilience is much harder to define. For some (government agencies in particular) this is problematic and there are continued efforts from some quarters to define resilience 'more clearly or 'more precisely'. Our approach has been to embrace the lack of precise definition and use the question "What does resilience mean to you?" as a prompt to open valuable local conversations. Those conversations developed into collective, regional understandings of what resilience has meant in the past and what it could mean in the future. That understanding can then lead to developing and deciding on appropriate priorities and actions.

Conclusions

IRR's work on the Regional Drought Resilience Plans has provided not only important outcomes – the RDRPs themselves are now reliable and valued regional assets for future investment in, or decisions about, drought preparedness and resilience – but also highlighted some critical issues that should be considered in future programs related to building resilience to drought and climate variability. The work has also helped shape ideas about the governance processes and structures needed to effectively manage drought in the future.

Acknowledgements
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Potentially useful legume accessions persist 32 years on in abandoned subtropical coastal pasture evaluation site

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Key words: Legume; persistence; *Arachis*; *Desmanthus*

Abstract

Over the decades, hundreds of pasture evaluation trial sites have been established across northern Australia with the aim of discovering plant accessions suitably adapted to particular climatic and edaphic conditions. The majority of such sites now lie abandoned, despite the fact that they represent a valuable repository of potentially useful genotypes, that have often been thoroughly tested by droughts, floods, fire, grazing and insect attack.

One such site was a legume evaluation trial established in 1992, at what is now the College of Public Health, Medical and Veterinary Sciences at James Cook University in Townsville. The objective of the trial was to evaluate the agronomic and morphological characteristics of 13 tropical pasture legumes sown on a low fertility, mildly acidic (pH 6.5), coastal duplex soil, with an AAR of 1,143 mm. The trial included a range of accessions from the genera *Arachis, Centrosema, Desmanthus, Glycine, Neonotonia, Macroptilium and Stylosanthes*. Following establishment, the site was abandoned after one season and has since endured heavy crash-grazing by sheep, earthworks disturbance, regular slashing, continuous macropod grazing pressure, and has been exposed to periods of significant drought over the last 32 years.

This paper summarises the results of the most recent survey of the site. Of the 13 genotypes originally planted, a number of resilient legumes continue to survive including *Arachis paraguanensis* (CPI 91419), *Desmanthus leptophyllus* (CPI 38351) *Stylosanthes hamata* cv. Verano and *Stylosanthes scabra* cv. Seca. These are persisting within a mixed sward dominated by *Chaemacrista rotundifolia*, *Bothriochloa pertusa,* and *Desmodium triflorum.* Additionally, *Centrosema brasilianum* (CPI 55698), and to a lesser degree *Macroptilium martii* (CPI 55782) were observed growing on a stream embankment, approximately 10 m from the site.

These surviving plants represent a potentially valuable collection of robust and persistent legumes, not only for northern Australia but similar climates across Africa, Asia and central and south America.

Introduction

Across northern Australia various institutions such as CSIRO, governmental agriculture departments, universities and seed companies have over the decades sown hundreds of pasture trials, consisting of multiple species and accessions with the aim of identifying new pasture plants that are well-adapted to particular edaphoclimatic conditions. Such trials are very often located on private properties and only receive operational funding for relatively short periods of time (2-4 years), before being discontinued and abandoned. The value of such sites however, is very often not exhausted at the conclusion of the associated experimental period as in many cases, many of the planted accessions possess traits for hard-seededness, permitting them to persist for decades.

As a result, such sites represent a valuable repository of potentially useful genotypes, that have often been thoroughly tested by droughts, floods, fire, grazing and insect attack. Such plants are potentially valuable not only for northern Australia but similar climates across Africa, Asia and Central and South America.

In 1992, one such legume evaluation trial was sown at the James Cook University Veterinary Science Precinct with the aim of evaluating the agronomic and morphological characteristics of thirteen tropical pasture legume accessions from the genera *Arachis, Centrosema, Desmanthus, Glycine, Neonotonia, Macroptilium and Stylosanthes* (Ossiya 1993). In 2024, a follow-up plant survey of the site was undertaken in order to identify persisting accessions. The results of this survey are summarised.

Methods

In 1992, a legume evaluation trial was sown at the James Cook University Veterinary Science Precinct (19_{0} 19’S 146_{0} 45’E) with the aim of evaluating the agronomic and morphological characteristics of the following 13 tropical pasture legume accessions:

- *Arachis paraguanensis* (CPI 91 4197)
- *Arachis paraguanensis* (CPI 1780) (formerly *Arachis erectoides* (CQ1780))
- *Arachis triseminalis* (CPI 91423) (formerly *Arachis pusilla* (CPI 91423))
- *Centrosema brasilianum* (CPI 55698)
- *Centrosema pascuorum* (CPI 55697)
- *Desmanthus leptophyllus* (CPI 38351)
- *Desmanthus virgatus* (CPI 79653)
- *Glycine latifolia* (CQ 3368)
- *Macroprilium martii* (CPI 55782)
- *Macroptilium bracteatum* (CPI 55770)
- *Neonotonia wightii* cv. Cooper
- *Stylosanthes hamata* cv. Verano
- *Stylosanthes scabra* cv. Seca

A factorial completely randomised block design was applied and included three blocks with three plots nested within each block. Within each block, the nested plots were assigned one of three superphosphate treatment rates (0, 125 or 250 kg/ha). The plot dimensions were 9.95 m x 2 m, thus providing a buffer spacing of 0.75 m between rows. The spacing between plots within each block was 0.5 m and 1 m between blocks.

The site is characteristic of a coastal, seasonally dry tropic environment and the soil is described by Murtha (1982) as a soil with a light grey-brown sandy loam A1 overlying a highly bleached sandy loam A2 horizon which changes abruptly to a mottled brownish grey and yellow brown heavy clay B horizon. The pH of both the A and B horizons is mildly acidic (pH 6.5). Following establishment, the site was abandoned after one season and has since endured heavy crash-grazing by sheep, earthworks disturbance, regular slashing, continuous macropod grazing pressure, and has been exposed to periods of significant drought over the last 32 years. The site has also endured significant climate variability since its establishment, including periods of significant drought.

In 2024, an approximate boundary of the old trial was demarcated using old photographs and satellite imagery for reference. Mowing was suspended for a period of three months from mid-January to permit sufficient regrowth for species identification, as well as an opportunity for surviving plants to flower and set seed. Following the spelling period, the entire site (200 m^2) was surveyed using a 1 m^2 quadrat. The top three dominant species (by visually estimated biomass) were recorded by two operators working in tandem for each quadrat. Individual plant counts were also performed for all occurrences of originally sown accessions present, with the exception of *S. hamata* and *scabra*, as these are naturalised and abundant within the local district. All sundry species present were also recorded.

Results

Of the 13 accessions originally sown, four were recorded persisting at the site 32 years after establishment including *A. paraguanensis*, *D. leptophyllus, S. hamata* and *S. scabra*.

A total of 80 *A. paraguanensis* plants were recorded across the site, equating to a plant density of 0.4 plants/m^2. Two *D. leptophyllus* plants were recorded, giving a density of 0.01 plants/m^2. As noted, *S. hamata* and *scabra* plants were not individually recorded.

Dominance rankings of all species are presented in Table 1. The most prevalent species was *C. rotundifolia*, which dominated 60% of quadrats followed *B. pertusa*, which dominated in 30% of quadrats. Both species ranked within the top three for dominance in 90% of quadrats. Other prevalent species recorded were *Sida rombifolia* and *Richardia brasiliensis*. Of the originally sown legumes, *S. hamata* ranked within the top three for dominance in 26% of quadrats, while *A. paraguanensis* and *D. leptophyllus* only ranked for dominance in three and one quadrat respectively. No visible effect of the phosphorus treatments was observed.

Table 4: Species dominance rankings recorded at the site from a total of 200 quadrats.

Species	*Number of times spp. recorded 1st dominant within a quadrat.*	*Number of times spp. recorded 2nd dominant within a quadrat.*	*Number of times spp. recorded 3rd dominant within a quadrat.*	*Weighted dominance score**
Chamaecrista rotundifolia	154	64	23	613
Bothriochloa pertusa	81	129	29	530
Sida rombifolia	15	15	20	95
Richardia brasiliensis	7	20	31	92
***Stylosanthes hamata* cv. Verano**	0	11	59	81
Eragrostis spp.	3	4	10	27
Alternanthera ficoidea	1	6	6	21
Corchorus olitorius	2	2	8	18
Alysicarpus vaginalis	1	3	5	14
Desmodium triflora	0	3	8	14
Ziziphus mauritiana	1	0	5	8
Desmodium scorpiurus	0	1	2	4
***Arachis paraguanensis* (CPI 91419)**	0	0	3	3
Desmanthus leptophyllus	0	1	0	2
***Stylosanthes scabra* cv. Seca**	0	0	2	2
Asteraceae spp.	0	1	0	2
Sida cordifolia	0	0	2	2
Mimosa pudica	0	0	2	2
Ocimum americanum	0	0	1	1

* Species dominance records applied to weighting multipliers of 3, 2 and 1 for 1st, 2nd and 3rd dominance rankings respectively and summed.

Discussion

The most recent survey of the site indicates that of the 13 accessions originally sown, four were recorded persisting at the site 32 years after establishment including *A. paraguanensis*, *D. leptophyllus, S. hamata* and *S. scabra*. This represents a further decline in species representation since the previous survey of the site conducted in 2017, in which Gardiner et al. (2017) additionally recorded *C. brasilianum* in abundance and to a lesser extent *M. martii*. *A. triseminalis, C. pascuorum, D. virgatus, G. latifolia, M. bracteatum and N. wightii* were not recorded in either the present study or the 2017 survey and thus appear to have failed the test of time under the combination of edaphoclimatic factors and prevailing patterns of disturbance particular to the site. *S. hamata* and *S. scabra* are naturalised in the local area and are known to be well adapted to the region.

While a total of 80 *A. paraguanensis* plants were recorded, equating to an average plant density of 0.4 plants/m^2, it should be noted that these plants were not distributed uniformly across the site and tended to cluster in association with subterranean seeding from parent plants. These plants were also observed to be low yielding in comparison to *C. rotundifolia* and *S. hamata* and *scabra,* however it should be noted that analyses of other forage peanut accessions withing the *Arachis* genus have recorded nutritional values equivalent to Lucerne (Lascano 1994). Within the context of the seasonally dry tropics, any additional protein source within grass dominated pastures is potentially advantageous to livestock production. It is also interesting to note that while *A. triseminalis* has not persisted at this site, it continues to survive in harsher, lower rainfall inland sites such as Hillgrove Station, north of Charters Towers and at Redlands Station, west of Balfes Creek (Gardiner and Swan 2008, Gardiner, pers. comment).

D. leptophyllus has continued to persist at the site, despite not being as well adapted to the soil texture or the heavy grazing and mowing pressures characteristic of the site when compared to species such as *C. rotundifolia* and *S hamata* and *scabra*. It is likely that its persistence is due to the existence of an accumulated seed bank with a high degree of hard-seededness.

The environmental and stressors exerted upon the site over the years are reflected in the dominant species recorded (Table 1). These represent species that adapted to the seasonally dry environment, infertile soils and the continual pressure imposed by macropod grazing and mowing.

The original phosphorus treatment plots were not visibly discernible, however they may be influencing survival and plant dominance rankings, as phosphorus is known to be both critical for legume growth and persistence.

Of note is the observation that a number of the originally sown accessions were found persisting in an adjacent streamline at the time of the survey, including *C. brasilianum*, *A. paraguanensis* and to a lesser degree *M. martii,* and *D. leptophyllus*. *A. paraguanensis* has also been observed growing well and spreading steadily at another local alluvial site, having spread approximately 1m from the original planted row over the course of four years.

The value of such abandoned sites cannot not be overstated as they represent potentially valuable repositories of accessions that have been thoroughly tested by droughts, floods, fire, grazing and insect attack. These robust and persistent pasture legumes are of potential utility not only for northern Australia but similar climates across Africa, Asia and central and south America. Indeed, the value of such sites has been underscored in recent years by the development of several new commercial lines of *Desmanthus* and *Stylosanthes* that were originally observed to be thriving at abandoned historical trial sites spread across Queensland, some planted over forty years ago (Gardiner 2016, Gardiner and Swan 2008, Peck et al. 2021). It is recommended that research organisations continue to invest in identifying persistent accessions at discontinued experimental sites as they may hold considerable value for grazing industries in the future.

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Ephemerals to the rescue! Or not?

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Key words: seasonal grazing; arid; plant cover; rainfall

Abstract

The vegetation along the west coast of South Africa is known for the floral displays by ephemerals during good winter rain seasons. Previous studies found that livestock will preferentially consume ephemerals over perennials when available and concluded that the presence of ephemerals allows for perennial forage plants to rest and set seed, regardless of grazing taking place during the growing season. Do these conclusions stand up to scrutiny?

A seasonal grazing trial in which paddocks were grazed for three monthly periods, was conducted at the Nortier Research Farm on the west coast of South Africa from September 1989 – September 1995. In this region, rainfall occurs primarily in the winter months of May through to August. The percentage canopy cover of the perennial plant species and ephemerals were determined every year at the start, June, and end, September, of the winter-grazing season.

Autumn rain determined the percentage cover of ephemeral plants by June. When both autumn and winter were dry, both ephemeral and perennial plant cover decreased during the winter grazing season. In wet winters, when ephemerals are in abundance, the perennial plant cover increased toward the end of the grazing season.

When ephemerals were abundant in winter, it allowed for perennial plants to regrow despite grazing. Farmers should take autumn rainfall into account in their fodder flow planning for the coming winter months. Dry autumn months resulted in fewer ephemerals being present, which resulted in livestock utilizing a greater amount of the perennial plants. As a result, they received minimal rest during winter and should receive rest from grazing during spring.

Introduction

The vegetation along the west coast region of South Africa is known for its floral displays by ephemerals during good winter rainy seasons (Van Rooyen et al. 1991). Ephemerals are herbaceous plants which are available for livestock grazing for only a few months during the wet season (Samuels et al. 2016). Livestock will preferentially consume ephemerals, which usually have a high nutritional value, over perennials when available. It is assumed that the presence of ephemerals, and their appeal to livestock, allows for perennial forage plants to rest and set seed while ephemerals are abundant during the wet season (Samuels et al. 2016). However, it has not been tested whether ephemerals in abundance contributed to an improved canopy cover of perennial plants at the end of the grazing season.

The vegetation of the west coast region of South Africa is divided into two biomes, namely the Succulent Karoo to the north and Fynbos to the south (Mucina and Rutherford 2006). This arid region has a mediterranean climate with cool wet winters and hot dry summers and is recognized as a biodiversity hotspot (Mittermeier et al. 2011). The primary land use of the region is livestock grazing. Sustainable utilisation with livestock is thus very important to ensure the conservation of this highly biodiverse area.

The objective of this study was to 1) determine the effect of rainfall on the percentage cover of ephemerals and 2) determine if ephemerals in abundance have a positive impact on the canopy cover of perennial plant species grazed during the wet season.

Methods

The trial was conducted at the Nortier Research Farm on the west coast of South Africa in the Fynbos biome. The site has a mean annual rainfall of 200 mm, receiving 64% from May–August based on rainfall data recorded daily at the research farm. Nortier is situated in the West Strandveld bioregion, on undulating dune fields that supports tall dense shrubland, with dominant perennial plant species including *Ehrharta calycina*, *Eriocephalus racemosus, Roepera morgsana, Salvia lanceolata, Tetragonia fruticosa,* and *Willdenowia incurvata*, and ephemerals, mainly forbs, include *Oncosiphon suffructicosum, Senecio arenarius, Wahlenbergia annularis* and *Zaluzianskya affinis* (Mucina and Rutherford 2006).

A seasonal grazing trial ran from September 1989 – September 1995. Treatments included four grazing seasons (Spring, Summer, Autumn, Winter) and three stocking rates (Low, Moderate, High). Each paddock was grazed for three months and rested for nine months. There was a total of 12 treatments with two replicates each and in a completely randomised design. As the impact of grazing/browsing on vegetation can be measured by the change in the percentage canopy cover of plants (Du Toit 1998), plant surveys were undertaken using the descending point method (Roux 1963) to determine the percentage canopy cover of the perennial plant species and ephemerals. These surveys were undertaken every year in June at the start of the wet season and in September towards the end of the wet season in each of the paddocks. This coincided with the start and end dates of the winter grazing season.

Data were analysed using Pearson's correlation, ANOVA, Fischer's Least Significant Difference test, and linear regression analysis.

Results

The percentage cover of ephemerals in June is strongly correlated with the previous three months' rainfall (r = 0.850; $p < 0.0001$) regardless of grazing season, but especially with the previous month's rainfall (r = 0.870; $p < 0.0001$) (Table 1). No significant correlations ($p > 0.05$) were found between the cover of ephemerals and the previous three month's rainfall from surveys done in September, December, and March.

Table 1: Pearson's correlation coefficients between percentage canopy cover of ephemerals present in June and the rainfall of the previous month and previous three months at Nortier Research farm. All correlations were highly significant ($p < 0.0001$).

Grazing season	Previous month	Previous three months
Autumn	$r = 0.849$	$r = 0.823$
Spring	$r = 0.899$	$r = 0.881$
Summer	$r = 0.921$	$r = 0.914$
Winter	$r = 0.901$	$r = 0.861$
Overall	$r = 0.870$	$r = 0.850$

A strong positive correlation ($r = 0.731$; $p < 0.0001$) was found between the change in the canopy cover of perennial plants from before, to after the grazing season and the percentage cover of ephemerals before grazing commenced in June in the winter grazed treatment. The better the cover of ephemerals are before grazing the more the cover of the perennial plants will improve during the winter grazing period.

The ANOVA showed significant differences in the changes in canopy cover of ephemerals ($p < 0.0001$; F = 7.168) and perennial plants ($p < 0.0001$; F = 15.725) between the years. When the veld is grazed during the growing season (winter) the ephemerals and perennials decreased significantly when the rainfall was less than 50% of the average in the autumn, such as in 1991, regardless of good winter rain (Fig. 1). There was also a non-significant decrease in cover of both ephemerals and perennials after grazing during the winter of 1992 following autumn rainfall of less than 40% of the average. This small decrease was most probably because of the carry-over effect of the 70% above average rainfall received during the previous winter (Fig. 1). In 1995 when the autumn and winter rain were less than 10% below average, the ephemerals slightly increased during the winter, but it was not enough to supply sufficient fodder for the animals to not utilise the perennial plants that decreased significantly compared to the years when average autumn and winter rainfall were received. The winter rain of 1995 was not sufficient to allow for regrowth of the perennials in the presence of grazing (Fig. 1). When above average autumn and winter rain was received there was an increase in canopy cover of ephemerals and perennials from June to September in the winter grazed treatment (Fig.1). The linear regression analysis however showed an interaction with stocking rate, where canopy cover of perennials ($p < 0.01$) and ephemerals was greater in the low than moderate and high stocking rates, and rainfall for the last three months influenced ephemeral cover ($p < 0.01$) (Data not shown).

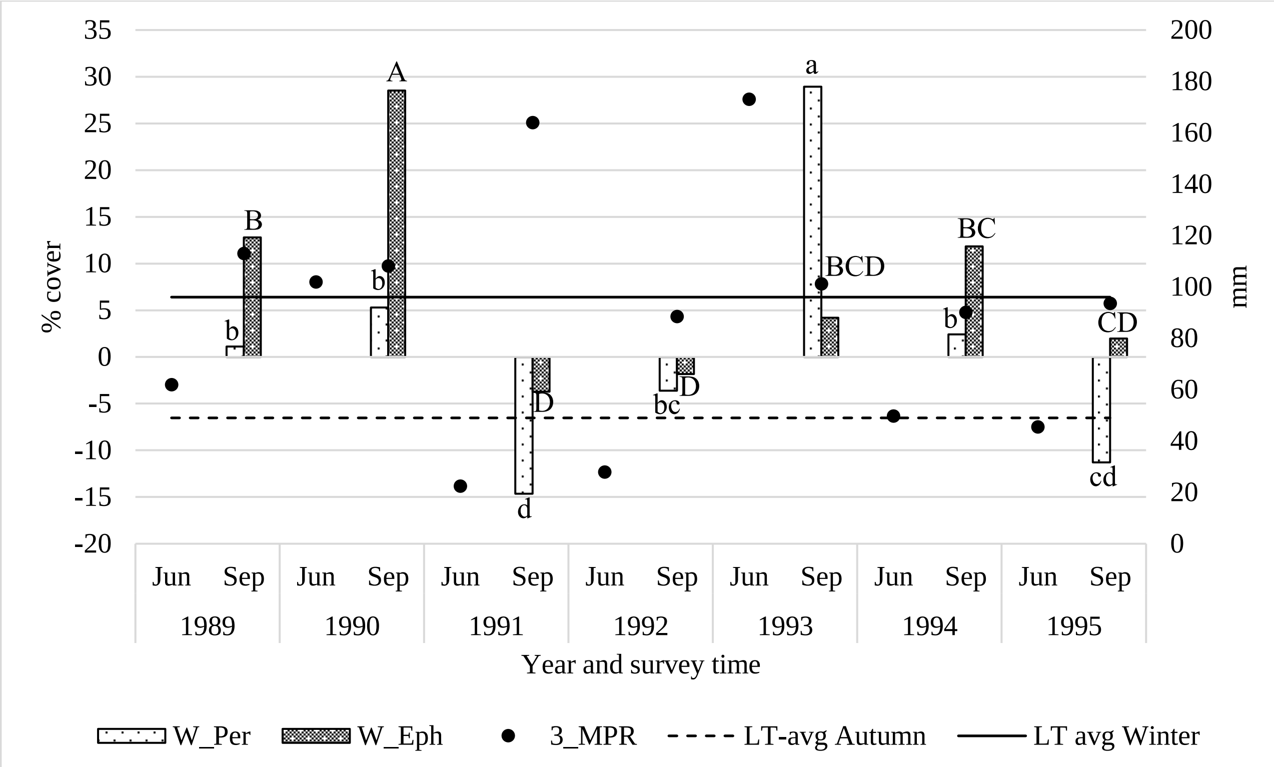

Fig. 1: The change in the percentage cover of the perennial plants and ephemerals, averaged across all stocking rates, during the winter (Jun -Aug) in the winter grazed treatments showing the rainfall (mm) in the three months prior to the surveys (3_MPR). W_Per = Winter-grazed treatment Perennial plants, W_Eph = Winter-grazed treatment Ephemerals; LT-avg Autumn = Long term average rainfall for Mar-May; LT-avg Winter = Long term average rainfall for Jun-Aug (Letters above bars indicate significant differences at the 0.05 level; small letters for perennials; capital letters for ephemerals)

Discussion

Different studies showed that rainfall of the preceding months plays an important role in the presence of ephemerals on the west coast of South Africa and other ecosystems across the world (Van Rooyen et al. 2018). In the transition zone between the Fynbos and Succulent Karoo on the west coast it is no different, as this study found a strong positive correlation between the cover of ephemerals present during June, at the start of the growing season, and the rainfall received during autumn and especially during the month of May. This is further supported by Van Rooyen et al. (1991) who found that ephemeral germination took place during autumn to mid-winter. Saayman et al. (2022) found that the grazing season and stocking rate are the drivers of vegetation change in this vegetation type, but it seems that for ephemerals, rainfall is the main driver of change (Van Rooyen et al. 2018) with only 5% of the change in ephemeral cover that is accounted for by grazing as found in another analysis in this study.

Ephemerals do not provide fodder for a long period of time and has little carry-over forage to the next season (Van Rooyen et al. 2018), but when present are preferred by livestock as a source of fodder over perennial plants (Samuels et al. 2016). This study found that after a dry autumn when the cover of the ephemerals was low at the start of the winter grazing season, little fodder from ephemerals was available and the livestock utilized the perennial plants more than they did during years with abundant ephemerals. In this situation, the cover of both the ephemerals and perennial plants decreased during the winter grazing season, ultimately lowering the cover of the perennial plants by the end of the grazing season (winter). In contrast, in wet years when ephemerals were abundant, the cover of the perennial plants increased by the end of the grazing season, since livestock likely have preferentially grazed ephemerals, allowing perennial plants to grow and increase in cover (Samuels et al. 2016). Applying low stocking rates will also have a positive impact on the growth of perennials during winter grazing.

Conclusions and Implications

Ephemerals make a large contribution towards the fodder supply during winter and spring in the winter rainfall region of South Africa and are largely dependent on the rainfall received during the month of May. This study supports the notion that when ephemerals are present in abundance during the winter grazing period it allows for perennial plants to regrow and set seed.

Farmers should take the autumn rainfall into account in their grazing management planning for the coming winter months. Dry autumn months will result in fewer ephemerals. This implies less forage material from ephemerals and livestock will utilize more of the perennial plants, lowering its cover. Therefore, the plants won't get the anticipated rest during winter and should receive rest from grazing during spring.

Acknowledgements

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Long-term South African arid region study shows relationships between rainfall, SPI, and ungrazed perennial plant cover amid climate change

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Key words: Drought; plant cover; climate change; Mediterranean climate; monitoring

Abstract
Climate change is projected to diminish the rainfall and lead to more frequent droughts in the cold arid desert of the west coast of South Africa. Long-term area-wide precipitation trend analysis indicates all-year reductions, but particularly in autumn (March–May), driven by the poleward contraction of mid-latitude storm tracks. The region has historically reliable winter precipitation and generally very dry summers. This study analysed the 60-year rainfall and 56-year ungrazed perennial plant cover recorded at Nortier Research Farm in the West Strandveld bioregion to identify possible climatic shifts, and the relationships between rainfall, Standardized Precipitation Index (SPI) and perennial cover. The hypotheses were that rainfall in a certain period preceding the plant survey is a strong predictor of perennial cover, and that climate change is already driving changes in cover. No significant rainfall trends were found but there was a shift towards wetter summers in the last 30 years. The Standardised Precipitation Index (SPI) indicated moderately to extremely dry years in 1966–1973. Apart from 1978 and 2017, no other drought periods (SPI $\leq$ -1.0) were identified. Around eight years were moderately to very wet (SPI $\geq$ 1.0) and occurred randomly. The study found a strong positive correlation (r^2 = 0.524) between the rainfall of the previous 18 months and the perennial plant cover, supporting the hypothesis that preceding rainfall is a strong predictor of perennial cover. However, no discernible changes driven by climate change were found. Rangeland managers should take the rainfall of the previous 18 months into consideration when making grazing decisions. Weather monitoring is continuing to track possible long-term climate changes. This research contributes to understanding the impact of climate change on arid regions.

Introduction
Perennial vegetation forms the basis of terrestrial ecosystems and rainfall is a key driver of vegetation dynamics. In semi-arid regions, plant cover is sensitive to rainfall variability, seasonality and cyclic droughts (Munson et al. 2016). Projected more frequent and extended droughts and rising temperatures under climate change will reduce water availability and negatively impact the vegetation.

The semi-arid southern west coast of South Africa has a Mediterranean-type climate with very dry summers and reliable winter rainfall, receiving less than 250 mm of rain per annum (Mucina and Rutherford 2006). The region is renowned for the high species diversity and endemicity of the Fynbos and Succulent Karoo biomes. A moderate and stable climatic history is key to this diversity, and the vegetation could be highly vulnerable to climate change

(Midgley and Thuiller 2007). Grazing of more palatable species and rainfall variability combine to determine plant cover in semi-arid south-western South Africa (Saayman et al. 2022). While research has focused on leaf- and stem-succulent shrubs and rare species, little information is available on total perennial cover in relation to short- and long-term rainfall dynamics, especially when livestock are excluded over a long period.

In this region, climate change will likely reduce rainfall, and droughts will become more frequent and intense. Some sub-regions may experience much stronger rainfall reductions than others due to different climatic drivers (Wolski et al. 2020). The long-term (1900–2020) area-wide precipitation trend analysis (Jack et al. 2022) shows a significant reduction in autumn (March–May) rainfall, associated with the poleward contraction of the rain-bearing mid-latitude cyclones and the dynamics of the Southern Annular Mode (Wolski et al. 2020).

This study focused on a coastal area that is historically cool and semi-arid with winter rainfall but is projected to shift in future towards hot and arid. Changes in perennial plant cover are expected to be driven by both short- and long-term rainfall dynamics. The hypotheses for this study spanning 57 years (ungrazed vegetation) were that rainfall in a certain period preceding the plant survey is a strong predictor of perennial cover, and that climate change is already driving changes in cover.

Methods

The study was conducted on the Nortier Research Farm near Lambert's Bay (-32.03524; 18.33274) on the west coast of South Africa. It is situated in the West Strandveld bioregion, a transitional zone between the Fynbos and Succulent Karoo biomes (Mucina and Rutherford 2006) and receives on average 205 mm rain per annum. Fifty eight percent of the rain falls during the winter months of June to August with only 8% falling during the summer months.

Daily rainfall data were collected on the farm since 1964. Livestock grazing was excluded from one of the paddocks, the Reserve, from 1965. Forty-six plant surveys, measuring plant cover and species composition, were done from 1967 until 2023. For the plant surveys the descending-point method (Roux 1963) consisting of 1000 points on a fixed line was used, recording canopy-spread cover of all the plants encountered at each point.

Using the data for 1964–2023, the Standardised Precipitation Index (SPI) was calculated to assess the degree of meteorological drought (National Drought Mitigation Center 2018). The monthly rainfall and ungrazed perennial plant cover data for 1967–2023 were analysed using Principal Component Analysis (PCA), Ward's Clustering and ANOVA to determine significant differences between clusters. Linear regressions were performed to determine if rainfall can predict perennial plant cover. All data was analysed using XLSTAT (Addinsoft 2023).

Results

The SPI shows moderate to extreme dry years (SPI < -1) from 1966 to 1973. Thereafter, there were no more periods of drought, except in 1978 and 2017. In the 60-year period, there were eight years that were moderately to extremely wet (SPI > 1), but these occurred randomly (Fig. 1).

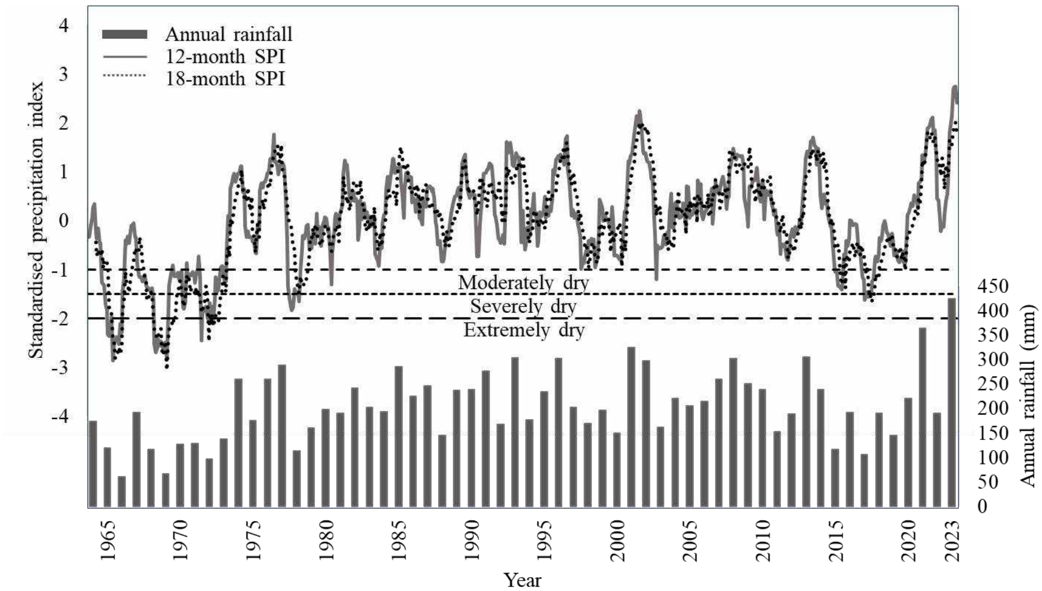

Fig. 1 Annual rainfall at Nortier Research Farm in 1964-2023 (bars) and expressed as Standardised Precipitation Index (SPI) for 12-month and 18-month periods, highlighting periods of increasing dryness.

To determine if there were any trends in the rainfall over time, further analysis using Principal Component Analysis (PCA), was done. Ward's clustering grouped the rainfall into five clusters, namely, driest years (all seasons), drier summers than usual, drier winters than usual, wetter summers than usual, and wetter winters than usual. From the PCA and Ward's clustering there were no definite trends, except for a shift towards wetter summers in the last 30 years (Fig. 2). The year 2023 was an outlier with a wetter summer than normal, and the wettest winter on record.

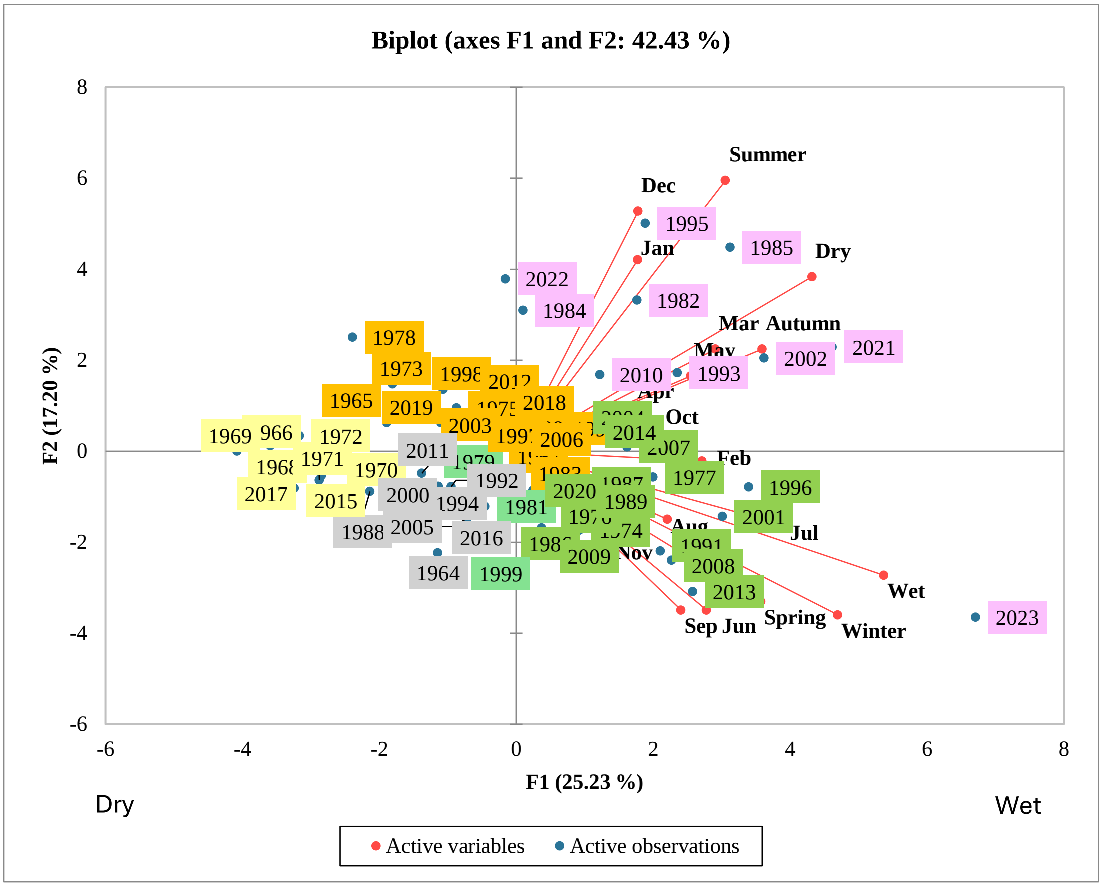

Fig. 2 Principal Component Analysis (PCA) of rainfall data from 1964–2023 at Nortier Research Farm. Ward's clustering is indicated with different colours (green = wetter winters; pink = wetter summers; grey = drier winters; orange = drier summers; yellow = driest years overall).

The study found a relatively strong positive correlation ($r^2 = 0.524$) between the rainfall of the previous 18 months and the perennial plant cover. A highly significant linear regression model ($p < 0.0001$) using the previous 18 months rainfall (18moPr) was developed to predict the perennial vegetation (Perennial = 27.613+0.178*18moPr). All the recorded plant cover values fell within the 95% confidence limits of the predicted plant cover.

Discussion

In a previous study of the succulent karoo (Hoffman et al. 2009), SPI analysis also identified drought periods in the 1960s–1970s and no significant trends in mean annual rainfall for 1900–2000. Despite the severely dry year of 2017 and an extended dry period in 2015–2019 at Nortier, the mean annual rainfall during the last 30 years (1994–2023) was higher (+37.2 mm) than in the first 30 years (1964–1993). Wolski et al. (2020) analysed the 2015–2017 rainfall anomalies across the southern winter rainfall region in the context of the 1900–2017 data set. Spatially and seasonally different rainfall trends in the short- and long-term are influenced by different climate drivers. The sub-region around Nortier commonly showed a wetting trend in 1981–2014, and the Nortier station itself experienced a weaker drought in subsequent years.

Our findings of summer wetting at Nortier align with previous studies (Wolski et al. 2020; Jack et al. 2022). This trend is likely associated with local, non-hemispheric process drivers such as cut-off lows, ridging highs, and convective summer rainfall. A possible increase in the latter may be associated with the increased convective available potential energy (CAPE) and regional synoptic changes brought about by climate change. Advective moisture-bearing coastal fog associated with the cold Benguela current is prevalent in summer, but analyses of trends and future projections of fog are unavailable (Midgley and Thuiller 2007). These drivers require further research.

The relatively strong positive correlation found between rainfall in the preceding 18 months and the perennial plant cover indicated that rainfall is a strong predictor of perennial plant cover in the absence of grazing and that there is a carry-over effect from the rainfall received in the previous seasons (Hoffman et al. 2009). This implied that there will be less cover following dry years and the vegetation will take longer to recover after a drought (Munson et al. 2016). If droughts along the west coast become more frequent it will negatively impact the perennial vegetation and ultimately the fodder availability for herbivores, increase the soil erosion potential and have a negative effect on essential ecosystem services (Munson et al. 2016). Rangeland managers should take the rainfall of the previous 18 months into consideration when making grazing decisions to lower the impact of droughts.

The second hypothesis, that climate change is already observed and driving changes in plant cover, was not supported. The 60-year observed Nortier data set showed no evidence of long-term reductions in annual or seasonal rainfall as projected (Jack et al. 2022). This may, however, change in the future as hemispheric and local climatic drivers respond. Therefore, weather and vegetation monitoring efforts are continuing to track possible long-term climate changes and their impact on the vegetation.

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Mulga populations at risk: 50% drought mortality outside reserve areas and low recruitment everywhere

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Key words: grazing; demography; semi-arid; tree mortality; seedling survival

Abstract
Mulga (*Acacia aneura* and related species) is a drought-tolerant tree that dominates large parts of Australia's arid and semi-arid zone. Following a severe drought in 2017-2019, mass mortality was reported across the distribution of mulga. In 2021-2022, there was substantial rainfall in some regions that was expected to stimulate a mulga recruitment pulse. In this study, we quantify mortality and recruitment following these events in two land uses that differ in their grazing pressure. We surveyed inside and outside the Arid Recovery Reserve, Roxby Downs, SA. Inside the conservation reserve, small native mammals are present—bettongs, bandicoots, and bilbies. Outside the reserve, the land is managed for pastoralism, with livestock, native kangaroos, and feral rabbits. During 2023-2024, we surveyed ten 0.5 ha plots in each land use. In each plot, we counted alive and recently dead mulga plants to quantify mortality and mulga seedlings to assess recruitment. We found that adult drought mortality was 1.8 times higher outside the reserve (50%) than inside (28%). Recruitment after the rainfall was insufficient to offset the drought mortality in either land use type. Inside the reserve, plots had 0.01 seedlings per dead adult and outside the reserve, there were no seedlings. Our results reveal high drought-induced mortality in mulga is exacerbated outside reserves, where livestock and feral animals are present. Low subsequent recruitment indicates that these mulga populations may be at risk. It is imperative to predict mulga population trajectories to conserve the vegetation and functioning of Australia's arid and semi-arid ecosystems.

Introduction
Mulga (*Acacia aneura* F. Muell. Ex Benth and nine related species; Miller et al., 2002) are dominant or co-dominant trees throughout much of Australia's large arid and semi-arid zone. Droughts and high temperatures are common in the Australian arid/semi-arid zone. Mulga has several adaptations, such as phyllodes, to cope with these stressful conditions. However, during the 2017-2019 drought, large dieback events in mulga were reported anecdotally across its distribution. During this period, rainfall was approximately half the long-term average (Bureau of Meteorology, 2023a). Additionally, many regions experienced their highest temperatures on record, especially during the dry months. Dieback events in mulga have occurred in the past (Evans, 1903; Godfree et al., 2019). However, with ongoing climate change, hot and dry conditions are predicted to increase in frequency and intensity (Jenkins and Warren, 2015).

Previous research indicates that mulga mortality is a function of rainfall deficit (Fensham et al., 2019) and other factors such as soil depth which determines water availability (Fensham, et al., 2012). Additionally, heavy grazing pressure can intensify mortality rates (Evans, 1903; Godfree et al., 2019) by reducing water availability due to reduced water infiltration and retention capacities (Witt et al., 2011), and by reducing nutrient availability due to lower diversity and cover of soil crusts (Williams et al., 2008). To predict the likely trajectory of mulga populations in the future, it is essential to quantify mortality and its dependence on climate and other factors. Additionally, an important question is whether recruitment will be sufficient to maintain the population despite severe dieback. Previous research suggests recruitment in mulga is particularly contingent on the timing and intensity of rainfall (Preece, 1971a and b) and is also strongly affected by grazing pressure (Hall et al., 1964; Munro et al., 2009). In 2021-2022, following the drought, significant rainfall occurred in some regions: annual rainfall totals in parts of central South Australia were 100-200% higher than the long-term averages (Bureau of Meteorology, 2023b). The rainfall may have stimulated a recruitment pulse.

Here, we quantify the 2017-2019 drought mortality and 2021-2022 rainfall-induced recruitment in mulga to assess if recruitment offsets mortality, under two land use types that differ in their grazing communities. We surveyed plots inside a conservation reserve (Arid Recovery Reserve), which has small native herbivores, and outside the reserve, on pastoral stations, which have livestock, native kangaroos, and feral rabbits. We compare i) drought-induced mortality and ii) recruitment between the two land use types. We hypothesise that mortality rates will be higher in the pastoral regions because mortality increases with grazing pressure, which we assume to be higher where livestock and feral grazers are present. We also hypothesise that seedling recruitment will be higher inside the reserve where livestock and feral grazers are excluded.

Methods

The study was conducted in and around the Arid Recovery Reserve (-30.33943 N,136.89982 E), near Roxby Downs, South Australia (Fig. 1). This fenced conservation reserve (123 km^2) was established in 1997 (Moseby and Read, 2006). In the part of the reserve where we conducted the study, all herbivores were removed in 1998 and native small herbivores were reintroduced over time, including western barred bandicoots, burrowing bettongs, and greater bilbies (Munro et al. 2009). Outside the reserve, on the adjoining pastoral stations, the chief herbivores are cattle, native kangaroos, and feral rabbits. The different grazing communities inside and outside the reserve represent the two land use types in this study. During 2017-2019, hot-dry conditions prevailed in the study area. The long-term average annual rainfall in the area is 182 mm (at Andamooka Station, Bureau of Meteorology 2023c). During the three years of the 2017-2019 drought, the mean annual rainfall was 86 mm, causing a cumulative rainfall deficit of 288 mm over the period. The long-term average daily maximum temperature of the driest quarter (January to March) is 34.8°C. During the drought, the average was 1 – 1.2°C higher, with some days hitting the highest on record at 48.1°C. However, above-average rainfall followed in 2021-2022. In these two years, the average rainfall was 231 mm, ~50 mm more than the average, and the average dry-quarter maximum temperatures dropped to 33.7°C.

In each land use type, we surveyed ten plots. Each plot was a circle of 40 m radius (0.5 ha) centred on an adult mulga tree. In each plot, we counted alive and recently dead adult mulga plants, and seedlings. Plants were classified as '*alive*' if green leaves were present. Plants were classified as '*recently dead'* if green leaves were absent, but fine twigs were present, and bark was intact; indicating that these plants died following the recent drought. Plants ≥2 m in height were classified as adults which have a recruitment potential, as most of these had flowers or pods. Plants ≤0.3 m in height were classified as seedlings and assumed to have recruited following the 2021-2022 rainfall events. We tested the effect of land use type on mortality and recruitment using a generalised linear model (Dobson 1990). For comparing mortality and recruitment percentages, the response variable was the ratio of the counts to the total with binomial family and logit link (i.e., the response variable for mortality was the number of recently dead tree counts divided by the total number of alive and recently dead trees and, total as weights). All analysis was done in R v.4.2.1 (R Core Team, 2022). The study area map was made using QGIS v.3.30.3 (QGIS.org, 2023).

Results

The average adult (alive and recently dead) density of mulga was 78 trees ha^{-1} inside the reserve and 59 trees ha^{-1} outside the reserve. The 2017-2019 drought caused an average mortality of 39% in mulga adults. Plots outside the reserve recorded higher adult mortality (50% outside and 28% inside, $p<0.01$) (Fig. 2). Despite the above-average rainfall in 2021-2022, a recruitment pulse was not observed. Only one plot inside the reserve had any evidence of recruitment, with one seedling present. Outside the reserve, no plots had seedlings. The recruitment did not offset the observed mortality. There was only one seedling for 288 dead adults.

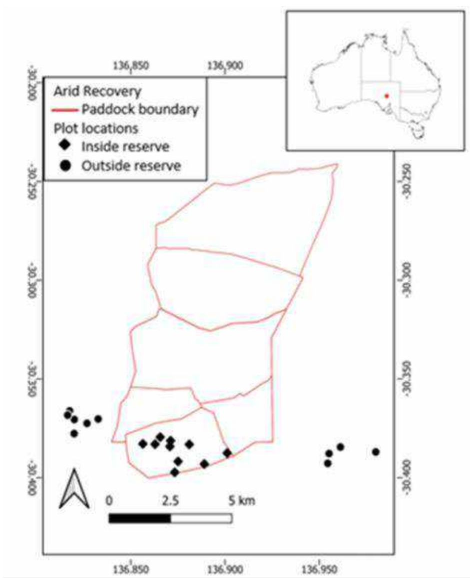

Fig. 1: Plot locations inside and outside the Arid Recovery Reserve. The map inset shows the location of the Arid Recovery Reserve within Australia, in a red star.

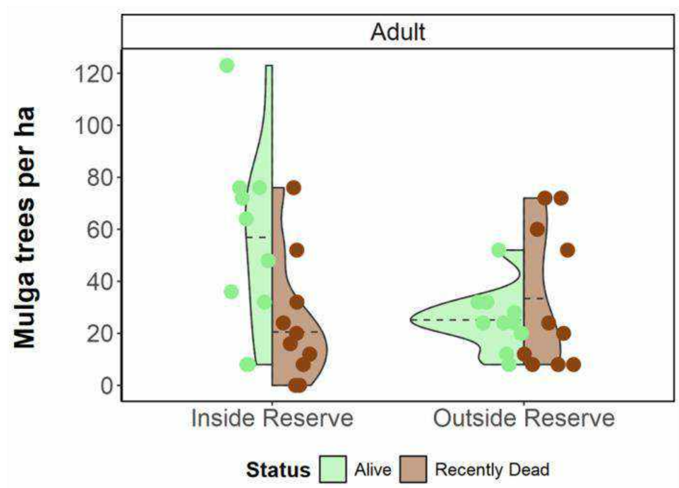

Fig. 2: Number of alive and recently dead mulga adults (≥2 m height) in plots inside and outside the Arid Recovery Reserve. The dashed lines indicate the respective medians.

Discussion

Many regions of Australia received less than half their average rainfall during 2017-2019, along with record-high temperatures. In the study area, this 3-year rainfall deficit and high temperatures caused significant mortality in mulga (39% of all adult plants). Moreover, despite above-average rainfall during 2021-2022, a recruitment pulse has not occurred (only one seedling was observed across all plots). The high mortality and low recruitment indicate that subsequent recruitment was insufficient to offset the occurred drought-induced mortality. The high mortality rate, coupled with poor subsequent recruitment rates, could lead to a local population decline in mulga. Drought-induced population declines are not restricted to our current study area; surveys during 2021 at Uluṟu-Kata Tjuṯa National Park also reported a 42% drought mortality in mulga (Wright et al., 2023). While drought-induced mortality has occurred in the past (Fensham et al., 2019), the lack of recruitment despite the subsequent above-average rainfall highlights the need to assess the population trajectory of mulga under a changing climate.

To understand population trajectories, it is vital to examine the drivers of mortality and recruitment. From our study and others (Fensham et al., 2019; Wright et al., 2023), it is evident that a rainfall deficit of less than half of total rainfall that lasts more than one year causes considerable dieback in mulga. This threshold can vary with soil depth (Fensham, et al., 2012), but this was not tested in this study.

Our study indicates that increased grazing pressure exacerbates drought-induced mortality. We found that the grazed areas outside the reserve had 1.8 times higher mortality than inside, supporting our hypothesis that mortality rates are higher where livestock and feral grazers are present. Anecdotal reports from the 1900s (Evans, 1903 in Fensham et al., 2019; Godfree et al., 2019) indicate high mortality in mulga occurred in overgrazed areas, but few studies have systematically studied the interaction between drought and grazing in determining mortality. Fensham et al., (2012) assessed mulga mortality as a function of a grazing intensity index (distance to watering points) but did not find a consistent relationship between grazing intensity and mortality rates. However, heavy grazing pressure reduces water availability and nutrient availability (Witt et al., 2011; Williams et al., 2008), indicating mechanisms by which grazing could increase drought-induced mortality.

Mulga seedlings were too rare in either land use to draw conclusions on the drivers of recruitment. However, recruitment clearly has not offset the drought-induced mortality.

The preliminary analysis presented here demonstrates an important effect of grazing on drought-induced mortality. Reducing grazing pressure may be important for maintaining mulga populations under future climate conditions. In future work, we will analyse the relationship of recruitment and mortality rates to more detailed drivers, including impacts of different grazer types and other factors such as soil and topography.

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Estimation of water-induced soil erosion levels across the rangelands of Ethiopia: an integrated RUSLE and GIS analysis

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Key words: K-factor; rainfall erosivity; soil erodibility; soil loss; sustainable land management

Abstract

Soil erosion poses a significant global threat, leading to widespread land degradation and the depletion of nutrient-rich topsoil. Understanding the spatial distribution of soil erosion is crucial for implementing effective management practices and preventing further erosion. This study utilized an analytical tool integrating the Revised Universal Soil Erosion Equation (RUSLE) with geographic information systems (GIS) to estimate water-induced soil erosion across the rangelands and other land use categories in Ethiopia. Rangelands, constituting 68% of Ethiopia's total land area, are essential for the livelihoods of millions of pastoralists and agropastoralists. Input data for the analysis were gathered from multiple sources, including in situ observations and remotely sensed data with various spatial resolutions. The estimated soil erosion rates were validated using previously published data from literature. Our results revealed significant variation in soil erosion, ranging from zero to 250 t ha^{-1} yr^{-1}. The average soil loss across the country was estimated at 13.5 t ha^{-1} yr^{-1}, amounting to an annual soil loss of about 1.5 billion tons, making Ethiopia one of the most severely affected countries by soil erosion worldwide. Disaggregated annual soil erosion estimates indicated that the highest soil loss occurs in rangelands (18 t ha^{-1}), sparsely vegetated (bare land) areas (16 t ha^{-1}), cultivated areas (10 t ha^{-1}), and forest areas (8 t ha^{-1}). These results underscore the urgent need to implement appropriate soil and water conservation practices across rangelands, embracing Sustainable Land Management practices that can significantly reduce soil erosion. Such efforts will support sustainable land resource use and potentially unlock new opportunities for the country.

Introduction

Water-induced soil erosion is a leading cause of land degradation worldwide, resulting in the loss of nutrient-rich topsoil. This process not only diminishes agricultural productivity but also disrupts ecosystems and contributes to reservoir sedimentation (Nathan et al., 2022; Stocking, 2003). Water-induced soil erosion presents significant challenges for sustainable land management and environmental conservation efforts. Although this issue affects regions globally, it is particularly severe in sub-tropical and tropical areas (Lal, 2001). In Africa, the threat of soil erosion poses a substantial risk to food security (Gomiero, 2016; Hossain et al., 2020; Rhodes, 2014). This challenge is further intensified by factors such as climate variability, unsustainable land management practices, and population pressure. Tackling soil erosion requires a comprehensive strategy that includes estimating its current and future spatial distribution, setting priorities, and implementing sustainable land management practices in vulnerable regions. This can be achieved using various models to assess current levels of erosion and forecast future trends.

There are various ways of estimating the spatial distribution of water-induced soil erosion, encompassing both biophysical and empirical statistical models (Borrelli et al., 2021; Golmohammadi et al., 2014; Pal and Chakrabortty, 2019; Wang et al., 2011). These models focus on evaluating the effects of agricultural management practices on several parameters, including plant growth, soil erosion, and surface runoff at various scales and environmental conditions.

Biophysical models require extensive data inputs for accurate parameterization and calibration, such as daily climate and streamflow data, soil properties, and sediment data. This reliance on detailed data can be a limitation in areas with limited data availability. In contrast, empirical models, like the Universal Soil Loss Equation (USLE) and its updated version, the Revised Universal Soil Loss Equation (RUSLE), offer simpler approaches, using fewer input parameters to estimate soil erosion. USLE incorporates core factors influencing soil erosion, such as rainfall intensity, soil type, landscape position, and land use. RUSLE builds on USLE by adding factors that account for erosion control practices and integrates these into computer applications, providing more refined estimates.

RUSLE’s ability to capture the effects of soil and water conservation practices allows it to assess management strategies' effectiveness in reducing soil erosion. The choice between biophysical and empirical models depends on the purpose of the study and data availability: while biophysical models require extensive, high-resolution data, empirical models need fewer inputs and deliver reasonably precise results. Additionally, empirical models like RUSLE are compatible with spatial applications, making them advantageous for mapping soil erosion.

Researchers and land managers use RUSLE to assess and manage soil erosion risks, guide land-use planning, and develop erosion control strategies. The model is particularly valuable in identifying areas vulnerable to soil erosion, understanding the impact of different factors on erosion rates, and evaluating the effectiveness of soil conservation practices. RUSLE has been widely applied in agricultural and environmental research, contributing to sustainable land management practices and erosion prevention strategies.

This specific study concentrates on assessing the spatial distribution of soil erosion in the rangelands and other land use groups of Ethiopia. The objective of this study is, therefore, to integrate RUSLE within GIS and evaluate the spatial distribution of soil erosion across Ethiopia. This study will contribute to the body of knowledge on soil erosion, which has limited comprehensive studies across Ethiopia.

Methods

The spatial distribution of soil erosion across the rangelands and other land use groups of Ethiopia were estimated using the RUSLE method. The methodology involved mapping essential factors such as rainfall intensity, soil texture and organic carbon content, landscape position, land use, and conservation practices, which significantly contribute to soil erosion. Those factors under RUSLE were represented with rainfall erosivity factor (R-factor), soil erodibility factor (K-factor), slope length and slope steepness factor (LS-factor), land cover management factor (C-factor), and conservation practice factor (P-factor). Input data required to estimate RUSLE factors, including annual average rainfall from 2000 to 2020, were collected from ground observation stations and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) when there is no or limited gauged rainfall data. Additionally, information on soil texture and organic matter, digital elevation model (DEM), and land use/cover were gathered from diverse global data sources with various spatial resolutions. The diverse factors were mapped, resampled, and overlaid using the ArcGIS platform to compute the spatial distribution of soil erosion. The validation of the estimated soil loss across the three countries was undertaken through a thorough literature review, which involved an examination of existing scientific studies and reports. This process aimed to assess the accuracy and reliability of the soil loss estimates generated using the RUSLE integrated with GIS. Finally, the soil erosion was disaggregated across the different land use groups and reported.

Results

Spatial Distribution of the Soil Erosion Factors

Rainfall erosivity (R-factor) in Ethiopia ranged between 64 and 1,388 MJ mm ha^{-1} hr^{-1} yr^{-1}, averaging 510 MJ mm ha^{-1} hr^{-1} yr^{-1}. The southeastern region exhibits the highest rainfall erosivity, while lowland areas that receive less than 300 mm of annual rainfall experienced the lowest rainfall erosivity. High R-factor values indicate strong rainfall energy, which can lead to significant soil erosion.

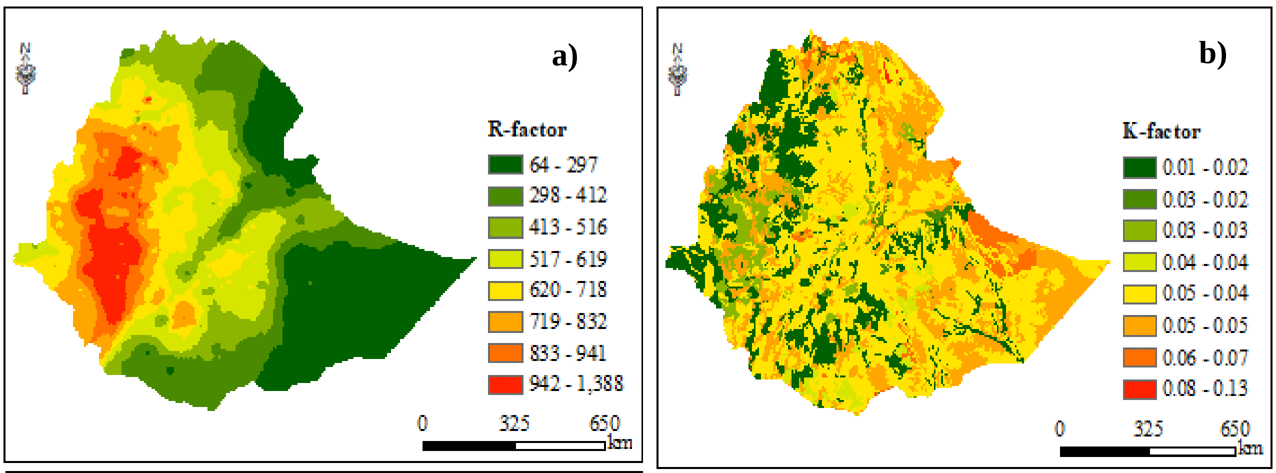

Figure 1. a) Rainfall erosivity (R-factor) [MJ mm ha^{-1} hr^{-1} yr^{-1}] and b) Soil erodibility (K-factor) [t ha hr ha^{-1} MJ^{-1} mm^{-1}] of Ethiopia.

The soil erodibility factor values estimated across Ethiopia ranged from 0.01 to 0.13 t ha hr ha^{-1} MJ^{-1} mm^{-1}, averaging about 0.04. The result of the analysis, in general, indicated that soil textures, including clay, silty clay, and silty clay loam, have lower K-factor values since those soils are resistant to particle detachment. Meanwhile, coarse-textured soils with lower resistance to detachment, such as sand, loamy sand, and sandy loam, were characterized by a higher K-factor value, signifying higher erosion rates.

The slope length and slope steepness factor (LS-factor [unitless]) estimated across Ethiopia exhibited the most significant variability with a coeffect of variation of 606%. The average LS-factor value for Ethiopia was approximately 13.2. The average C-factor for Ethiopia, determined from land use/cover conditions was approximately 0.15. A higher C-factor value signifies a higher potential for soil erosion under the current land cover and management condition. The conservation practice factor (P-factor) value estimated using slope class and land use condition indicated an average value of 0.66 across the country.

RUSLE Estimated Annual Soil Loss.

The estimated annual soil erosion rate in Ethiopia varied from zero to more than 250 t ha^{-1} yr^{-1}, with a coefficient of variation of 380%, showing a significant variation due to the largest range in rainfall, soil, and altitude. The average soil loss across the country was 13.5 t ha^{-1} yr^{-1}, which amounts to an annual soil loss of about 1.5 billion tons, making Ethiopia one of the most severely affected countries by soil erosion worldwide (Tamene and Vlek, 2008; Tsegaye, 2019). Levels of soil erosion estimated across the major land use groups indicated that the highest soil loss is estimated in the rangelands (18 t ha-1), sparsely vegetated (bare land) areas (16 t ha^{-1}), cultivated areas (10 t ha^{-1}) and forest areas (8 t/ha). Soil erosion was classified based on severity classes as indicated in Haregeweyn et al. (2017); the results show that 21% of the country is experiencing "Moderate" to "Excessive" soil erosion risk, of which 4% is "Severe" and 6% is "Excessive". The remaining 79% of the country is experiencing "Low" and "Very Low" erosion risk. The finding of this work is consistent with Tsegaye (2019) and Tamene and Vlek (2008). From among the 72 administrative zones in Ethiopia, the highest soil erosion is estimated in Hadiya (45 t ha^{-1}), Dawuro (38 t ha^{-1}), and Wolayita (27 t ha^{-1}), located in the Southern Nations and Nationalities region, and in Wag Hemira (32 t ha^{-1}) and East Gojam (30 t/ha) in the Amhara region. Soil erosion in Ethiopia is one of the most serious causes of soil degradation, which has been directly linked to a substantial decrease in soil fertility and crop yield (Aleminew and Alemayehu, 2020; Taddese, 2001; Yebo, 2015). This underlines the urgent need for soil conservation measures across the country.

Discussion and Conclusions

This study highlights the urgent soil erosion risks affecting Ethiopia's rangelands, revealing critical insights for sustainable land management in regions essential to the livelihoods of pastoralists and agropastoral communities. The RUSLE-GIS-based analysis illustrates that rangeland, covering the majority of Ethiopia's land, face the highest rates of soil erosion, estimated at 18 t ha^{-1} annually. Given that these areas are vital for livestock and agriculture, the findings underscore a pressing need for targeted soil and water conservation practices in Ethiopia's rangelands to mitigate erosion and its adverse effects on land productivity and environmental health.

High rainfall erosivity and soil erodibility in specific regions further exacerbate the erosion risk, particularly in Hadiya, Dawuro, Wolayita, Wag Hemira, and East Gojam zones, which show some of the highest soil loss rates. This calls for immediate action in these zones through localized erosion control practices, emphasizing sustainable land management practices like reforestation, conservation tillage, and optimized grazing management to protect soil resources.

The study's findings reinforce the need for policy interventions that prioritize soil conservation strategies, particularly in the most vulnerable rangelands. Integrating these practices into Ethiopia's broader environmental policy and development programs could significantly alleviate soil degradation. Further research could refine the model by incorporating additional local data, enabling even more accurate soil erosion mapping and, ultimately, more effective interventions. In conclusion, this study offers a critical foundation for advancing Ethiopia's land conservation efforts, aiming to support sustainable land use while protecting vital rangeland ecosystems.

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THEME 6. LIVESTOCK PRODUCTION SYSTEMS IN A WORLD OF CHANGING DRIVERS

Animal productivity

A general faecal nitrogen model for estimating intake in cattle and sheep fed multi-species native forage

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Key words: faecal crude protein; grazing; Pampa biome; rangeland; ruminant

Abstract

The Rio de la Plata grassland ecoregion in southern America, which includes Uruguay, south of Brazil and part of Argentina, plays a crucial role in providing feed to livestock in outdoor extensive production systems due to its high plant species richness, chemical composition and annual production. Estimating animal intake in this heterogeneous grassland environment poses a significant challenge. Therefore, our goal was to develop a general linear regression model based on faecal nitrogen excretion (FNe) to estimate organic matter (OM) intake in cattle and sheep fed multi-species native forage using data from different zones of the Rio de la Plata region. We collated data from previous studies conducted based on the same protocol in Brazil and Uruguay, comprising 219 individual observations (72 from cattle and 147 from sheep); 15 data points from sheep in Uruguay remain unpublished. The trials were conducted using metabolism cages and animals were fed fresh or hay native forage. Mixed linear models were developed using R software. The best-fitting model was selected based on the Bayesian information criterion (BIC) and Akaike information criterion (AIC). The predictive accuracy of the fitted OM intake model was evaluated using 5-fold cross-validation. The resulting linear regression model revealed a positive relationship between FNe and OM intake ($p < 0.001$; $R^2 = 0.851$) across the entire dataset [Intake (g OM/kg BW/day) = 3.335 + 106.321 × FNe (g N/kg BW/day)]. The animal species effect was not significant ($p = 0.337$). Pearson correlation between predicted and observed values of the animal forage OM intake model was 0.957, with a root mean square error (RMSE) of 1.598, a mean absolute error (MAE) of 1.241 and a concordance correlation coefficient (CCC) of 0.937. In conclusion, our findings highlight that a general linear regression model, developed using combined data from both cattle and sheep, can be used to precisely estimate OM intake using FNe for animals fed multi-species native forage from the Río de la Plata region.

Introduction

In the Rio de la Plata region of South America, which includes all of Uruguay, the central-eastern part of Argentina, and a portion of southern Brazil (Baeza and Paruelo 2020), most ruminants graze on native grasslands. These grasslands are characterised by highly diverse native vegetation (Andrade et al. 2018), with a rich variety of plant species that create a heterogeneous environment. Therefore, estimating animal forage intake in this grazing environment is challenging. To address this, several studies have focused on developing specific linear regression models using faecal nitrogen excretion (FNe) to estimate organic matter (OM) intake in beef cattle and sheep fed native forage in Brazil (Kozloski et al. 2018; Azevedo et al. 2024) and Uruguay (Tafernaberry et al. 2024). These studies indicated that it is possible to develop accurate models for estimating OM intake in cattle and sheep separately or together for southern Brazil forage based on FNe. Given that faecal nitrogen is a well-established proxy for estimating intake in ruminants (Lancaster 1949; Peripolli et al. 2011), an important question arises: can a single model reliably estimate OM intake for both sheep and cattle fed native forages with similar vegetation across different zones of the Rio de la Plata region? We hypothesize that a general linear regression model can accurately predict OM intake for both species using data from different zones of the Rio de la Plata region. The objective of this study was to develop and validate a general linear regression model using FNe to estimate OM intake in cattle and sheep fed multi-species native forage from the Río de la Plata region.

Methods

This study was conducted using a comprehensive database compiled by researchers from Uruguay and Brazil. The database included data from previous experiments performed between 2014 and 2022 with beef cattle and sheep housed in metabolism cages and fed fresh or hay-preserved multispecies native forages typical of the Rio de la Plata region in South America ($n = 219$). Most of the data in this database ($n = 204$) have been previously published in peer-reviewed scientific articles (Kozloski et al. 2018; Azevedo et al. 2024; Tafernaberry et al. 2024). However, 15 data points from sheep in Uruguay remain unpublished. Of the 219 individual observations, 72 were from steers (Angus and Hereford breeds) and 147 were from male sheep (Corriedale and Texel × Corriedale crosses). The body weight (BW) of the animals was 273 ± 73 kg for steers and 38 ± 9 kg for sheep, respectively.

All experiments adhered to a consistent methodology as described by Rymer (2000). Briefly, in all experiments, all animals had a 5-day acclimatisation period in metabolism cages before starting the 10-day adaptation period to the different amounts of forage offered, followed by a 5-day period for forage and faeces sampling. During the first 5-day acclimatisation period, the same amount of forage (*ad libitum*) was offered to all the animals, while during the following 10-day adaptation period to the treatments and the 5-day sampling, they received different amounts of forage, which corresponded to their treatment. The treatments in each trial differed, but in general, animals were receiving forage in daily amounts ranging between 15 and 25 g of dry matter (DM) per kg BW or *ad libitum*. When forage was offered fresh, every day, the forage required to feed the animals was harvested using a mower and stored overnight in a refrigerator. For the trial in which animals were fed hay, native forage was cut 3 cm above the ground, dried in the field, and stored in a shed for later feeding. Fresh forage or hay was offered twice a day (at 8 and 17 h) to animals individually according to their BW and treatment. Every morning, prior to feeding the animals, forage refusals of each animal from the previous day were removed and weighed. During the 5-day sampling period, samples of offered and refused forage were collected, oven-dried at 55°C, and ground (1 mm) for subsequent analysis of DM and OM; these data were used to determine OM intake. To estimate daily faecal excretion, each animal was equipped with a harness and bag. Dung bags were emptied once daily for sheep and twice daily for cattle before feeding. The total daily fresh faecal excretion of each animal was weighed and homogenized. A sub-sample representing 20% and 10%, for sheep and cattle, respectively, was taken from the total and oven-dried at 55°C for subsequent analysis of DM, OM, and nitrogen.

The analysis, performed in R software, aimed to develop and validate a predictive mode for OM intake using FNe as a predictor in linear mixed-effects models. Five candidate models, each including animal species (sheep and cattle) as a fixed effect and differing in random effects structures, were compared using Akaike information criterion (AIC) and Bayesian information criterion (BIC). The coefficient of determination (R^2) and Pearson correlation (r) were calculated to assess the model's explanatory power, while ANOVA was used to test the significance of fixed effects. The predictive accuracy of the fitted OM intake model was evaluated using 5-fold cross-validation (James et al. 2014), where the dataset was randomly split into 80% training and 20% testing subsets for each fold. Performance metrics included mean absolute error (MAE), root mean squared error (RMSE), concordance correlation coefficient (CCC), and Pearson correlation (r), ensuring a comprehensive evaluation of predictive accuracy.

Results

Figure 1a shows the representation of the best model developed to estimate OM intake in sheep and beef cattle fed native forage. The resulting linear regression model revealed a positive relationship between FNe and OM intake ($p < 0.001$; $R^2 = 0.851$) across the entire dataset [Intake (g OM/kg BW/day) = 3.335 + 106.321 × FNe (g N/kg BW/day)]. The best model was identified as having animal species as a fixed effect and random effects structured as ~1|Trial, and showed the best predictive performance, with the lowest AIC (945.7) and BIC (962.5). The animal species effect was not significant ($p = 0.337$).

The cross-validation using the model developed in this study is shown in Figure 1b. Pearson correlation between predicted and observed values of the animal forage OM intake model was 0.957, with an RMSE of 1.598, an MAE of 1.241 and a CCC of 0.937.

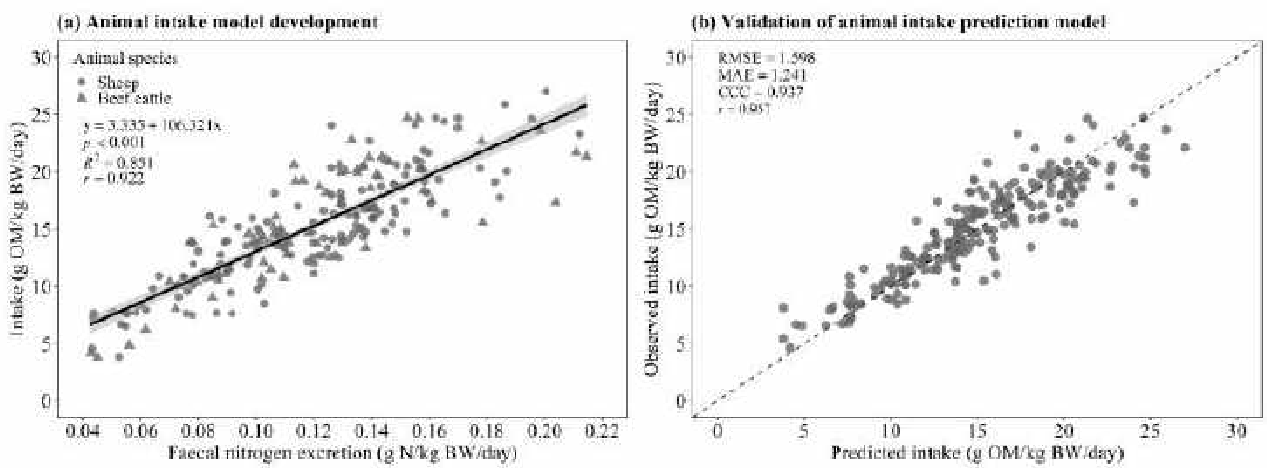

Figure 1. Relationship between faecal nitrogen excretion and organic matter intake in beef cattle and sheep (a) and predicted and observed animal organic matter intake validation using the developed model (b).

Discussion

This is the first study to utilize a database comprising 219 individual observations (72 from cattle and 147 from sheep) from two countries within the Rio de la Plata region to develop a general model for estimating forage intake in both beef cattle and sheep fed native forage, using FNe. The previous studies using sheep and cattle fed native forage in this region proved that the FNe can be precisely used to estimate intake in those animals (Kozloski et al. 2018; Azevedo et al. 2024; Tafernaberry et al. 2024). Nevertheless, the primary goal was to develop a single linear model using combined data from both beef cattle and sheep to estimate their intake. Our hypothesis was that this approach would be feasible. The results confirmed this hypothesis: FNe has a strong relationship with OM intake, regardless of the animal species. This finding demonstrates that a single general model can precisely ($r = 0.922$; Figure 1a) and accurately ($r = 0.957$; Figure 1b) estimate intake in both sheep and cattle consuming this multispecies native forage. Therefore, this represents a significant advancement in pasture and animal science in our region, particularly within the context of heterogeneous environments such as multispecies native grasslands. In conclusion, our findings support the hypothesis that a general linear regression model, developed using combined data from both beef cattle and sheep, can be used to precisely estimate OM intake using FNe for animals fed multi-species native forage from the Río de la Plata region in South America.

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Comparison of equations to predict the metabolizable energy content as applied to lucerne

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Key words: Forages; energy prediction; digestibility; feed assessment; feeding systems

Abstract

Metabolisable energy (ME) intake determines productivity in ruminant production systems and estimates of the ME content of feeds underpin nutritional production models and feeding standards across the world. An inaccurate estimation of ME content of a feed means nutritional models and decision support tools are erroneous, resulting in significant variance in expected liveweight gain or carrying capacity of a pasture. Currently in Australia there are a range of equations used to estimate ME of feeds. Utilising appropriate ME equations suitable for Australian forages, in this case, lucerne, is vital for predictive modelling for production and for any required ration or supplement formulation. The current study compared 24 ME equations in lucerne. Lucerne samples were taken at four different vertical strata grown in field trials of plants of different heights to generate samples of differing nutrient quality.

This research demonstrated that different ME estimation equations generate different ME values for the same lucerne sample. This is exemplified with ME values ranging from 10.25 to 16.58 MJ ME/kg DM for a sample in the top strata, and 7.7 to 13.75 MJ ME/kg DM for another sample in the bottom strata. The Minson (1984) equation, ME (MJ/kg DM) = 0.157 DOMD + 0.059 CP – 1.073, appeared the best equation to use for lucerne according to its lowest SD. This was congruent to the ME equation analysis for forage sorghum samples (Lwin et al. 2022).

This study did not determine which equations were biologically correct, however ME equations based on a combined regression using DOMD and CP parameter were most suitable for use in both forage sorghum and lucerne. This work needs to be validated across multiple forages in Australia to develop ME feeding standards for wider and improved applications for the extensive grazing industry.

Introduction

The ME is a nutritive characteristic and cannot be determined using standard analytical techniques. Feed ME values are estimated via regression equations based on chemical composition (Weiss et al. 1992), estimation of digestibility with *in vitro* methods (Minson 1984; Givens et al. 1990) or gas production methods (Menke &

Steingass 1988; Robinson et al. 2004). These regression equations were originally developed on the basis of calorimetry feeding trials and then related to analytical attributes of a dataset of feeds. Over time, many ME equations have been derived independently using different feed datasets. Equations are then applied, often without consideration of the dataset and parameters with which the equation was determined.

There is limited standardisation of ME equations in Australia. Feeds can be analysed by different methods, using different ME equations through domestic laboratory services but also international laboratory services. Feed ME values can also be obtained by nutritional text feeding tables or using online nutritional tables such as feedipedia. The different equations cause a disparity in ME estimations, particularly in tropical forages. Discrepancy between ME equations was established by Robinson et al. (2004). This work compared and evaluated six ME equations to predict ME based on chemical and *in vitro* components, from US (NRC 2001, University of California at Davis (UC Davis)) and UK (Agricultural Development and Advisory Service - ADAS: Morgan 1972) across a range of feeds. They concluded that no procedure they assessed was able to reliably predict the ME values determined *in vivo* for all feeds. Additional to this in Australia, McLennan (2005) found that ME content estimated by the Australian feeding system standards such as SCA (1990) or Nutrient requirements of domesticated ruminants (NRDR) (Freer et al. 2007) and the Cornell net carbohydrate and protein system (CNCPS) (Fox et al. 2004), which is also commonly used in Australia, differed in tropical forages. Furthermore, Lwin et al. (2022) demonstrated in a study comparing 24 ME equations, that vastly different ME values were generated for each of the 120 forage sorghum samples, and that most equations were not comparable, nor did samples rank similarly across ME equations.

There is a lack of agreement on the appropriate ME equation to use across different environments and production systems in Australia. Livestock production models often use different ME equations to derive intake of ME and predict ruminant production (Robinson et al. 2004). Given the variability between ME equations and lack of information on contextual appropriateness of different models, it is not surprising that these models do not often agree with production results observed in the field. This is particularly so in the predictive productive performance of ruminants fed subtropical forages. Overestimation of ME in a feed will be associated with lower in field production values. This is particularly apparent in tropical forages, as the high NDF content (particularly indigestible NDF) also limits feed intake.

This study aims to compare ME equations to predict the ME content of lucerne. The study objectives were (1) to establish if ME values differed for each lucerne sample and, (2) establish the most appropriate ME predictive equations for lucerne (Best Bet). Appropriate ME assessment will improve the accuracy of ration formulation and production modelling, and integration in existing decision support tools will enable producers to make more informed grazing, supplementation and animal management decisions to maximise productivity.

Methods

Lucerne samples

The lucerne variety, Titan seven was grown at Gatton Research Facility (27°32′45″S, 152°19′44″E) during 2018 and 2019. Different heights of lucerne pasture were sampled. At sampling, plants were harvested 5 cm above the ground, plant height measured, then samples were cut into four equal vertical strata (Benvenutti et al. 2016) tagged and placed into labelled sample bags. Samples were dried in an oven at 60ºC and ground through a 2 mm screen (Retsch Mühle rotary grinder, Germany). A total of 96 samples were selected from a large sample set and used for further analysis. These samples were selected to represent a diverse range of nutritional parameters.

Laboratory analysis

Subsamples were sent to the Dairy One Forage testing laboratory (Ithaca, NY, USA) for nutritional analysis according to CNCPS. Samples were analysed to determine crude protein (CP), ethanol-soluble carbohydrates, lignin, crude fat, acid detergent fiber (ADF), amylase, sodium sulfite treated neutral detergent fiber (NDF) and mineral content by using wet-chemistry services (Dairy One 2007). The Dairy One Forage Lab uses a multiple component summative approach, using total digestible nutrients (TDN) for ME prediction employing a CNCPS approach (Eqn 1 in Table 1).

Subsamples were further analysed locally by using an *in vitro* two-stage rumen fluid pepsin procedure (Tilley and Terry 1963) modified for a Daisy ANKOM system. Estimations were made of dry-matter digestibility (DMD), organic matter digestibility (OMD) and digestible organic matter in the DM (DOMD; Holden 1999). Organic matter (OM) was determined by ashing dried samples at 600°C in a muffle furnace (Modutemp, Midvale, WA, Australia) for 3 hours. Ash-free NDF content was determined according to the method of Goering and Van Soest (1970) modified by Mertens (2002), by using the ANKOM system (ANKOM 200 Fiber Analyzer, Macedon, NY, USA). Other required values for equation application were derived from Dairy One laboratory analysis.

Metabolizable energy equations

A total of 24 equations were used to estimate the ME content in lucerne samples (Table 1). These same equations were applied for the Lwin et al. (2022) study and obtained from a range of Australian, UK and USA feeding standards. All ME equations were utilized for forages.

Table 1. Estimation of ME from different equations in analysis of lucerne samples

Equation number	Author	Equation
Equations based on chemical composition		
1	CNCPS (Fox et al. 2004)	DE (MJ/kg DM) = ((TDN%/100) x 4.409) x 4.184
	NRC (2001)	ME (MJ/kg DM) = ((DE (Mcal/kg DM) x 1.01) – 0.45) x 4.184
2	Minson (1984)	a) ME (MJ/kg DM) = 0.260 CP (%) + 4.653
		b) ME (MJ/kg DM) = 21.574 – 0.207 NDF (%)
		c) ME (MJ/kg DM)) = 16.654 – 0.241 ADF (%)
		d) ME (MJ/kg DM) = 13.764 – 0.165 CP (%) – 0.118 NDF (%)
		e) ME (MJ/kg DM) = 10.738 + 0.161 CP (%) – 0.131 ADF (%)
		f) ME (MJ/kg DM) = 7.735 + 0.17 CP (%) – 0.335 lignin (%)
3	Abate and Mayer (1997)	ME (MJ/kg DM) = 8.11 + 0.1341 CP (%) – 0.1065 ash (%)
Equations based on digestibility		
4	ADAS (Morgan 1972)	ME (MJ/kg DM) = 0.84 + 0.14 DOMD (%)

5	Givens et al. (1990)	ME (MJ/kg DM) = 0.37 + 0.0142 DOMD (g/kg DM) + 0.0077 CP (g/kg DM)
6	Minson (1984)	a) ME (MJ/kg DM) = 0.153 DMD (%) – 1.057 b) ME (MJ/kg DM) = 0.15 OMD (%) – 1.126 c) ME (MJ/kg DM) = 0.184 DOMD (%) – 1.827 d) ME (MJ/kg DM) = 0.157 DOMD (g/100g) + 0.059 CP (%) – 1.073
7	AFRC (Alderman and Cottrill 1993)	ME (MJ/kg DM) = 0.0157 DOMD (g/kg DM)
8	NRDR/CSIRO (Freer et al. 2007)	a) ME (MJ/kg DM) = 0.172 DMD (%) – 1.707 b) ME (MJ/kg DM) = 0.169 OMD (%) – 1.986 c) ME (MJ/kg DM) = 0.194 DOMD (%) – 2.577
9	AFIA (2011)	ME (MJ/kg DM) = 0.203 DOMD (%) – 3.001
10	SCA (1990)	a) ME (MJ/kg DM) = 0.18 DOMD (%)– 1.8 b) ME (MJ/kg DM) = 0.16 OMD (%)– 1.8 c) ME (MJ/kg DM) = 0.17 DMD (%) – 2.0
11	Freer et al. (2004)	ME (MJ/kg DM) = 0.172 DMD (%) – 1.71

Where; Dry matter digestibility (DMD) = (feed DM – residual DM)/feed DM

Organic matter digestibility (OMD) = (feed OM – residual OM)/feed OM

Digestible organic matter in DM (DOMD) = (feed OM – residual OM)/feed DM

Statistical analyses

The set of predicted ME values generated by the 24 equations for each of the 96 lucerne samples underwent a series of analyses. Firstly, an ME index was calculated to account for each height stratum within each sample. The ME index was calculated by ranking from lowest to highest, the average ME values for each stratum within each sample across all ME equations. The predictions generated by the different ME equations were then regressed against the ME index by fitting linear mixed effects (LME) models. Model comparisons using Akaike, and Bayesian information criterions indicated that a random slope and intercept structure was optimal. The set of ME equations was narrowed by selecting only those equations whose random slope and intercept fell within the 95% confidence interval of the overall LME fixed effect slope and intercept, i.e., those equations that generated ME predictions closest to the overall mean predictions across all ME equations combined. The 'optimal' ME equation was then identified by selecting the equation from the narrowed subset of equations with the lowest standard deviation of its predictions, i.e., had the lowest variability across the range of ME values tested.

Results

The 24 ME equations had variable ME predictions for each lucerne sample. The full set of 24 ME equations was narrowed to eight preferred equations based on their random slopes and intercepts falling within the 95% confidence interval of the overall fixed effect slope and intercept. These eight equations were all based on digestibility, whether as a sole parameter or digestibility combined with a CP parameter. (equation 6d, 8a, 8b, 8c, 9, 10b, 10c and 11). When SD were taken into account equations: 10b (SCA 1990) was considered Best Bet for the top strata, 6c (Minson 1984) for strata 2, 6b (Minson 1984) for strata 3 and equation 5 (Givens et al. 1990) for the bottom strata. This is not practical to have different equations preferred for the various strata and as such a preferred equation was considered across all strata. These equations that were within the 95% Cl of both fixed effect slope and intercept were then ranked using standard deviations (SD) (Figure 1). The equation with the lowest SD was selected as the Best Bet ME equation for lucerne. The ME equation with the lowest SD was Eqn 6d (ME (MJ/kg DM) = 0.157 DOMD (%) + 0.059 CP (%) – 1.073) (Minson 1984).

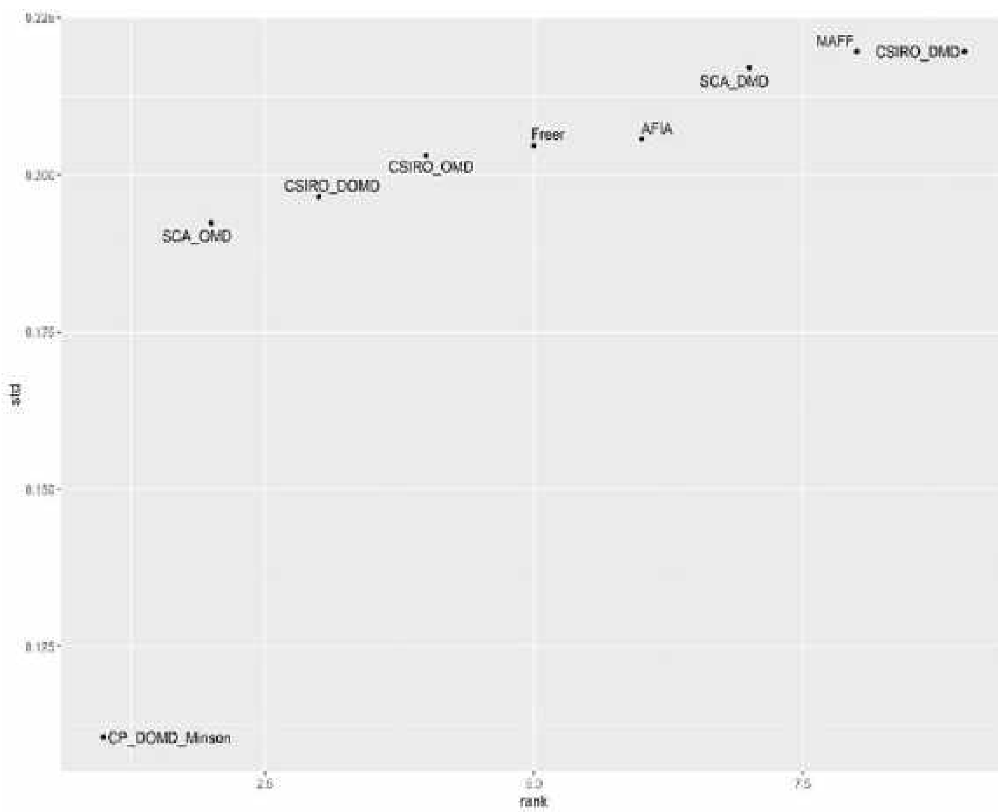

Figure 1. Equations ranked by standard deviations (SD) from lucerne sample dataset. Equations are: CP_DOMD_Minson = Equation 6d, SCA_OMD = Equation 10b, CSIRO_DOMD = Equation 8c, CSIRO_OMD = Equation 8b, Freer = Equation 11, AFIA = Equation 9, SCA_DMD = Equation 10c, MAFF = Equation 9, CSIRO_DMD = Equation 8a. Each equation (Eqn) is defined in Table 1.

Discussion

This research focused on the estimation of ME in lucerne as a model crop for legumes. The ME value is the first limiting nutrient and determines the maximum productivity of the ruminant. The content of ME in feed is most accurately measured via ruminant calorimetry studies (Blaxter & Clapperton 1965) but this is not practical for a feed analysis measurement. As such ME equations have been derived from regression relationships between digestibility or chemical composition with ME values. It is assumed that this relationship varies between feeds and that ME can be predicted satisfactorily by different laboratory methods (Minson 1980). An accurate estimation of ME content is fundamental to accurate prediction of productive performance of ruminants and to better assist producers to make grazing management decisions. The current study compared 24 equations to estimate the ME content in a lucerne dataset of 96 samples. Lucerne samples were taken at four different vertical strata grown in field trials containing plants of different heights. The ME equations were that used by Lwin et al. (2022) and was not an exhaustive list but rather a selection of equations that are utilized in recognized feeding systems. These equations selected were either developed using chemical composition, digestibility data, or a combination of both chemical composition and digestibility data. It was also important to have knowledge regarding the equations associated feed databases such as the number of feeds and type of feeds. Only equations derived from forage databases were utilized.

Our research shows for each individual lucerne sample, different ME estimation equations will give vastly different ME values. Similarly, Lwin et al. (2022), using the same equations for comparison, observed very different ME estimations on individual forage sorghum samples. In many of these samples, ME estimations were not biologically sensible (over 17 MJ/kg DM). This variability in estimations was even greater in higher quality lucerne (top strata 1 and 2) compared to lower quality forage (bottom strata 3 and 4). This variability between ME estimations for the same sample in this research using legumes and also in Lwin et al. (2022) using a topical grass, exemplifies the importance of utilizing appropriate ME equations. Utilising an ME equation that is not suitable for a feed type would likely provide incorrect ME values. It is also imperative to know the derivation of feed ME values (when using feed laboratories or feed table values) when comparing different feeds e.g. for ration formulation, as this research has shown that there will be major inconsistencies when comparing ME values from different equations.

As with the Lwin et al. (2022) equation analysis for forage sorghum, this study with lucerne samples, could not definitively determine which equation was biologically correct, however through a series of statistical approaches, these equations were compared and Best Bet equations were ascertained. For lucerne, ME equations using a digestibility parameter provide acceptable ME estimations compared to those equations based solely on chemical composition. In particular, the equations based on a combined regression using the parameters digestible organic matter in the DOMD and CP were most suitable for use, The predicted ME equation from Minson (1984) based on CP and DOMD is the best equation to use for lucerne according to its lowest SD which is ME (MJ/kg DM) = 0.157 DOMD + 0.059 CP – 1.073. These results are congruent to the ME equation analysis for the forage sorghum study.

Utilizing digestibility as a parameter in an ME estimation equation is biologically appropriate. ME is the energy in the feed remaining after subtracting the energy of the faeces, urine and combustible gases such as methane. There is a biological correlation of ME with digestibility (Alderman and Cottrill 1993; Freer et al. 2007). Minson (1984) further discussed that ME has a high correlation with DMD and OMD with lower error compared to feed ME estimations from chemical composition when working with *Digitaria setivalva*. Similarly, Armstrong (1964) noted less SD of ME estimation from digestibility based values compared to utilizing chemical composition attributes in sixteen grasses.

The inclusion of CP as a parameter is also significant. The calorific value of digestibility of OMD has a significant relationship with CP as higher digestibility occurs with increasing proportion of CP in forages (Terry et al. 1974) attributable to a higher N supply for microbial activity (Satter and Slyter 1974). The protein also when broken down is a further source of energy to the animal that needs to be accounted for. Lwin et al. (2022), in an analysis of 24 ME equations found, using forage sorghum as a sample set, the Best Bet equations were DOMD and CP from Givens et al. (1990) and Minson (1984). As such, based on the current research, ME equations which utilized the parameters of DOMD and CP can be used universally in both tropical grasses and lucerne. Moreover, the Best

Bet equation from CP and DOMD in Minson (1984) can easily be analyzed in the laboratory and also obtained through faecal NIRS estimates from rangeland animals.

Conclusion and implications

There is a need for agreement on the appropriate ME equation to use in various production systems, as this will improve the accuracy of ration formulation, and importantly for grazing management decisions and livestock production modelling.

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Assessing risk of plant-associated toxicosis using sentinel farms and historical records

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Key words: tall fescue; fescue toxicosis; ergovaline; ergopeptine alkaloids; species composition; cool-season pasture

Abstract

Assessing toxicity of grassland/rangeland plants and their impact on livestock production and morbidity is an issue around the world. Tall fescue (*Schedonorus arundinaceus* Schreb.) is a naturalized grass species occurring on over 14 million ha in the USA with the majority infected with a fungal endophyte that produces ergopeptine alkaloids (primarily ergovaline). The objective of this paper is to show how an innovative pasture evaluation system at the University of Kentucky has been used to incorporate plant toxicity information and species composition measurements to assess risk to livestock. Over the last 20 years over 500 horse farms have been intensively evaluated to determine total botanical composition and the ergovaline content of tall fescue present in pastures. Using various strategies, these measurements have been used to develop risk categories, which have then been communicated to the farms to enable stocking decisions. This project will establish sentinel farms that will provide additional information on seasonal variability for ergovaline levels and the potential impact on livestock. This assessment strategy can be used to assess risk to livestock in many ecological regions around the world.

Introduction

Traditional methods to alleviate risk of plant-associated poisonings in livestock on rangelands and grasslands have been to monitor species composition and livestock health and then to avoid/reduce exposure or remove toxic plants by mechanical or chemical methods (van Raamsdonk et al. 2015). There are situations where the plants of concern are endemic and/or compromise a major component of a grassland system. For example, the tall fescue cultivar Kentucky 31 (KY-31) was widely planted in the eastern USA after being released in 1943 because of superior persistence, long growing season, and biomass production. It is now considered a naturalized species and occurs on 14 million ha in the USA. In the 1980's, it was discovered that the persistence of KY-31 was primary due to the mutualistic relationship with a fungal endophyte (*Acremonium coenophialum*). Unfortunately, this endophyte produces toxic ergopeptine alkaloids which cause a range of symptoms which vary depending on livestock species. Pregnant broodmares in the last 30-60 days of gestation are most sensitive (Bacon, 1995). Ergovaline and other ergopeptine alkaloids consistently cause decreased or absent colostrum and milk production in late-gestational mares and failure of passive transfer in their foals. Other effects in mares include prolonged pregnancy, dystocia, premature placental separation, and other reproductive abnormalities. Dysmaturity, overmaturity, postmaturity, and septicemia can occur in foals. In cattle, low weight gain, reduced pregnancy rates, decreased milk production, and temperature-dependent effects of vasoconstriction (e.g., heat stress during warm temperatures or sloughing of hooves, ears, and tail switches during extreme cold). Non-toxic endophyte-free and novel endophyte tall fescue cultivars have been developed, but it is not feasible to replace all 14 million ha due to the terrain of many farms, reduced persistence, and the cost of reestablishment. When properly managed, toxigenic tall fescue can be a useful or at least a tolerated species in grasslands.

The effects of toxic tall fescue on pregnant mares can be significant, but risk is difficult to evaluate. While testing for endophyte presence and ergovaline concentration are easily conducted, a true risk assessment must include an estimation of the amount of tall fescue in the diet. Ergovaline concentrations also vary seasonally and based on pasture management. The University of Kentucky (UK) Horse Pasture Evaluation Program combines ergovaline and endophyte testing with species composition data to objectively assess the risk to horses grazing individual pastures, assist farms in “triage” of pastures, and help determine when mitigation and management strategies can be utilized or when complete renovation is recommended. Additionally, several farms have committed to becoming sentinel farms and conduct monthly sampling of pastures to inform the entire livestock industry in the region when ergovaline levels are increasing or decreasing in general.

Methods

To evaluate livestock risk on pastures, “Ergovaline in Total Diet” is calculated using the percentage of tall fescue in the pasture compared to other available forages, and the concentration of ergovaline within tall fescue plants.

Species composition is determined using an occupancy method (Payne et al., 2023; Vogel and Masters, 2001) with 75cm x 75cm wire grids that contain 25 smaller squares, 15cm x 15cm. Each smaller square is evaluated individually for botanical composition and the most dominant species or category is recorded. Species and categories include tall fescue, Kentucky bluegrass (*Poa pratensis* L.), orchardgrass (*Dactylis glomerata* L.), white clover (*Trifolium repens* L.), broadleaf weeds, nimblewill (*Mulenbergia schreberi* J.F Gmel.), warm-season annual grasses, bare soil and “other forages”. Grids are randomly placed at 10 to 20 locations depending on pasture size with a normal range of 0.25 ha to 16 ha. By evaluating all plant species and not just the amount of tall fescue present, the amount of tall fescue in the grazing diet can be calculated, and other management recommendations such as seeding and broadleaf weed control can be tailored to the needs of the pasture.

Grab samples of tall fescue material are also collected from 10-20 locations within the pasture at average grazing height, ranging from 7 to 10 cm from the soil. These samples are submitted to the University of Kentucky Veterinary Diagnostic Laboratory for analysis. Details on sampling, handling during transport and storage and analysis can be found in Lea et al. (2014). The total concentration of ergovaline plus its epimer ergovalinine is reported on a dry matter basis in parts per billion (ppb) within the tall fescue sample.

Previous research suggests that horses graze different forage species in similar proportions to how they are present in the pasture (Morrison et al., 2008). Therefore, the species composition data collected and the ergovaline analysis can be combined to calculate ergovaline in total diet using the formula below:

$$\left(\frac{\%\ \text{TF}}{\%\ \text{TF} + \%\ \text{BG} + \%\ \text{OG} + \%\ \text{WC} + \%\ \text{OF}} \right) \times \begin{array}{c}\text{Ergovaline}\\ \text{(ppb)}\end{array} = \begin{array}{c}\text{Ergovaline in}\\ \text{Total Diet (ppb)}\end{array}$$

Figure 3. Formula for calculating ergovaline in total diet.
(TF=Tall Fescue; BG = Kentucky Bluegrass; OG = Orchardgrass; WC = White Clover; OF = Other Forages

Results

Assessment of Pastures by calculating Ergovaline in Total Diet

Using the calculation of Ergovaline in Total Diet instead of simply ergovaline concentration or tall fescue percentage provides farm managers with additional stratification of pastures when evaluating the farm as a whole. Table 1 contains an example abbreviated datasheet containing several pasture species compositions and ergovaline concentrations.

Table 1. Abbreviated datasheet from a Lexington, KY, USA, area horse farm.

Pasture	Acres	%Tall Fescue	% Desirable Forages	% Undesirable Components	Ergovaline (ppb)	Ergovaline in Total Diet (ppb)
Pasture 6	29.7	7	88	5	309	23
Pasture 7	31.1	68	31	1	119	81
Paddock 3	0.7	67	19	14	384	302
Paddock 10	0.5	17	38	45	564	172
Paddock 12	1.8	63	29	8	741	500

Pasture 7 and paddock 3 and 12 all contained similar percentages of tall fescue (63-68%), however, the ergovaline concentration ranges widely (119 – 741 ppb). Therefore, ergovaline in total diet was quite low in pasture 7, high in paddock 12, and moderate in paddock 3. Pasture 6 and paddock 10 contained less tall fescue and only moderate ergovaline levels, but very different amounts of desirable forages. Pasture 6 contained a high percentage of other desirable forages, therefore ergovaline in total diet was very low (23 ppb). Paddock 10 contained a high percentage of undesirable components, limiting ergovaline dilution in the diet and resulting in a higher ergovaline in total diet (302 ppb).

Data such as this allows horse farm managers to select pastures that can be grazed without additional management (pastures 6 and 7), pastures that need improved management to reduce tall fescue (paddock 10), and pastures that likely need total renovation (paddock 12),

Use of Sentinel Farms to Monitor Seasonal Ergovaline Concentrations

Ergovaline is known to vary throughout the year and typically produces a spike in the spring in conjunction with seed production and a secondary, smaller spike in the fall coinciding with fall growth (Figure 2). However, in recent years the monitoring of sentinel farms has shown that the fall spike can plateau and remain high for months. Climatic conditions in years where ergovaline levels have plateaued in the fall have had warm, dry falls followed by consistent precipitation and mild early winter conditions.

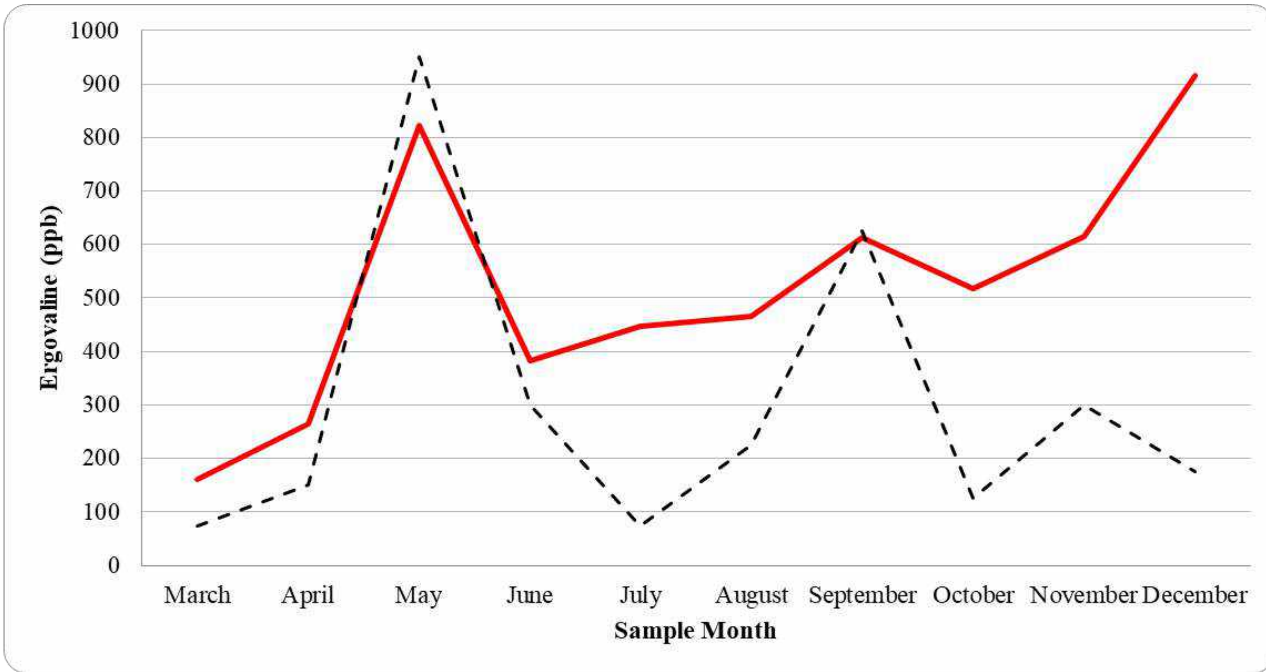

Figure 2. Seasonal variation of ergovaline concentration.

Figure 2 presents data from a single pasture in 2007 (dotted black line), showing the "normal" ergovaline concentrations across the year including a significant spring spike and a smaller fall spike. The red line represents data from many farms that were part of the UK Horse Pasture Evaluation Program in 2023. With an exceptionally dry fall and mild early winter, ergovaline concentrations remained high and even increased from October through the end of the year. Mares due to foal in January would be at their most susceptible stage during November/December (last 30-60 days of gestation) and the risk of complications such as prolonged gestation and dystocia, low or no milk production and thickened, retained placenta, would be greatly increased (Boosinger et al., 1995).

Discussion

Other research focusing on toxic plants in grasslands and rangelands have also shown the benefits of evaluation of the whole system when considering the impact of toxic plants. Pfister et al. (2002) stressed the importance of recognizing the factors that contribute to livestock poisoning, such as environmental conditions, changes in plant composition and animal behaviour. Holechek (2002) found that "poor" range management was not always corelated with livestock losses to poisonous plants and that management of such plants is more complex than just improved overall management. Finally, Krueger and Sharp (1978) found that precipitation and temperature can also influence plant growth, which in turn affects the distribution and palatability of toxic plants. Livestock managers need to adapt their management strategies based on a range of factors including weather, species composition, and animal behaviour. The UK Horse Pasture Evaluation Program has demonstrated a method of forage evaluation and sentinel farm monitoring that helps to inform horse farm managers of the relative risk posed by each pasture using the following categories: very low, low, significant, high, and very high. This allows them to make more informed decisions and can serve as a model for other evaluation methods in grasslands and rangelands.

In conclusion, reducing risk by monitoring species composition and toxin concentration has proven effective with tall fescue and this or similar methods have potential application for managing non-lethal toxic plants on rangelands and grasslands worldwide.

Acknowledgements
The authors of this paper would like to thank the numerous students that have assisted in data collection and the horse farms that have been part of the UK Horse Pasture Evaluation Program and supported on-going research at the University of Kentucky. We also want to thank USDA-ARS-FAPRU unit in Lexington, KY for providing supplemental funding for the graduate students who have worked on the project.

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Feeling the heat: a retrospective investigation of thermal load impacts on calf loss

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Key words: northern Australia; heat load; calf loss; pasture utilisation; body condition

Abstract

Northern Australia's beef industry annually experiences high heat loads and variable pasture conditions, yet their impact on reproductive wastage remains relatively unquantified. This study analysed retrospective herd data (26,903 cow-production years; 17 herds) to identify predictors of foetal and calf loss (FCL) in northern Australia, integrating climatic, pasture, and animal-level variables. Multilevel logistic regression revealed animal class, lactation status, relative pasture utilisation rate, body condition score and calving period as major factors. Counterintuitively, monthly heat stress indices (CCI) showed no direct association ($p=0.59$), potentially masked by monthly averaging or its effect moderated by other factors contained in the model. These results further underscore the importance of grazing and nutritional management in mitigating reproductive losses in northern beef cattle herds.

Introduction

Approximately 60% of Australia's national cattle herd is in northern Australia, encompassing Queensland, the Northern Territory and the northern regions of Western Australia (Bray et al., 2016). Beef production in a major industry in the region, characterised by extensive grazing on native pastures with limited augmentation with legumes. The breed composition is predominantly Bos indicus, due to its adaptability to the tropical and subtropical climate.

Northern Australia experiences extreme heat and humidity during summer, with temperatures frequently exceeding 35°C and relative humidity levels above 70%(Gaughan et al., 2010). Such conditions pose significant risks of heat stress in livestock, a metabolic state arising when heat accumulation surpasses an animal's capacity for thermoregulation (Brown-Brandl, 2018). Heat stress manifests in reduced feed intake, impaired growth and diminished milk production. The adverse effects of heat stress on reproductive performance (including reduced fertility rates, prolonged calving intervals, and elevated embryonic loss) are well-documented, though research has predominantly focused on dairy production systems (Takahashi, n.d.).

The repercussions of heat stress extend to neonatal health and immunity. Late-gestation heat stress in cows has been linked to reduced circulating immunoglobulin levels and suppressed milk yield (Monteiro et al., 2016). For calves, colostrum intake within the first hours of life is critical for establishing passive immunity, a key determinant of morbidity and mortality reduction in beef herds. Heat stress exacerbates dehydration risk in neonates due to suppressed milk supply, impaired thermoregulatory capacity and reduced suckling behaviour. Compounding this, heat-stressed calves exhibit suppressed immune function, increasing disease susceptibility(Tao et al., 2018).

This work formed part of the broader *Sweet Spot* project, which developed a retrospective dataset to investigate the relationship between pasture utilisation and reproductive performance of beef breeding females in northern Australia. This paper reports the results of an explanatory analysis determining the impacts of pasture and environmental conditions during the month of calving influenced the risk of calf loss. Additionally, parameters associated with beef breeding females and pasture conditions were investigated to assess their impact on losses between confirmed pregnancy and weaning.

Methods

A retrospective animal performance dataset was constructed by collating herd records from participating properties using a standardised data template. This template captured individual animal identifiers (e.g., electronic and visual ID, breed, location), management group details (e.g., age class, paddock), and muster-event variables such as body condition score (BCS), lactation status, pregnancy status, foetal age, live weight, and dates. To ensure consistency, farm-reported BCS scales were standardised to a 1–5 system, and heterogeneous Excel datasets were merged into a unified format. This enabled longitudinal tracking of individual females across annual production cycles, defined as the interval between consecutive pregnancy-testing musters.

Losses between pregnancy and weaning were assessed using annual pregnancy status (binary: 1 = pregnant, 0 = not) and lactation status. Using an assumed gestation length of 285 days, the month of conception and expected calving month were estimated based on foetal age and the date of pregnancy testing, pregnancies were assigned to an annual production year, with a September 1 cutoff for conception. Advanced pregnancies detected post-September were attributed to the subsequent cycle. Lactation status classified females as lactating or non-lactating. Calf loss occurred when a female confirmed pregnant in year t was non-lactating post-calving in year $t+1$, with successful rearing requiring lactation confirmation.

Climatic conditions during the month of expected calving were characterised using historical data sourced from SILO (https://www.longpaddock.qld.gov.au/silo/). To quantify heat stress risk, the Temperature Humidity Index (THI) and Comprehensive Climate Index (CCI) were calculated for each site. For each site, maximum daily index values were then summarised by mean and median and the proportion of days exceeding established heat stress thresholds.

Pasture dynamics were modelled for the annual growth cycle (1 October – 30 September) across 60 paddocks in northern Australia as part of the *Sweet Spot* project. The GRASP model (Rickert et al. 2000) was applied to simulate pasture growth and utilisation, integrating gridded historical climate data from SILO (https://www.longpaddock.qld.gov.au/silo/) supplemented with site-specific rainfall records where available. Modelled pasture growth was calibrated against ground-truthed measurements, including satellite-derived green ground cover and paddock-level Total Standing Dry Matter (TSDM). To assess pasture conditions during critical reproductive phases, modelled outputs were averaged across three temporal windows: (1) the month of expected calving, (2) the two preceding months and (3) the three-month post-calving period.

Statistical analyses were conducted using R (R Core Team 2024) to evaluate the relationship between pasture and animal parameters and foetal and calf loss. Mixed logistic regression analyses were performed with animal as the unit of analysis with animal within station and year specified as random effects. A forward stepwise modelling approach was applied. Continuous variables were assessed for linear or non-linear trends, and interactions were explored and only biologically plausible interactions retained. Results are reported as adjusted means with standard errors, reflecting adjustments for all model terms.

Results

The starting dataset contained 26,903 rows of data representing a production year for an individual cow. On average, each individual cow contributed 1.76 (95% CI, 1.74-1.77) animal-production years of data for which a valid foetal or calf loss was ascribed. Seventeen herds contributed information to the analytical dataset with a median of 1085 (interquartile range, 500 - 2387) FCL outcomes relating to an individual herd.

The final multilevel model, accounting for hierarchical data structures, which explained the greatest variation in foetal and calf loss contained the fixed effects: animal class (*Heifer, 1st Lactation cow, Mature cow, Aged Cow;* F=8.78, p<0.001), a quadratic polynomial of body condition score (F=3.23, p=0.04), Estimated period of calving (*Jul-Aug, Sep-Oct, Nov-Dec, Jan-Feb, Mar-Apr, May-Jun;* F=1.93, p=0.09), annualised lactation status (*Lactated, Didn't lactate*; F=45.18, *p*<0.001), Pasture utilisation rate relative to recommended safe carrying capacity (continuous; F=24.90, *p*<0.001), average maximum comprehensive climate index for the expected month of calving (continuous; p=0.59) and region category (*NE Qld, South NT, Central NT, North NT;* F=0.93, p=0.48), with a significant interaction between calving period and region (F=4.04, *p*<0.001).

The occurrence of foetal and calf loss was predicted for each factor using the final multilevel model, with predicted probabilities and approximate 95% confidence limits of the mean presented in Figure 1.

Discussion

This paper is one of the few that describes the influence of pasture utilisation and heat load indices in relation to the reproductive performance of free-grazing beef females in northern Australia, specifically foetal and calf loss. However, it is important to acknowledge that the analyses were conducted using a retrospective dataset comprising both research and commercial herd performance data. Consequently, the individual datasets exhibit inherent idiosyncrasies and management practices may have been influenced by trial design and an appropriate level of caution is advised in interpreting the findings presented in this paper.

The final model highlighted the importance of management practices that support the nutritional requirements of pregnant females to maximise reproductive performance. These effects were nuanced by the expected calving period, highlighting the need for tailored nutritional strategies. Notably, pasture utilization rate relative to safe carrying capacity had a strong influence on calf loss, with overstocking leading to increased losses. This finding reinforces the critical role of nutrition in maternal support, particularly through milk and colostrum production. Animal class was a critical determinant. Consistent with previous research findings, heifers were found to exhibit greater calf loss compared to 1st Lactation and mature cows (Fordyce et al., 2022). Heifers generally have higher energy requirements due to the simultaneous demands of growth and lactation, leading to increased competition for nutrients. This heightened demand can result in a negative energy balance, which may negatively impact their reproductive performance. Overall, cows that lactated in the previous reproductive cycle (contributed a weaner) had 3.8 percentage points lower occurrence of calf loss. These findings align with previous research demonstrating that cows with a history of producing calves tend to have improved reproductive efficiency (Fordyce et al., 2022).

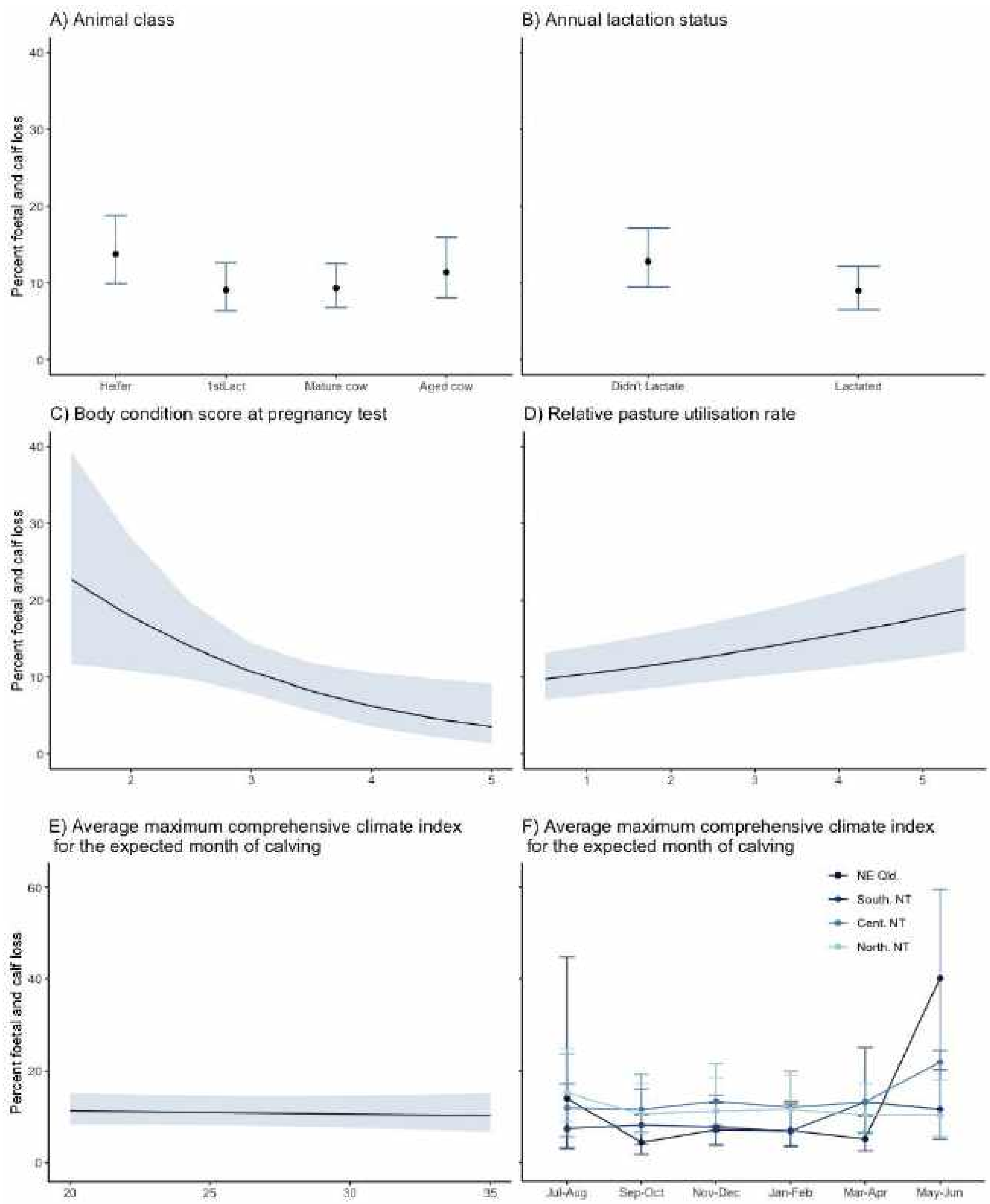

Figure 1: Predicted mean (and 95% confidence limits) occurrence calf mortality across levels of risk factors and their significant interactions identified in the final multilevel logistic regression model. Predictions are based on estimated marginal means adjusted for all variables in the model. Subfigures represent individual risk factor effects or interactions: A) animal class; B) annual lactation status; C) body condition score; D) relative pasture utilisation rate E) average maximum CCI during expected month of calving and interaction between predicting calving period and region.

Counterintuitively, heat stress indices during calving months showed no significant association with calf loss. This absence of a direct relationship may reflect limitations in the resolution of the dataset: monthly averaged CCI values could obscure short-term, acute heat stress events critical to neonatal survival. Alternatively, heat stress impacts may be indirectly mediated through correlated variables in the model, such as calving period, which encapsulates seasonal shifts in both climatic extremes and pasture conditions. Future research should integrate finer-scale heat stress metrics and direct physiological markers (e.g., colostrum IgG levels / calf vigor / actual birth events) when assessing the effects of heat stress on extensively managed beef females.

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Rumination as a measure of heat tolerance: a case study in rangeland beef in northern Australia

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Key words: beef cattle, climate change, heat stress, rumination

Abstract

Climate change poses significant challenges to both productivity and welfare in extensive beef production systems. The identification of heat tolerant individuals is essential for developing resilient herds capable of withstanding increasing temperatures and prolonged periods of heat. The ability to capture relevant phenotypic data for incorporation into genomic evaluation programs, however, remains a significant limitation in extensive environments. This study reports on the use of sensor-based rumination detection to assess individual responses to increasing heat. Thirty-eight cows were equipped with accelerometer ear tags to monitor individual rumination responses to increasing heat during baseline and heat stress periods. The results highlight the potential of a sensor-based rumination detection system to identify heat tolerant individuals in extensive beef systems.

Introduction

Rising global temperatures and the increasing frequency of extreme weather events associated with climate change pose significant challenges to livestock production systems (Godde et al., 2021). In cattle, increased heat is associated with reduced feed intake (Brown-Brandl, 2008), compromised reproductive performance (Dash et al., 2016), reduced growth rates (Lees et al., 2019), and increased mortality rates (Lees et al., 2019). The implantation of strategies to develop heat tolerant herds is essential to ensure the resilience and sustainability of the extensive beef industry in the face of climate change induced pressures – one such strategy is through genomic selection.

A heat tolerance breeding value was initially developed for dairy cattle in 2017 in order to identify individuals that are capable of maintaining a higher milk, fat, and protein yields in hot and humid conditions (Nguyen et al., 2016; Osei-Amponsah et al., 2023). In contrast, developing an analogous breeding value for heat tolerance in extensive grazing systems presents significant challenges, primarily due to the difficulty in collecting relevant phenotypic data due to paddock size and limited animal monitoring and interaction.

Sensor systems offer a promising solution by enabling the continuous collection of behavioural data, supporting phenotype capture in extensive systems. One promising phenotype that is worth exploring is rumination time. Rumination is strongly correlated with a cow's productivity and overall welfare, serving as an indicator of both health and physiological status (Paudyal, 2021).

The integration of sensor systems to monitor rumination behaviour continuously in extensive environments offers an opportunity to generate high resolution phenotypic data that can be used to inform genomic investigations. This study highlights how variations in individual rumination response to heat stress in extensive beef cattle systems can be utilised to support the development of genomic estimated breeding values (GEBVs) for heat tolerance.

Methods

Animal management

This study was conducted at Belmont Research Station (23°13′S, 150°24′ E), 26km north of Rockhampton, Queensland, Australia in November to December 2023. A total of 38 multiparous cows (tropically adapted *Bos taurus*) were grazed in a 65.2 ha paddock. The paddock consisted primarily of alluvial plains, with areas of eucalypt and Brigalow forests. Grass species included spear grass, kangaroo grass, and Queensland blue grass.

Accelerometer ear tags and rumination model

The experimental animals were fitted with Axivity AX3 accelerometer devices (Axivity Ltd., Newcastle, United Kingdom) mounted on modified Allflex Maxi Female ear tags (Allflex Australia Pty Ltd., Murarrie, Australia). The accelerometers recorded data at a sampling frequency of 12.5Hz. Raw accelerometer data was retrieved using the AX3/AX6 OMGUI Configuration and Analysis Tool (Open Movement, Newcastle, United Kingdom). A total of 240 features were generated from the raw data using a mixed model epoch approach (Chang et al., 2022b). A machine learning model for rumination detection was subsequently developed for each animal using the methodology described by Chang et al. (2022a). The individualised rumination models were then applied to calculate daily rumination time across the experimental period.

Weather data

Weather data was obtained from the Bureau of Meteorology station at Rockhampton Aero (site number: 039083), located approximately 16km from the research site. Dry bulb temperature and relative humidity were captured at one minute intervals. The temperature-humidity index (THI) was then calculated at one minute intervals and subsequently summarised to a daily value. The THI was calculated using the formula described in Mader et al. (2006):

$$THI = 0.8 \times T + RH \times (T - 14.4) + 46.4$$

Where

T = dry bulb temperature (ºC)

RH = relative humidity, expressed in decimal form

Statistical analysis

A linear mixed effects model was generated in R using the ‘nlme’ package to evaluate the relationship between rumination time and mean daily THI (Pinheiro et al., 2020). Mean daily THI was a fixed effect, while individual animals were included as a random effect to account for repeated measures (Fogarty et al., 2020). The analysis aimed to establish baseline rumination levels and identify the threshold at which a significant change in rumination time was observed relative to mean daily THI. The proportion of change in rumination time was quantified by comparing the average rumination time before and after the critical THI threshold.

Results

A significant decrease in rumination time was observed when the mean daily THI exceeded 66 (Fig. 1).

Baseline rumination time varied between animals (range: 22.7% – 41.9%). When the mean daily THI reached the critical threshold, rumination decreased across all animals, with a proportionate change ranging from 35.8% to 73.8% (Fig 2).

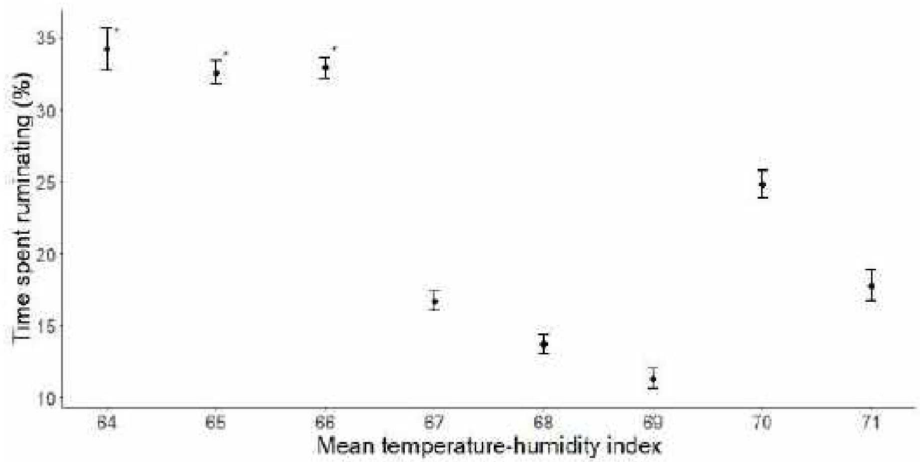

Fig 1. Time spent ruminating vs. mean temperature-humidity index. Significant differences in rumination time between groups are denoted by asterisks (P < 0.05).

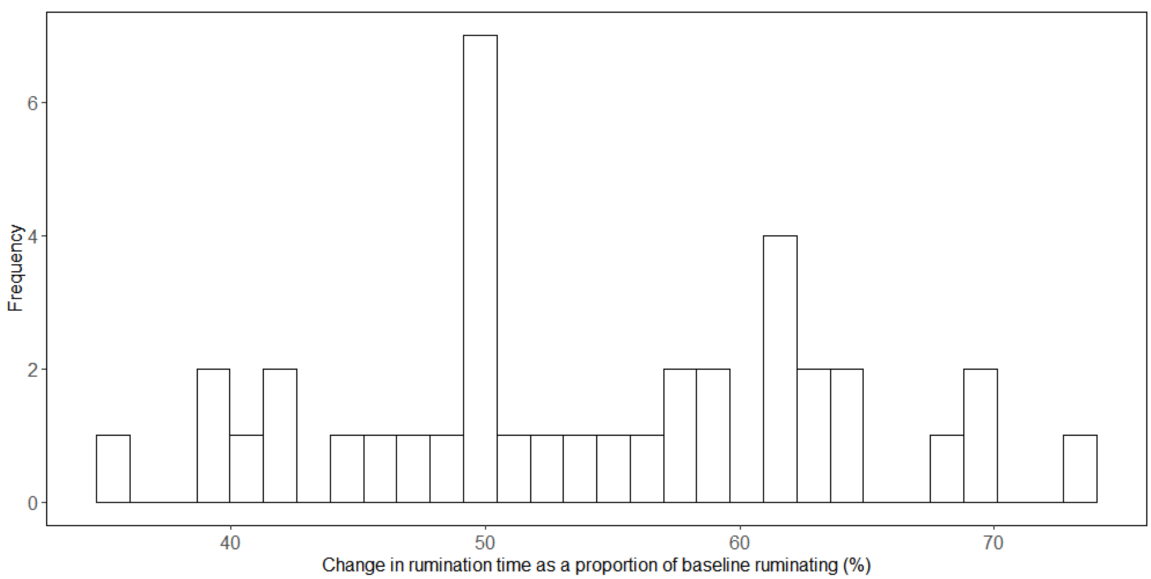

Fig 2. Frequency of the change in rumination time as a proportion of baseline rumination (mean daily THI ≤66).

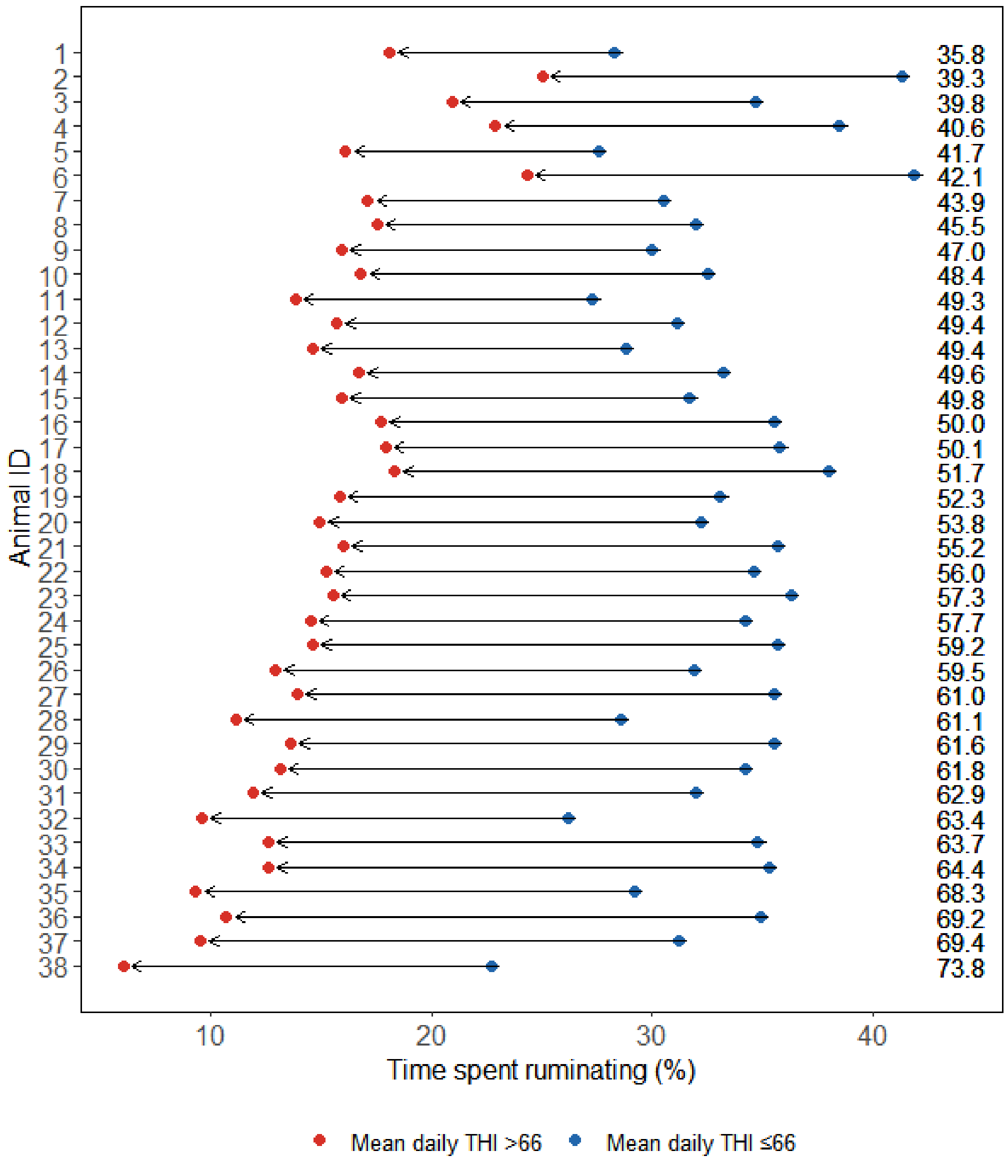

Fig 3. Time spent ruminating by individual experimental animals below and over the critical mean daily temperature-humidity index (THI) threshold. Labels refer to the change in rumination time as a proportion of baseline rumination (mean daily THI ≤66).

Discussion

The findings of this study support existing literature indicating that rumination decreases with increasing heat (Soriani et al., 2013; Moretti et al., 2017; Antanaitis et al., 2024). When exposed to increased heat, humidity, and solar load, cattle engage in various behavioural and physiological strategies to maintain thermoregulation, including reducing rumination (Soriani et al., 2013). Despite the variability in baseline rumination time and the degree of reduction, the decrease in rumination across all animals when the mean THI threshold reaches 66 underscores the potential of rumination as a reliable indicator of heat stress in extensively grazed cattle.

The degree of rumination decrease varied considerably between animals, potentially reflecting differences in individual heat tolerance. These results highlight the opportunity to use rumination data in genomic evaluations to identify heat tolerant individuals. Integrating this data into targeted breeding programs could enhance herd resilience to heat stress, contributing to improved productivity and welfare under increasingly challenging climatic conditions.

Further research is required to validate the inclusion of rumination data as a phenotype for developing GEBVs for heat tolerance. The methods outlined in this study provide a framework for generating high resolution phenotypic data in reference populations, enabling the identification of genetic markers associated with heat tolerance. This could in turn facilitate the selection of individuals with superior heat tolerance, ultimately enhancing the productivity, welfare, and sustainability of extensive grazing systems in the context of climate change.

Acknowledgements
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Maternal productivity for the rangelands

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Key words: Beef, body condition score, reproduction.

Abstract

Given pastoralists in arid regions have little control over season conditions and cannot easily manage stocking rate or supplementary feeding, the biggest lever of cow productivity is through genetics. Weaning rate which is a function of maximising calves born and minimising calf loss is the biggest driver of profit. Conception rate in heifers is related to joining weight and growth during joining. In cows, condition score is the key predictor. The EBV of greatest importance for reproduction is days to calving. EBVs for other traits like growth, calving ease, temperament and recently cow condition are important also. Cows in the greatest condition which show the greatest resilience are likely to have eaten more when feed was available rather than being metabolically more efficient.

Introduction

This paper reviews 35 years of research on beef cattle primarily led by the author. Although not conducted on rangelands per se, there are important insights for rangeland producers. The rangelands that I am focused on are Australia's arid zone - as defined by annual rainfall <250mm. An example of this region is Alice Springs, which has a mean annual rainfall of 285mm, but with huge variation as the median is 126mm, decile 1 6mm and decile 9 804mm (BOM 2024). The median rainfall is 90% in the summer half of the year (October-March), with winter rainfall being a greater proportion in areas to the south.

In the southern rangeland production systems described, little to no nutritional supplementation occurs.. The possible exception is hay fed to young cattle around the time of weaning. Feed supply is primarily only managed in extreme conditions and through stocking rate. Thus, once pasture management is optimised, one of the few strategic levers producers have for productivity improvements is through genetics, which mostly occurs through bull purchases. Given the region of focus is of very low humidity, the focus is on *Bos taurus* cattle. Factors associated with maternal productivity have been reviewed by Walmsley et al. (2018)

Genetic progress in Angus cattle

During the 35 years that this review relates, Angus cattle have changed significantly (Angus Australia 2024) – exemplified by a substantial increase in growth; 119kg for 600d weight and 102kg for mature cow weight. Birth weight has only increased by 4kg so there has been some improvement in calving ease. Favourable changes in other traits include: mature cow body condition, days to calving, docility, eye muscle area and intramuscular fat. However, there has been negligible change in carcass fat depth. Given that feed costs in the rangelands are low, the greater size of cows does not represent a major cost unless pasture utilisation levels are very high. All other traits have improved in favourable directions. Although Angus breed genetics have improved significantly, commercial cattle breeders struggle to compare breeds due to breed societies controlling the databases. There is a current project running Angus, Charolais, Hereford, Shorthorn and Wagyu cattle head to head. This is tremendous but expensive relative to the approach reported by Pitchford et al. (2021).

Feed efficiency

Feed efficiency can be defined in many ways. A common method in feedlots is to focus on the cost of gain with the measure being feed conversion (feed eaten / weight gain, Koch et al. 1963). Productivity is typically measured as output per unit input. In growing beef cattle, weight gain varies more than feed intake, so both measures are maximised by the fastest growing cattle.

In an attempt to overcome the problems of ratios, Koch et al. (1963) introduced the concept of residual or net feed intake (NFI). This has become a major focus of many groups around the world. However, Pitchford et al. (2018) demonstrated that when feed is limited, there is negligible variation in NFI. The implication of this is that there is negligible variation in maintenance requirements and so genetic improvement is not possible.Additionally, Pitchford et al. (2018) reported that variation in NFI under favourable feed conditions is associated with fatness. The implication of this is that variation in NFI must be through appetite rather than efficiency *per se*. The application of this work to the rangelands is that rather than select for animals with low NFI and supposed greater efficiency, it is likely that the best animals are those that eat more when feed is available, build up condition and then are more resilient during times if feed shortage.

Accioly et al. (2018) reported the performance of lines of Angus cattle divergent for fatness or NFI from the Beef CRC Maternal Productivity project (Pitchford et al. 2014). While all cattle gained and lost condition throughout the annual production cycle of feed availability and lactation status, the High-Fat and High-NFI lines were always fatter than the Low-Fat and Low-NFI lines respectively. The impact of this during times of feed shortage was that the leaner lines were always the ones to trigger supplementary feeding. Specifically, calculations based on the data in the Accioly paper estimate that if cows lose condition at a rapid rate (1 condition score/month), then a cow with an extra 1 mm rib fat EBV would take 7.5 days longer to reach the same supplementary feeding threshold. Maintenance of healthy body condition is a crucial trait in the rangelands so selection for increased condition is likely important.

Body composition

Following the work demonstrating the relationship between fatness and cow resilience, there has been an increased emphasis of commercial producers selecting bulls with above average fat EBVs. The result of this is increased fatness of both slaughter and breeding cattle. While this is advantageous for grass-finished steers (Deland et al. 2018), it leads to greater cost of gain and lower meat yields for feedlot-finished steers.

Pitchford (2023) examined the relationship between mature cow body condition and carcass EBVs for growth, muscle and fat. It was demonstrated that approximately ¾ of the genetic variation in cow condition is independent of carcass composition traits. Fat and muscle measured in heifers at yearling and pre-calving were highly correlated (De Faveri et al. 2018). Fat and muscle measured in cows across lactations were also highly genetically correlated. However, the correlation between maiden pre-calving and weaning measures was much lower. Thus, rangeland producers wanting to select bulls that breed more resilient cows should focus on the mature body condition EBV rather than on carcass EBVs.

While genetic selection for growth has resulted in significantly bigger cows, Hebart et al. (2024) have shown that in current commercial cows at 4.5 years of age and adjusted to a condition score 3 (scale 1-5), the average weight was around 550kg.

Productivity and profitability

In the Beef CRC Maternal Productivity project, Hebart et al. (2018) reported nutrition and genetics effects on productivity differences and Anderton et al. (2018) reported the effects on profitability. Variation in maternal productivity defined as weight of calf weaned per unit feed intake by the cow and calf, was associated with feed intake (50%), weaning rate (37%) and only 9% due to the weight of the calf. In the rangelands with cheaper feed, weaning rate will be the strongest profit driver (McCosker et al. 2010).

Anderton et al. (2018) reported that the Low-Fat lines were more profitable than the High-Fat lines. However, the design of the project (Pitchford et al. 2018) was that when one line (always the Low-Fat line) triggered the need for supplementary feed (a single animal dropping below condition score 2, Graham 1985), both lines would be fed (Accioly et al. 2018). The idea was that treating them the same was important for design but with the benefit of hindsight this may not have been wise. The impact of the design was that the High-Fat lines were fed more and maintained in a greater condition score, so there was greater investment in feed than necessary. In rangeland conditions where there is not this level of control, it is likely that those that maintain greater body condition are more resilient, more productive and more profitable.

Reproduction

Pitchford et al. (2022) reported results from the "Black Baldy" trial run with Hereford's Australia. The cattle were run in large mobs in northern Tasmania. While the environment is very different to the rangeland focus herein, they were run in large mobs and at high stocking rates and so provide a model for what could happen in other commercial herds. As expected, attainment of puberty in heifers prior to joining at 13-15 months was associated with the sire scrotal circumference EBV which reflects age at puberty in yearling bulls. However, this only had a weak association with weaning rate. As expected, the EBV with the strongest association with weaning rate was days to calving, a measure of the time taken from joining to calving. In naturally mated mobs, some of the variation in days to calving is associated with gestation length, but much more is associated with post-partum anoestrus and associated time to conception. The relationship was 8% more calves weaned in two joinings per day variation in the EBV. Similar results were found in the Beef CRC data (unpublished).

To address potential bias in conclusions for commercial producers coming from the Beef CRC data, a recent project on productivity of over 14,000 heifers on commercial properties has been conducted (Hebart et al. 2024). There are some key outcomes that have relevance for rangeland systems. A high aim could be to achieve 80% conception rate within two cycles (6-week joining). The two biggest factors affecting this are joining weight and during joining weight gain. If during joining gain is low, then heifers should be >350kg. However, if heifers are rapidly (>1kg/d) gaining during joining then much lighter weights will suffice. In the rangelands following a rain event, it is likely that cattle will be gaining rapidly so conception could occur at quite light weights (<300kg). As expected, conception rates of cows was most closely associated with condition score. Those with low condition due to high milk production or low feed intake will be most at risk of not conceiving.

Heterosis

Estimated from a genomic analysis, the heterosis effect in the Hereford x Angus crosses in the Black Baldy trial was 4% for pre-joining weight, 1% for pre-joining height, 6% for P8 fat and 13% for proportion pubertal (Pitchford et al. 2021). This demonstrates the value of heterosis or hybrid vigour for contributing to resilience.

Pitchford et al. (1993) reported heterosis effects on growth and reproduction in Brahman x Hereford crosses. The effect on growth was large on high-quality pasture (21%), but much less on low-quality pasture (1%). The conclusion was that the mechanism of heterosis was to increase appetite rather than metabolic efficiency as the effect can only be seen when the additional appetite was satisfied (high-quality pasture). This conclusion both guided and supported the same conclusion about the causes of biological variation in NFI (Pitchford et al. 2018). In the Brahman x Hereford crosses, the heterosis effect was large (39%) for weaning rate (Pitchford et al. 1993).

Conclusions

Given pastoralists in arid regions have little control over season conditions and cannot easily manage stocking rate or supplementary feeding, the biggest lever of cow productivity is through genetics. It is very likely that conclusions about genetic variation reported in Angus cattle in Mediterranean and Temperate grazing systems does provide valuable insights for the arid rangelands. However, the lack of multi-breed and commercial rangeland data in current genetic evaluation systems is limiting genetic progress for the rangelands. Genomics offers a significant opportunity to address this shortfall.

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Emissions management in grazing

Trade-offs between farm profit and greenhouse gas emission reduction

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Key words: enteric methane emissions; soil carbon sequestration; multiple mitigation strategies; programming model.

Abstract

To develop sustainable sheep production, there is a need to stack multiple mitigation interventions on the one land parcel, such as grazing management associated with soil organic carbon (SOC) accrual and feed additives for enteric methane reduction. The study, thus, aimed to investigate trade-offs between farm profit and greenhouse gas (GHG) emission reduction associated with those interventions.

We used soil carbon data measured in a long-term field experiment in New South Wales and data of net emissions (associated with using different feed additives) on two sheep farms (440 ha and 3786 ha), representative for small-scale and larger-scale farms. Then, a mixed-binary nonlinear programming model was applied to identify combinations of grazing management and feed additives to maximise farm profit and minimise net GHG emissions.

The results of both farms indicated that the most appropriate grazing management and feed additives varied depending on farmer's objective was profit or emission reduction or both. If profit was key goal, combination of multi paddock-fast rotation-high stocking rate and 1% walnut shell biochar would be adopted. In contrast, 15 paddock-slow rotation-low stocking rate and flexible grazing stacking with 0.2% Bovaer would be considered to minimise net emissions. If the objective was to maximise profit and minimise net emissions simultaneously, results of adopting multiple grazing management varied depending on farm size. The small-scale farm tended to adopt 15 paddock-slow rotation-low stocking rate and flexible grazing, while the larger-scale farm implemented 15 paddock-fast rotation-high stocking rate and flexible grazing. Furthermore, carbon price was a driver of farmer's decisions on mitigation interventions. The larger-scale farm would change to adopt 15 paddock-slow rotation-low stocking rate and flexible grazing when carbon price was equal or more than $AU50/tonne CO_2-equivalent. Thus, policies and legislative process relevant to increases in carbon price should be considered.

Introduction

There is a need to adopt mitigations for sustainable production that balance economic viability with environmental responsibility. Farm management relevant to soil carbon (Meyer et al. 2018) and feed additives (Gerber et al. 2015) are key for GHG emission reduction. While each mitigation has its strengths, combinations of grazing and feed management may provide greater benefits by enhancing emission reduction, improving soil health and boosting farm profitability. This study aims to determine what combination of feed additives and grazing management results in the lowest net farm GHG emissions while maximising profit.

Methods

In terms of data source, measured data of soi carbon sequestration was from a field experiment (Simmons, pers. comment.) at the Orange Agricultural Institute, New South Wales, Australia; while simulated data of sheep production (sheep productivity, feed volume, sheep age, total GHG emissions and emission intensity) were calculated through GrassGro software and SB-GAF tool. Farm characteristics (revenues of selling sheep and wool, land management cost, selling cost, stock management cost, pasture cost, supplement cost, and fixed costs) was collected though two real commercial sheep farms, 430 ha and 3786 ha. Consistent with Pham-Kieu et al. (2024), we extrapolated experimental data to the farm scale and combined with sheep production, then a invoked programming modelling approach.

We developed three mixed-binary nonlinear programming models to identify optimal combinations of grazing treatments – feed additives, grazing area allocation, the number of sheep sold and their age. These models aimed to maximize farm profit, minimize net GHG emissions, or achieve a balance between the two objectives. While the models differed in their objective functions, they shared a similar set of constraints. We assumed that farmers would maintain consistent grazing and feed management practices over a six-year period for a single sheep flock. Then the models were formulated below:

<table>
<tr><td></td><td>Model I</td><td>Model II</td><td>Model III</td></tr>
<tr><td>Objective function</td><td>Max
Sheep profit</td><td>Min
Net GHG emissions</td><td>Max
Profit = Sheep profit + environmental income</td></tr>
<tr><td>Subject to all constraints</td><td colspan="3">- Constraints of SOC accrual
- Constraints of sheep productivity and enteric methane reduction
- Constraint of total GHG emissions
- Constraints of stocking rate and sheep numbers
- Constraints of revenue and production costs</td></tr>
</table>

Results

Optimal grazing and feed management

When profit was prioritised on two farms (Model I), they would raise more sheep (approximately 1.5 times larger than those of Model II), achieved higher sheep profit and released higher emission intensity (Fig.1). While 15 paddock-fast rotation-high stocking rate was dominated on larger farm, there was a split between grazing area subject to this treatment and 30 paddock-fast rotation-high stocking rate on small farm (Fig.2). Despite generating greater profit, large farm had an emission intensity of approximately 0.6 tCO2-e/DSE higher than small farm. In contrast, if the primary goal was to reduce GHG emissions, higher emission reduction and lower profit were realised with flexible grazing and 15 paddock-slow rotation-low stocking rate. For trade-off between profit and emissions, similar adoption was considered on small farm, while combination of 15 paddock-fast rotation-high stocking rate and flexible grazing was adopted on large farm. Such grazing regimes led to higher emission intensity (about 0.4 tCO2-e/DSE higher) and lower environmental income (around $AU3/DSE less) compared with small farm. 1% biochar was used to maximise profit, while 0.2% Bovaer was considered to minimise net emissions or achieve both goals on 2 farms.

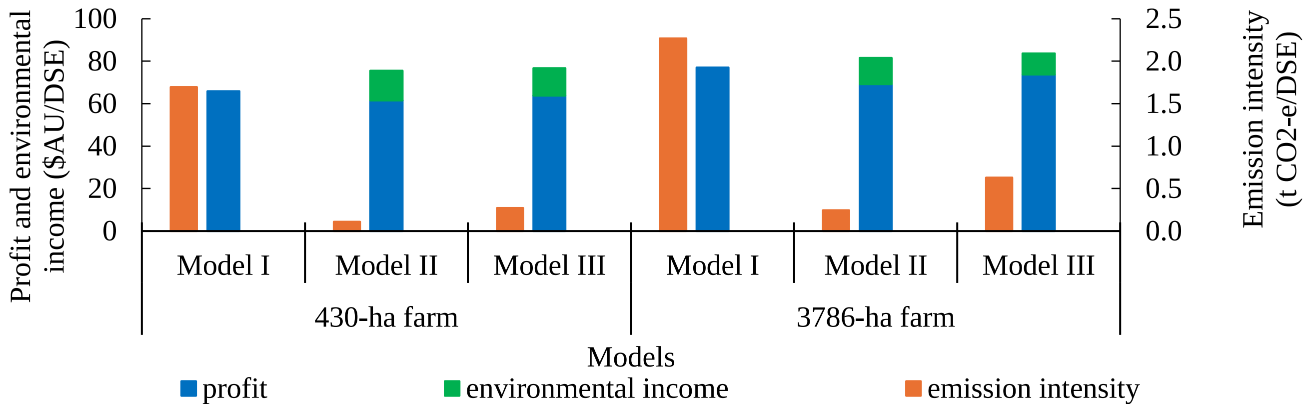

Fig. 1. Farm profit and emission intensity over 10-year simulation for three models subject to adoption of grazing treatments and feed additives

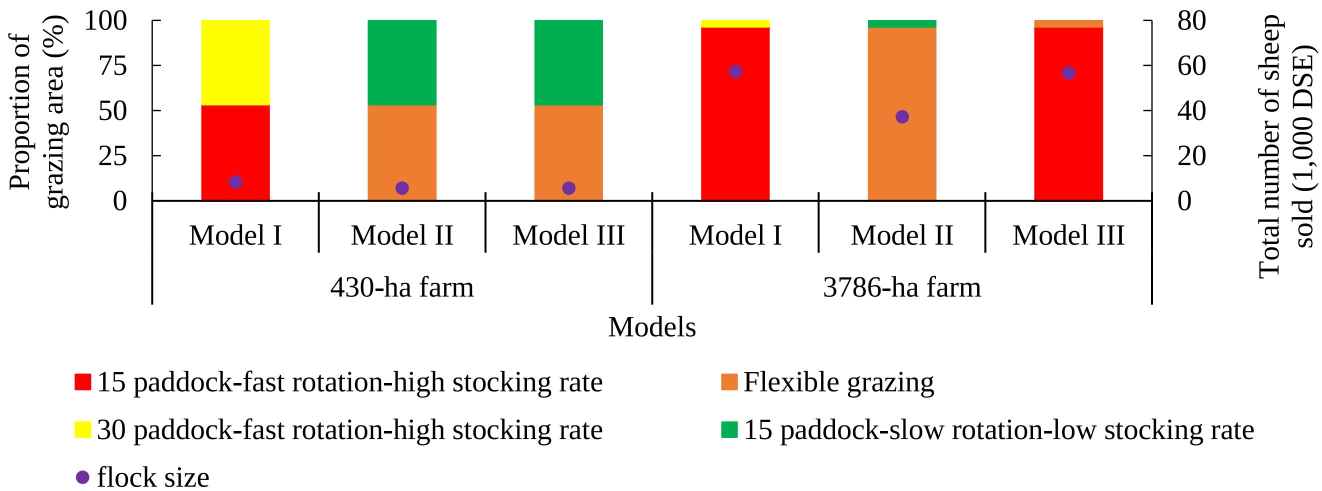

Fig. 2. Grazing management scenarios examined in the study and simulated number of sheep sold.

Impacts of carbon price on farm decision-making

When carbon price increased, small-scale farmer tended to sell sheep at early age, but did not alter their decisions on adopting grazing and feed management. In contrast, large-scale farmer adjusted their grazing management, shifting from 15 paddock-fast rotation-high stocking rate to 15 paddock-slow rotation-low stocking rate with flexible grazing dominated the grazing area, although they did not change feed management or the timing of sheep sales.

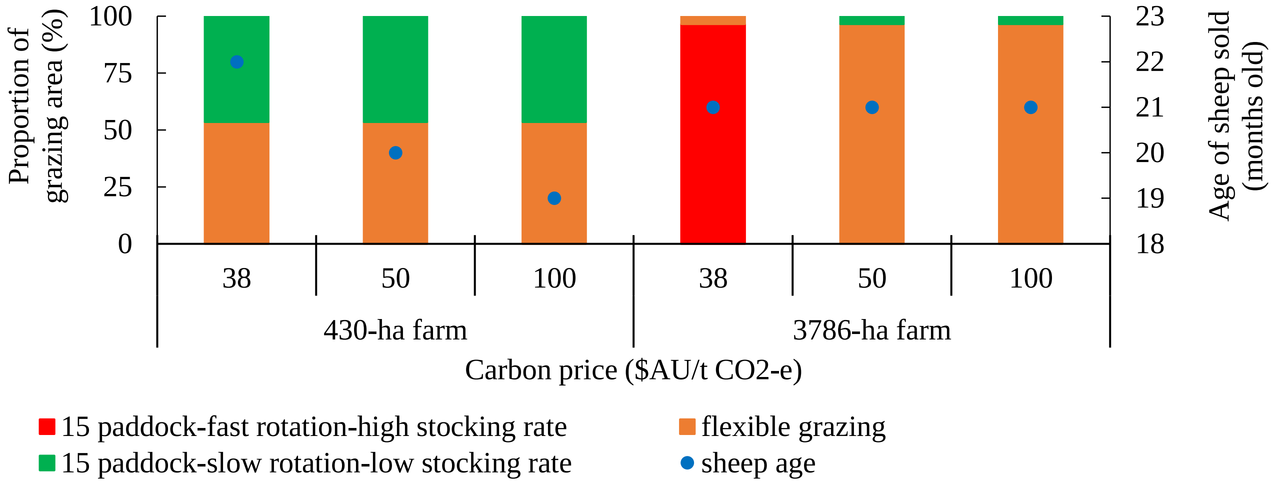

Fig. 3. Impacts of carbon price on grazing area allocation and emission intensity on farms.

Discussion

Align with Beauchemin et al. (2022), we found that combinations of grazing and feed management varied depending on farmer's objectives, even though these combinations bring greater results in emission reduction than any single management (Fujisaki et al. 2018; Harrison 2021). Fast rotation-high stocking rate with 1% biochar was most conducive to profit-aim, while flexible grazing and slow rotation-low stocking rate with 0.2% Bovaer was more conducive to emission-aim. Fast rotation-high stocking rate, though preferred for profit, is detrimental to SOC in the long term as it would negatively impacts on pasture productivity, decreasing above- and below-ground biomass and reducing SOC (Bilotto et al. 2023). In contrast, flexible grazing or slow rotation-low stocking rate (Rouquette 2015; Badgery et al. 2017) can reduce grazing pressure, promote forage growth, and increase both above and below-ground biomass, contributing to greater SOC accrual. Although multiple paddock systems can optimise pasture use and promote environmental sustainability (Jorns et al. 2023), the 30-paddock system was not preferable on large farm due to its high costs and substantial infrastructure requirements. For feed additives, biochar was preferable for profitability due to its ability to improve animal productivity (Mirheidari et al. 2019) and its lower cost compared with other feed additives, wheares Bovaer was more effective in reducing enteric methane emissions (Martínez-Fernández et al. 2014). Asparagopsis was excluded from all models due to its high cost.

Consistent with Pham-Kieu et al. (2024), our results indicated that trade-offs between profit and emission reduction was context-dependent, varying across farm size. Large-scale farmer tended to favour grazing treatments with lower infrastructure cost since they focus on optimising efficiency and minimising infrastructure investment to reduce overall production costs. Small-scale farmer, however, split the adoption of low- and high-cost treatments, likely due to higher potential for environmental income. As farmers would alter management relating to mitigation when potential profit was greater than their current activities, increased carbon price may attract more participants to join carbon credit markets and mitigate net emissions on their farms. However, the extent of these changes may depend on farm size, as large-scale farmer is likely to be responsive with price fluctuation. This could be due to their greater capacity to absorb risks, access to resource, or more substantial economic incentives. In contrast, the small farm may have limited financial resources and less flexibility to make major changes unless the financial benefit is clearly significant. Hence, future policies and legislation should thus consider mechanism to increase carbon prices and create opportunities to realise economic, environmental, social and cultural co-benefits associated with carbon farming practices.

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Transforming ruminant livestock systems for nature, human wellbeing, and climate: Diverse systems require nuanced solutions

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Key words: food systems; grazing lands; rangelands; socio-ecological systems; sustainability

Abstract

Ruminant livestock production is among the most controversial land uses and sectors of our global food system today. It also may be the most consequential, impacting half the land on earth, supporting over one billion people directly, and contributing significant greenhouse gas emissions. This sector must be part of food systems transformation to support nature, tackle climate change, and improve human wellbeing. However, the environmental, economic, and social context and outcomes from these systems varies enormously. Silver bullet solutions or misapplication of scientific findings can lead to trade-offs and inefficiencies. We developed case studies from a range of biomes, production system types, socio-political and economic contexts around the world. We then did a comparative qualitative analysis to identify patterns in contextual factors that enable or create barriers to implementation of a range of management practices, and can be used to inform policy or other interventions. In this paper, we describe the contextual factors that influence uptake of different practices in three rangeland-based case studies which we chose to exemplify the three major production system types, and a cross-section of climatic and socio-economic settings – Eastern Africa, the Tibetan Plateau of China, and the Great Plains of the United States. We highlight that research and resulting policy to improve climate, biodiversity, and human wellbeing outcomes must be better tailored to the unique, often-changing local conditions than they have been in the past.

Introduction

Grazing lands make up over a quarter of ice-free land (FAO 2023) and can provide wildlife habitat, soil carbon stocks, livelihoods and cultural value in addition to livestock production (Sala et al. 2017). Globally, livestock production systems based in grazing lands exist across diverse ecological, economic, social and cultural contexts, (Rivera-Ferre et al. 2016) and outcomes (Poore and Nemecek 2018). To meet calls for greater environmental sustainability in livestock production, there is a need to understand how context – both historical and current – informs potential practice change and related outcomes. Here, we used a case-study approach to identify patterns in: 1) the key contextual factors that influence systems; 2) use of different management practices; and 3) enabling conditions and barriers for change towards improved sustainability. Our aim is to highlight how context can inform effective policy and investments to encourage sustainable livestock practices that maximize benefits and reduce harms for people, climate, and nature.

Methods

We conducted a qualitative, comparative thematic analysis of case studies from diverse livestock production systems and agroecological regions around the world (Kazanski et al. *in review*). Case studies were developed based on region-specific knowledge and experience, published literature, and input from local and regional practitioners or experts in livestock production. The case studies and the comparative analysis enabled us to explore the relative weights of the impacts of contextual factors on current practices and potential to change. Here we focus on rangeland cases from Eastern Africa, the Tibetan Plateau in China, and the cow-calf phase of cattle production in the Great Plains of the United States, which provide a cross-section of common economic/market and ecosystem contexts (Kazanski et al. *in review*). We also focus on the practice categories of agroforestry, animal management, technology and information within these case studies.

Results

Numerous environmental, economic, social and cultural characteristics shape livestock production systems (Kazanski et al. *in review*). The rangeland-based cases explored here highlight the diversity of production systems when all these elements are taken into consideration (Table 1). The case studies are predominantly based in semi-arid to arid rangelands where precipitation is the primary constraint on forage production. In Eastern African systems, livestock and wildlife coexist, introducing conflict and considerations on forage use. In the Great Plains, ranching with sound management can support wildlife by maintaining intactness of grazing lands that could otherwise be converted to crop production or developments that could reduce habitat (Cameron et al. 2014). Management and land tenure also varies: in Eastern Africa, communal grazing is predominant; in the Tibetan Plateau land was historically communally managed but has shifted to more individualized allotments; and in the Great Plains land is individually managed. In both the Eastern African and Tibetan Plateau pastoralist systems, livestock are a primary source of livelihoods (Lind et al. 2020), although tourism is an increasing source in the Tibetan Plateau (Gongbuzeren et al. 2024). Livestock also predominantly support hyper-local markets. In contrast, in the Great Plains, while ranching is core to many livelihoods, ranching families increasingly have additional jobs to diversify incomes (Wulfhorst et al. 2022) and production is linked with intensive row crop farming in service of commercial, national and global markets.

The case studies highlight that livestock production "best" practices depend on context and should not be universally applied. For example, in settings with a history of some tree canopy (e.g. in some systems across Eastern Africa), agroforestry offers benefits like improved feed and nutrition and adaptation to climate change (Balehegn et al. 2015; Balehegn et al. 2017). However, in systems that did not evolve with trees (e.g. the Great Plains or Tibetan Plateau), agroforestry practices could jeopardize biodiversity and ecosystem services (Veldman et al 2015) or fail due to soil and rainfall constraints (Briske et al. 2024). We find that even categories of practices that are generally beneficial tend to have important specific considerations depending on context (e.g. technology and information services and animal management). For example, technical services are identified as a gap/opportunity in both the Tibetan Plateau and Great Plains cases. Yet, agricultural "innovations" might look different across contexts. While ag-tech and innovation is often about robotics, precision agriculture, or new varieties, well established or traditional practices with multiple benefits may be a missed opportunity that could be bridged, e.g., through use of mobile phones with chat or video features for veterinary telehealth. Similarly, while animal management is broadly applicable, the specific goals of genetic selection and breeding, for example, can differ by context. In some cases, breeding aims for larger and faster growing animals (e.g. the commercial systems in the Great Plains). However, these breeds tend to require high nutrition, which may be limiting in low-input extensive rangeland systems. In contrast, animals with smaller mature size can be better adapted to harsh conditions (e.g., poor nutrition, extreme temperatures), and could be increasingly valued across systems as the impacts of climate change intensify. Taking context into consideration when identifying practices or system change to support sustainability is therefore critical.

We also find that the primary barriers and enabling conditions for practice implementation strongly differ by contexts (Table 1). In the analysis, economic and market settings emerged as primary drivers of change: in the Great Plains case study (an example of commercial production in a high-income country), consumer and market demands, regulatory enhancement, investment in technology research and development, and safe-to-fail trials are promising enablers for change. In contrast, in Eastern Africa and the Tibetan Plateau (multipurpose systems in low- and middle-income countries), capacity building and investment in technical assistance, culturally appropriate training on herd management, and climate investments for inputs or technology are more likely to facilitate change. We find the ability to change practices or systems is also often constrained by environmental factors, like precipitation, which is becoming increasingly variable (Sloat et al 2018). Cultural tradition and history also appeared to ossify behaviors, greatly informing future practices and systems, and what change might be possible.

Table 1. Livestock production system case study summaries. Case study details were compiled by regional experts based on the literature and additional expert input as described in a prior study (Kazanski et al. *in review*).

	Eastern Africa	Tibetan Plateau of China	Great Plains of the U.S.
Dominant production systems	**Pastoralism.** Mobile pastoral systems of diversified herds (cattle, sheep, goats). Livestock are multipurpose, providing meat, milk, and blood[1]. Many people and their livestock are located far from urban market centers.	**Pastoralism**. Yak and sheep graze high-altitude pastures for the provision of food, fuel (manure) and socio-cultural purposes. There is a history of communal land and animal management, but this is changing[9].	**Ranching**. Mostly cattle grazed in arid rangelands during cow-calf phase, then fattened/finished on grain. The system is entirely integrated into the global economy with some local and regional market opportunities.
Dominant ecosystem	Tropical and subtropical grasslands, savannas and shrublands	Montane grasslands and shrublands	Temperate grasslands, savannas and shrublands
Environmental context	Degradation of grazing lands, characterised by soil erosion, encroachment of woody	Fragile alpine soils	Climate change impacts threaten economic viability of this system[12, 13].

	species, loss of biodiversity[2].	Increased stocking rates have negative impacts on vegetation and soils[10].	
Economic context	Livestock production is core to community livelihoods[3].	Livestock products are sold into domestic markets; tourism presents opportunities to diversify livelihoods[11].	Global market integration; beef is sold into both domestic and export markets, especially Asia[14]. Profit margins are tight.
Social and cultural context	Deep cultural value of livestock[4, 5]; pastoralism has a 10,000+ year-history in the region[6].	Deep cultural history and tradition	Rural community livelihoods Ranching and cowboy culture are culturally significant
Barriers	Difficult for vulnerable communities and households to take risks on new practices[7].	Little opportunity to improve or diversify production within this ecosystem.	Consumers driven by price Capital improvements are unaffordable
Enabling conditions	Commitment to adapting livestock systems to keep them central to livelihoods[8]	Livestock production and tourism are being explored for further integration and diversified marketing strategies. Government policy is encouraging community-level grazing land management and reaggregation of livestock.	Tax breaks, insurance and subsidies can facilitate practice change

[1]Lind et al., 2020; [2]Gil-Romera et al., 2010; [3]Lind et al. 2020; [4]Dabasso et al. 2022; [5]Galaty 2021; [6]Learn, 2018; [7]Boruru et al., 2011; [8]Mahdavi et al., 2023; [9]Gongbuzeren et al., 2016; [10]Zhuang et al., 2019; [11]Gongbuzeren et al., 2024; [12]Klemm et al., 2020; [13]Briske et al., 2021; [14]USDA, 2024

Discussion

The three case studies highlight how context informs current and potential production systems and practices. Economic and market setting, the role of livestock in culture and livelihoods, and ecological setting all interact to inform what might be considered best practices. We also see that environmental constraints, history, and cultural tradition inform what future practices or systems might be possible. It is clear that environmental, economic, and social and cultural elements are key to understanding production systems and opportunities for change. The inclusion of additional perspectives could shift the picture of these systems.

The observation that context is important is not new, but worth emphasizing, particularly to inform policy and investment. In global fora and multilateral policy efforts, there is increasing attention on livestock systems and rangelands (e.g. at recent climate COPs; the upcoming International Year of Rangelands, 2026; and FAO's recent Global Conference on Sustainable Livestock Transformation, 2023). For an equitable and just food system transformation, decision makers must incorporate understanding of context into policy and investment approaches.

Doing this, while considering multiple outcomes from livestock systems for people, climate, and nature, will be critical to crafting policies that maximize benefits and reduce harms (Harrison et al. 2021).

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Cows, carbon, and conservation

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Key words: carbon market; cow-calf; ecosystem modelling; life cycle analysis

Abstract

Managed grazing lands cover ~25% of global land area. Carbon stored in grazing land soils (top 1 m) represent 20% of total global soil organic carbon (SOC) stocks with a potential annual SOC sequestration rate of 0.5 ton C ha^{-1} yr^{-1}. Conversely, grazing animals produce greenhouse gases (GHG). Although the US beef industry has made significant advances in reducing its environmental footprint, extensive grazing operations (e.g., the cow-calf and stocker phases) are responsible for ~ 70% of the GHG emissions from the beef value chain. Multiple stakeholders are interested in the potential effect carbon market participation may have on the financial status of the beef industry and its cascading effects to conservation and climate mitigation. Producers are interested in carbon markets to diversify income sources and drive increased profitability. Financially viable producers support diverse industries, ranging from fertilizer, feed, equipment, and beyond. Conservationists are also interested in carbon markets as a tool to fund the protection of grazing lands to benefit conservation goals. The question remains how extensive grazing operations can engage in carbon markets. We utilized life cycle analysis and an ecosystem model to understand net carbon sequestration at Archbold Biological Station's Buck Island Ranch, a commercial cow-calf grazing operation in Many ranchers are being approached by carbon credits brokers aiming to trade ranch carbon credits in carbon markets. If effective, these markets ensure globally reduced atmospheric greenhouse gas concentrations when buyers pay sellers for reduced emissions or increased sequestration. For Buck Island Ranch to credibly be paid for carbon sequestration, new management reducing emissions or enhancing sequestration is needed, even though the ranch is presently a net carbon sink. Credible carbon markets include the concept of additionality which refers to the need for payments to result in newly avoided emissions or increased sequestration beyond what would have already been occurring without the payment. Emissions could be reduced either from cattle or the environment. Inhibiting cattle methane through feed additives shows promise in the dairy industry (Belanche et al. 2020) and may be useful for pasture-based systems. Increasing soil C stocks is more difficult because many producers are already implementing effective SOC management (Silveira et al. 2024). To have a meaningful impact on climate change, ideally contracts should span at least several decades (Dynarski et al. 2020).

. Life cycle analysis estimated annual average emissions as 11,294 Mg CO2 eq. The ecosystem model estimated annual soil organic carbon sequestration as 12,391 Mg eCO2/year. Sequestration offset emissions with 1,097

metric tons CO2e remaining. A preliminary survey of ranchers' (n=23) interest in carbon markets showed barriers to enrolling in carbon markets were lack of awareness of existing programs, lack of information on programs, and not receiving credit for existing practices. Lastly, we explored the possibility for ranchers to participate in carbon markets considering common program credibility concerns.

Introduction

There is increasing interest in management of grazing lands for carbon sequestration. At the same time, there is also interest in reducing greenhouse gas (GHG) emissions from cattle on grazing lands as 70-80% of the US beef industry's GHG emissions result from the cow-calf phase of the beef life cycle, which is managed on grazing land (Rotz et al. 2019). It is critical to accurately quantify carbon uptake and emissions from grazing lands to manage carbon sequestration and reduce emissions.

Economic incentives through carbon markets are an emerging tool for conservation of grazing lands. Producers are interested in carbon markets to diversify income sources and increase productivity (Silveira et al. 2024). The potential for carbon to affect the financial status of the beef industry through carbon market participation has cascading effects to conservation. Ranching can benefit conservation goals by providing wildlife habitats, connectivity and wildlife corridors, and preserving multiple ecosystem services ranging from water quantity and quality, open space, and recreation. Therefore, maintaining economically viable ranches is an important conservation strategy. However, there is a lack of information about the producer community's interest in these programs and the barriers or incentives to participating.

Understanding baseline ranch-scale carbon emissions and uptake is the first step towards ranch participation in carbon markets. For ranch operations, life cycle assessment (LCA) is a method for evaluating environmental impacts associated with the production of goods (Rotz et al. 2019). Ecosystem process-based models can be used to quantify ecosystem carbon dynamics but these models must be validated (Zhou et al. 2021).

Here we: 1) quantify all carbon emissions from a representative ranch operation with LCA; and 2) utilize a process-based ecosystem model validated with *in-situ* ground measurements to understand ecosystem carbon emissions and uptake. To address the need for producer community interest in carbon markets we conducted a survey.

Methods

This study took place at Archbold Biological Station's Buck Island Ranch, located in south-central Florida, USA, a 4249-ha cow-calf operation with ~3,000 cattle. The ranch contains 1,953 ha of cultivated pastures planted with *Paspalum notatum* and 2,290 ha of semi-native grasslands dominated by a mixture of native grasses (*Andropogon* spp, *Coleataenia* spp, *Axonopus* spp) and *P. notatum*. The climate is subtropical with a mean annual temperature of 22ºC (1998-2021) and mean annual precipitation is 132 cm.

The carbon footprint was calculated by way of LCA employing the Beef EA model (Alltech E-CO_2, Stamford, United Kingdom), a bespoke tool employed in both research and industry. Independently accredited to be compliant with carbon footprint standards globally (ISO, 2018), the model is rooted in the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories. Emissions modelling follows the IPCC Tier 2 Framework (IPCC, 2006; 2019), however facilitates incorporation of site-specific Tier 3 data when available. This approach enabled detailed account of cows' dietary intake, for example, and incorporation of higher granularity data from an ecosystem model (described below) for estimates of CH_4 and N_2O arising from cows' deposition at pasture.

The system boundary was defined as cradle-to-gate, covering emissions arising in all inputs and processes through the supply chain and on-farm, up to the point at which the product cattle left the ranch. Operations data were collected for the period from 2015 to 2020 and GHG emissions estimated for each of the six calendar years. This included account of all ranch inputs (e.g. fertilizer, lime, pesticide, herbicide, feed use), fuel and electricity use, animal excreta and applications to the land, and enteric fermentation by cattle.

We quantified total ranch emissions in two ways: *Scenario 1*) including enteric methane and calculating direct and indirect N_2O loss and manure CH_4 by LCA Tier 2 method, but not including ecosystem methane; and *Scenario 2*) including enteric methane using LCA approach and including ecosystem methane, N_2O and manure CH_4, all calculated using an ecosystem model (*ecosys*). Not including ecosystem methane as in Scenario 1 is typical of LCA practices that consider this source a process of the natural ecosystems.

The process-based model *ecosys* was utilized (Zhou et al. 2021). This model implements biogeophysical and biogeochemical principles to simulate water, energy, carbon, and nutrient cycles over the soil-plant-atmosphere continuum at hourly time steps. The model estimates photosynthesis, autotrophic and heterotrophic respiration, and soil nitrous oxide emissions and soil emissions caused by field-level responses to environmental forcing and practice data (e.g., manure input and fertilizer). Other model inputs included animal use days for all pastures and fertilizer inputs. The initial soil carbon stock was derived from the gSSURGO database. Data from on-site groundwater wells was incorporated to ensure accuracy of the hydrology of the site, where groundwater typically rises to the surface in the wet season and recedes in the dry season. The model gross primary productivity (GPP), ecosystem respiration (Reco), and ecosystem methane were validated using eddy covariance data comparisons to model estimates. Soil carbon increases were modeled for 1 m depth of soil.

We did not include wetlands, ditches, or woodlands, but focused on pastures as the largest land use on the ranch and the landscape primarily utilized for beef production. Future work will incorporate the entire ranch ecosystem as a third scenario.

Producer Survey

We conducted a survey of beef producers in Florida to determine interest in carbon markets for pasture-based beef production. The survey asked about the incentives and barriers to practicing climate-smart agriculture and participating in carbon markets (Campbell et al. 2019). We obtained a sample of beef producers through the data procurement company DTN. We collected responses using online survey software Qualtrics between June 2023 and October 2024 and offered a $15 Amazon eCard as compensation. This survey was approved by the Archbold Ethics Review Committee, #2023-001.

Results

Throughout the six-year period, total annual emissions for scenario 1, averaged 6,294±1095 (stdev) metric tons CO2eq between 2015 - 2020 (Table 1). This resulted in an emissions intensity value of 20.97 kg CO2 eq/kg of live weight. In scenario 2, annual average emissions were 11,294 metric tons CO2 eq. Emissions intensity was 38.53 kg CO2 eq/kg live weight. Annual emissions were driven by variability in enteric fermentation, fertilizer use, and ecosystem emissions.

Ecosystem Model

The site-level simulations showed that the *ecosys* model captured both the magnitude and seasonal patterns of carbon fluxes measured by an onsite eddy covariance tower (i.e., ecosystem gross primary production (GPP), and ecosystem respiration (Reco)) with R^2 equal to 0.8 and 0.79, for GPP and Reco, respectively. The eddy covariance tower net ecosystem productivity (NEP) was -2.39 ± 0.41 Mg C ha^{-1} yr^{-1}. The *ecosys* model estimated the annual average C sequestration rate was 1.84 Mg C/ha/year. At the ranch scale, the annual increase in SOC was 12,391 metric tons eCO2/year.

Net Carbon Balance at the Ranch Scale

In Scenario 1, the net carbon balance was -6,097 metric tons CO2eq. Net emissions intensity was on average -20.31 kg CO2eq/kg live weight for calves leaving the ranch. In Scenario 2, the annual average sequestration exceeded annual average emissions by 1,097±3026 metric tons CO2eq. This resulted in an average net emissions intensity of as -3.65 kg CO2eq/kg live weight for calves leaving the ranch.

Table 1. Carbon emission and sequestration analysis from Buck Island Ranch from 2015 – 2020. Results are generated with LCA and the process-based ecosystem model *ecosys*. All units are in metric tons CO2eq, except otherwise noted.

	2015	2016	2017	2018	2019	2020	Average
Fertilizer	0.0	430.0	0.0	336.5	127.4	0.0	149.0
Herbicide	0.7	0.0	3.5	3.2	0.5	1.1	1.5
Supplemental Feed	368.4	200.8	250.3	404.3	198.1	239.2	279.9
Farm Machinery Use	140.9	141.0	91.1	135.5	153.1	150.4	135.3
Farm Electricity Use	37.3	30.7	20.3	28.8	13.4	36.6	27.9
Direct N2O (*ecosys model*)	645.5	763.1	318.0	459.9	530.3	524.6	540.2
Indirect soil N2O (*ecosys model*)	17.1	30.9	2.3	0.7	1.6	0.0	8.8
Enteric fermentation	5,826.5	6,126.2	3,883.6	4,595.8	5,142.9	4,405.4	4,996.7
Manure methane (LCA method)	56.2	60.9	38.4	44.1	51.1	41.4	48.7
Soil methane emissions (*ecosys model*)	7,793.8	7,270.5	2,915.0	3,775.6	3,912.8	4,625.4	5,048.9
Carbon credit/ deduction	137.8	-0.5	64.2	70.0	-60.6	444.9	109.3
Scenario 1: Total emissions per year w/manure CH4 (LCA)	7,230.3	7,783.1	4,671.7	6,078.8	6,157.7	5,843.6	6,294.2
Scenario 2: Total emissions per year with *ecosys* Soil Methane emissions	14,967.9	14,992.7	7,548.4	9,810.3	10,019.4	10,427.6	11,294.4
Calf live weight sold	303.3	323.2	185.0	249.5	376.7	363.5	300.2
Scenario 1: Emissions intensity(kg CO2eq/kg LW)	23.8	24.1	25.3	24.4	16.4	16.1	21.0
Scenario 2: Emissions intensity(kg CO2eq/kg LW)	49.4	46.4	40.8	39.3	26.6	28.7	38.5
Soil Carbon sequestered (*ecosys model*)	12,391.1	12,391.1	12,391.1	12,391.1	12,391.1	12,391.1	12,391.1
Net Carbon Scenario 1	-5,160.8	-4,608.1	-7,719.4	-6,312.4	-6,233.4	-6,547.5	-6,096.9
Net Carbon Scenario 2	2,576.8	2,601.6	-4,842.8	-2,580.9	-2,371.7	-1,963.6	-1,096.8
Net Carbon Intensity Scenario 1(kg CO2 eq/kg LW)	-17.0	-14.3	-41.7	-25.3	-16.6	-18.0	-20.3
Net Carbon Intensity Scenario 2 (kg CO2 eq/kg LW)	8.5	8.1	-26.2	-10.4	-6.3	-5.4	-3.7

Producer Survey

We received a total of 23 survey responses. The results from these respondents are not meant to be representative of all Florida beef producers and are not generalizable. Respondents engaged in climate-smart practices to improve soil condition (n=20), maximize profitability (n=20), and increase yield and/or productivity of the land (n=19). Nearly all respondents (n=20) conducted soil test-based fertilizer applications and rotational grazing (n=19). Barriers to engaging in climate-smart agriculture included lack of or not enough knowledge about practices (n=10, n=9 respectively) and the uncertainty about the impact on farm business (n=8). The primary barriers to participating in carbon markets reported were lack of awareness of and information on existing programs (n=10, n=9 respectively) and no credit for existing practices of past use (n=9). When asked about incentives to participate, payments for past practices (n=14) and no out of pocket program costs (n=14) were top responses.

Discussion

Here we showed that a typical ranch in the humid subtropics, is on average, a net sink of carbon. The modelling approach we employed can be utilized to determine baseline carbon footprints and assess management interventions to mitigate emissions or increase soil carbon sequestration. The model estimate of 1.8 Mg C ha $^{-1}$ yr^{-}

^{1} (1 m depth) was in line with sequestration estimates measured by soil sampling (20 cm depth: 0.9 Mg C ha $^{-1}$ yr^{-1}) and eddy covariance (1.1 -1.4 Mg C ha $^{-1}$ yr^{-1}) (Silveira et al. 2024).

Many ranchers are being approached by carbon credits brokers aiming to trade ranch carbon credits in carbon markets. If effective, these markets ensure globally reduced atmospheric greenhouse gas concentrations when buyers pay sellers for reduced emissions or increased sequestration. For Buck Island Ranch to credibly be paid for carbon sequestration, new management reducing emissions or enhancing sequestration is needed, even though the ranch is presently a net carbon sink. Credible carbon markets include the concept of additionality which refers to the need for payments to result in newly avoided emissions or increased sequestration beyond what would have already been occurring without the payment. Emissions could be reduced either from cattle or the environment. Inhibiting cattle methane through feed additives shows promise in the dairy industry (Belanche et al. 2020) and may be useful for pasture-based systems. Increasing soil C stocks is more difficult because many producers are already implementing effective SOC management (Silveira et al. 2024). To have a meaningful impact on climate change, ideally contracts should span at least several decades (Dynarski et al. 2020).

Producers are interested in these programs but lack information about climate smart practices, carbon markets and the best way to engage. They are concerned about the lack of acknowledgment for the benefits of existing practices and require more information about how participating in carbon markets affects farm business.

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Mulberry (*Morus* spp.) for mitigating enteric methane emissions and ensuring sustainable livestock feeding systems in India

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Key words: *Mulberry*, Reduced Methane Emission, Sustainable, Livestock, Feeding System

Abstract

Mulberry (*Morus* species; Family: *Moraceace*) leaves are source of highly palatable as well as digestible fodder during summer season and are rich in crude protein content (14.0–34.2%) and macro as well as micro nutrients. These leaves are rich in secondary metabolites known to enhance livestock production including the flavonoids present in mulberry leaves are known to show efficacy in managing fatal livestock diseases such as neonatal calf diarrhea and reducing enteric methane production. Moreover, mulberry species is easy to propagate, and produces high leaf biomass yield and can be grown under vast climatic conditions from arid, semi arid, tropical, subtropical to temperate conditions. Further, mulberry species can be managed as a tree, shrub or hedge and has been found to be compatible to be grown under agro-forestry systems, as high density plantations, as boundary plantations and bund plantations etc. Thus, given the pressing issues of declining livestock productivity, increasing enteric methane emissions, and the prevalence of livestock diseases, harnessing the potential of mulberry species emerges as a sustainable solution which needs promoting cultivation of mulberry species ensuring sustainable livestock feeding systems in India. For cultivation, identification of elite germplasm that are well suited to the various climatic conditions along with higher and uniform leaf biomass yield, high protein as well as nutritional profile, nutraceutical potential (flavanoid rich) and methane reduction potential is required which can be promoted for cultivation among farmers. Thus, there is an urgent need to initiate screening of mulberry species germplasm for identification of superior genotypes of mulberry for ensuring economically viable way to reduce enteric methane emissions and ensuring sustainable livestock feeding systems in India under various agro-climatic zones.

Introduction

In India, livestock plays a key role in sustaining rural economy and nutritional requirements of the rural people. Besides this, livestock sector also contributes 4.11% and 25.6% respectively to total GDP and agriculture GDP of India. The average milk productivity of milk animals in India is significantly lower than in developed countries such as the USA and UK (Intodia, 2017). Sustaining livestock production is crucial for bolstering the rural economy in India, where the livestock population stands at 535.78 million, according to the 20th Livestock Census (2019), reflecting a 4.43% increase since the 2012 census (Singh, 2020). However, low productivity is primarily attributed to a persistent shortage of quality fodder. The rising livestock population exacerbates this demand-supply gap, emphasizing the urgent need for strategies to enhance fodder availability and ensure sustainable livestock production. According to reports, India faces a deficit of 11.24% for green fodder and 23% for dry fodder (Roy et al. 2019). Moreover, feedstuff and fodder that is fed to our livestock is of poor quality especially feed/fodder stuff that is fed during the dry/lean period is poor in crude protein content, digestible nutrients, metabolizable energy, vitamins and macro as well as micro mineral content (Devendra 2011, Simbaya 2020). Because of poor quality of feed, digestibility as well as utilization of nutrients gets reduced and it leads to increased enteric methane emission from livestock, the lesser body weight gain and reduced milk production (Devendra 2011, Simbaya 2020). Therefore, ensuring round the year quality nutritious fodder supply and improving protein availability for livestock during lean period is need of the hour to ensure fodder security, reduce enteric methane emission from livestock via inhibiting the growth of methanogenic bacteria and ciliates inside gut and sustain livestock productivity. Under such case, tree fodder leaves are sustainable option for ensuring round the year quality fodder supply and to address dry season protein and nutrients deficiency for livestock and reduce enteric methane emissions (Jetana et al. 2010, Chibinga et al. 2012). Therefore a literature review was carried out to shortlist important fodder tree species to identify tree species that are easy to grow as well as widely distributed; protein, macro micro nutrient as well as secondary metabolite rich to ensure round the year quality fodder supply, reduce enteric methane emissions and enhance livestock productivity.

Methods

Literature review was carried out using relevant sources, including peer-reviewed journals, government reports, institutional publications, and databases like Scopus, Web of Science, and Google Scholar to identify important fodder tree species that are easy to grow as well as widely distributed; protein, macro micro nutrient as well as secondary metabolite rich to ensure round the year quality fodder supply, reduce enteric methane emissions and enhance livestock productivity. Based on the literature review, mulberry species was found to be the potential fodder species to fulfil above mentioned concerns. Thereafter, ICAR-IGFRI, Jhansi, India started collection of mulberry species germplasm via exploration in Himalayan zone as well procurement from various research organizations from India covering various agro-climatic zones for evaluation and selection of high yielding and nutritionally rich genotypes of mulberry for semi arid and temperate conditions.

Results

Mulberry (*Morus* species) belonging to family Moraceae are potential fast growing fodder tree species that are found growing under various agro-climatic zones from arid, semi arid, tropical, subtropical to temperate conditions. Mulberry leaves contain higher crude protein content (14 – 35%) than the traditional forages; are rich in macro as well as micro nutrients (Ca, P, K, Na, Mg, Fe, Zn, Mn, B, Cu, Mo); are highly palatable as well as highly digestible (75–85%); available during during summer season and rich in secondary metabolites especially mulberry leaf flavonoid that enhance livestock production (yield and quality), reduce enteric methane production via inhibiting the growth of methanogenic bacteria and ciliates inside gut and are also utilized in livestock disease management like neonatal calf diarrhea (Bi et al. 2017, Hassan et al. 2020). Moreover, mulberry leaf supplementation to dairy animals has been proved to enhance milk yield and quality (protein, fat content) (Datta et al. 2002, Venkatesh et al. 2015). Supplementation of livestock feed with 5–10% of mulberry silage have been reported to improve rumen micro-biota, fermentation, and enhance the production of fiber-digesting, propionic acid synthesizing and milk fat enhancing microorganisms leading to the improvement in milk yield in dairy animals (Li et al. 2020). Secondary metabolites especially mulberry leaf flavanoids present in mulberry leaf have been reported to enhance milk production improve health and manage serious disease like neonatal calf diarrhea (Gonzalez et al. 2010, Bi et al. 2017, Li et al. 2020). Further, mulberry leaves can be easily converted into hay, silage, leaf meal etc. thereby can also be stored for feeding the livestock during fodder scarcity. Another advantage with mulberry species is that they are fast growing, easy to propagate, and produces high leaf biomass yield of 25-30 t/ha depending upon the species, harvest cycle and plant density (Venkatesh et al. 2015). Moreover, mulberry species can be grown in various forms such as tree, shrub, hedges etc. and being perennial, deep rooted tree species they are less susceptible to changing climatic and weather conditions. Huge genetic variation in mulberry species germplasm with respect to the growth, leaf yield, and fodder quality traits, secondary metabolites (flavanoid content) as well as biochemical, methane reduction potential, ensiling traits; physiological, phenological, agro-morphological traits etc. has been reported (Taikader and Kamble 2009, Kandylis et al. 2009, Gonzalez et al. 2010, Doss et al. 2012, Suresh et al. 2017, Yu et al. 2018, Hassan et al. 2020, Krishna et al. 2020). This genetic diversity among mulberry species germplasm have a huge potential to be exploited for identification of elite germplasm of mulberry species for mitigating enteric methane emissions and ensuring sustainable livestock feeding systems across various agro-climatic zones in India.

However, despite being a potential species for ensuring fodder security, mitigating enteric methane emissions and enhance livestock productivity, mulberry has not been utilized quality fodder production in the country and limited attention to *Mulberry* has been given by livestock and fodder researchers. Therefore, ICAR-Indian Grassland and Fodder Research Institute, Jhansi have initiated the research work on these aspects and collected a diverse collection (73 collections) of mulberry germplasm at IGFRI, Jhansi belonging to the five species (*Morus alba*, *M. latifolia*, *M. indica*, *M. laevigata* and *M. bombycis*). These collections are being evaluated under semi-arid and temperate conditions for fodder yield as well as quality traits and during initial observations under nursery conditions huge variations for growth, morphological, biochemical and fodder traits have been observed in *M. alba* germplasm. The germplasm revealed wide variations for height (81.67 to 200 cm), diameter (8.70 to 15.56 mm), and number of leaves per plant (39.33 to 189.33), total chlorophyll content (0.90 to 1.93 mg/g of fresh weight), and total carotenoid content (24.60 to 88.20 µg/g of fresh weight). Furthermore, significant variation was observed in qualitative morphological traits of leaves. Leaves were either homophyllous or heterophyllous; leaf lobation varied from being unlobed, bilobed, trilobed & tetra-lobed, leaf apex varied from acute or narrowly acute to acuminate; leaf margin was either crenate or crenulate; leaf base was either cordate or truncate or combination of both. These variations can be linked to yield and quality traits, enabling indirect selection.

Given these findings, there is a pressing need to initiate an extensive evaluation of mulberry germplasm collections to identify and screen out promising genotypes suitable for ensuring sustainable livestock feeding system in India.

Discussion

Mulberry species are potential affordable as well as scalable option for ensuring fodder security, mitigating enteric methane emissions and enhance livestock productivity in India. Therefore, there is need to collect diverse germplasm of mulberry species and evaluate it across various agro-climatic zones in India for screening out promising genotypes for fodder yield as well as quality traits and reducing enteric methane production to ensure sustainable livestock feeding system in India.

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Potential of pastoral-based agroforestry systems in climate change mitigation in the northwestern Himalayas

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Key words: Agroforestry; pasture; biomass; carbon stock; climate change

Abstract

Silvipastoral systems, which integrate trees, forage, and grazing livestock on the same land, have gained importance because of their potential for carbon storage and for improving farmers' livelihoods. A study conducted in the subtropical region of the northwestern Himalayas along the elevation gradient (Zone I: <600 m amsl and 600-1200 m amsl). In Zone I, five agroforestry systems were identified: agrisilviculture, agrisilvihorticulture, agrisilvipastoral, pastoralsilviculture, and silvipastoral, whereas Zone II represents six agroforestry systems (agrisilviculture, agrisilvihorticulture, agrisilvipastoral, pastoralsilviculture, and silvipastoral). The pastoral-based agroforestry systems were specifically categorized as agrisilvipastoral, Pastoral silviculture, and silvipastoral. Six grass species (*Simarouba glauca, Imperata cylindrica, Cercocarpus montanus, Haemonchus contortus, Cymbopogon martini* and *Apluda mutica*) were recorded in both zones under pastoral-based systems, with tree species such as *Bauhinia variegata*, *Terminalia bellerica, Albizia chinensis, Ficus palmata, Grewia optiva, Acacia catechu, Bombax ceiba, Melia azedarach, Toona ciliata, Dalbergia sissoo, Populus deltoides, Leucaena leucocephala,* and *Morus alba*. In Zone I, the Agrisilvihorticulture system had the highest total biomass, followed by silvipastoral, agrisilviculture, agrisilvipastoral, and pastoral silviculture. In Zone II, the order was agrisilvihorticulture > silvipastoral > agrisilviculture > agrisilvipastoral > agihorticulture > pastoral silvicultureHowever, soil carbon stock was the highest in the silvipastoral system, resulting in the highest overall carbon stock in the silvipastoral system, these findings suggest that silvipastoral systems in subtropical regions have significant potential for carbon storage while meeting livestock forage demands, making them a valuable strategy for climate change mitigation in the subtropical western Himalayas

Introduction

Livestock is a key component of the agricultural system in India, and is crucial for the livelihood of rural households (Hemme and Otte 2010). Due to the rise in livestock population, increased forage demand has led to low livestock production (DAHD&F 2021). Forage production in India has always been hampered by the unavailability of sufficient arable land with irrigation facilities and changes in the land-use system. In addition, climate change has affected the productive capacity of land for high-quality forage production. Therefore, a balanced and sustainable land-use system is required to meet the forage demand, climate change mitigation, and livelihood security of rural communities. Incorporating fodder trees with grass/other components of land use is considered a climate-change-resilient land-use system (Mbow et al., 2014). The integration of fodder trees with agricultural crops or grasses is termed agroforestry practice.

In agroforestry, the integration of fodder trees with agricultural crops or grasses is classified into different systems such as Agrisilviculture, Agrisilvihorticulture, Agrisilvipastoral, Pastoralsilviculture, and Silvipastoral systems. By integrating ecological functions with productive agricultural activities, silvopasture systems hold immense promise for confronting the challenges posed by climate change (Lawson et al., 2018; Rosenstock et al., 2019). Silvopasture/pastoralsilviculture systems represent a dynamic fusion of trees, forage, and livestock, meticulously orchestrated to optimize land productivity and ecological resilience (Jose, 2009; Peters et al., 2013). However, the synergies of tree-grass associations need to be explored and exploited by evaluating different fodder tree species with a combination of grass species under different climatic conditions. Furthermore, besides fulfilling fodder demand, agroforestry has been identified as having the greatest potential for carbon sequestration among all land uses (Nair and Garrity, 2012). The global assessment of carbon accumulation in agroforestry varied from 0.29 to 15.2 Mg C ha^{-1} $year^{-1}$ aboveground and 30–300 Mg C ha^{-1} $year^{-1}$ for soils down to 1 m depth (Nair et al. 2009). Based on the areas assessed as suitable for agroforestry interventions, a carbon storage potential of 1.1–2.2 Pg. C have been estimated globally (Albrecht and Kandji, 2003). Therefore, agroforestry is receiving increased attention in global initiatives, such as Reducing Emissions from Deforestation and Forest Degradation (REDD), because of its implication in improving and regulating climate variability (Jose and Bardhan, 2012). While previous studies have highlighted the potential of agroforestry systems for carbon sequestration, the specific contribution of silvopastoral systems in the northwestern Himalayas remains understudied, particularly across agroforestry systems. This study aims to evaluate the biomass and carbon sequestration potential of pastoral-based agroforestry systems across two elevation zones in the northwestern Himalayas, with a focus on silvopastoral systems as a climate-resilient strategy.

Methods

The study was conducted in two elevation zones, Zone I (< 600 m amsl) and Zone II (600-1200 m amsl), in the Nalagarh block of the Solan district of Himachal Pradesh, India. The stratified random sampling technique was used for the selection of the study area at two elevation zones, and then the sample plots were randomly distributed in each elevation zone. The existing agroforestry systems in the selected study area were classified into six types based on the structure (nature and arrangement) and function (role/output) of their components.

A 30 × 10 m^2 sample plot was laid in each agroforestry system. Within each sample plot, two subplots of 10 × 10 m and four subplots of size 50 × 50 cm were marked to observe respectively shrubs and herbage. To estimate agricultural crop biomass, four quadrats of size 2 × 2 m were marked for each system type. The aboveground tree biomass was estimated by a non-destructive method using volume equations developed by FSI (1996). Soil samples were collected from each plot at depths of 0-20 cm using a soil auger. Tree, herb, shrub, crop biomass, and tree carbon stock was calculated using the methods described by Singh and Kumar (2018). (2022). The collected data were statistically analyzed at a 5 percent level of critical difference using the software package "STATISTICS".

Results

Identification of pastoral-based silvopasture systems.

In zone I, the pastoralsilviculture system incorporated timber, fuel, and fodder trees, such as *Terminalia bellerica, Dalberigia sisso, Albizzia chinensis, Bauhinia variegata*, and *Ficus palmata*. Alongside these trees, various grass components, including *Seteria glauca, Imperata cylindrica, Chrysopogon montanus, Heteropogon contortus, Cymbopogan martinii*, and *Apluda mutica* were present. In the agrisilvipastoral system in Zone I, maize, brinjal, okra, rice, blackgram, and tomato were cultivated during the kharif season, whereas wheat, cauliflower, radish, barley, and onion were grown during the rabi season. Along the field bunds Various trees, such as *Cassia fistula,* *Dalbergia sissoo, Terminalia bellerica*, and *Toona ciliata*, were strategically planted in different quantities and arrangements. *Populus deltoides* trees played a significant role in this agroforestry system, being intentionally planted at various densities. Additionally, a mix of grasses, such as *Imperata cylindrica, Heteropogon contortus, Apluda mutica, Cymbopogon martini*, and *Chrysopogon montanus*, adorned the field bunds in assorted combinations.

In zone II, the pastoralsilviculture system comprised six distinct system units, incorporating a range of grasses, such as *Apluda mutica, Seteria glauca, Imperata cylindrica, Chrysopogon montanus, Heteropogon contortus*, and *Cymbopogon martinii*. Alongside these grasses, the system featured tree components, such as *Terminalia bellerica, Bauhinia variegata, Ficus palmata,* and *Albizzia chinensis*. Within the agrisilvipastoral systems in Zone II, farmers cultivate three primary cereal and vegetable crops (maize, rice, and okra) during the Kharif season and wheat, mustard, radish, and barley during the Rabi season. Along the field bunds in these systems, farmers intentionally planted trees, such as *Leucaena leucocephala, Morus alba, Albizzia chinensis, Grewia optiva, Bombax ceiba*, and *Bauhinia variegata*. Grasses such as *Digitaria stricta, Themeda anathera, Imperata cylindrica, Apluda mutica*, and *Cymbopogon martinii* were also cultivated. The pastoralsilviculture includes the trees species like *Grewia optiva, Bauhinia variegata, Ficus palmata, Morus alba, Leucaena leucocephala, Albazzia chinensis*, and *Bombax ceiba* along with *C. martinii, D. stricta, A. mutica, H. contortus, P. maximum*, and *T. anathera* as grass component.

Biomass and soil carbon density

The different types of agroforestry systems and varying elevation zones significantly influenced aboveground, belowground, and total biomass. In elevation zone I, the sequence of total aboveground biomass was highest in agrisilvihorticulture (29.57 t/ha), followed by Silvipastoral (27.97 t/ha) and Agrisilviculture (24.68/ t/ha). Similar trends were observed in Zone II, where Agrisilvihorticulture achieved 11.32 t/ha, followed by Silvipastoral (9.53 t/ha). The maximum belowground biomass in zone I was reported in Agrisilvihorticulture, Agrisilviculture, and Silvipastoral. Conversely, in elevation zone II, the maximum belowground biomass was recorded in the agrosilvihorticulture system, followed by the silvipasture system. The total biomass was found to be the highest in the Agrislivihorticulture system. The soil bulk density at elevation zone I was the highest in pastoral-silviculture, followed by silvipasture. In contrast, in elevation zone II, the highest value was recorded in the slivupasture system, followed by the pastoralsilviculture system. The soil organic carbon was found highest under Silvipastoral system (0.81 %) followed by Pastoral silviculture system (0.78 %).

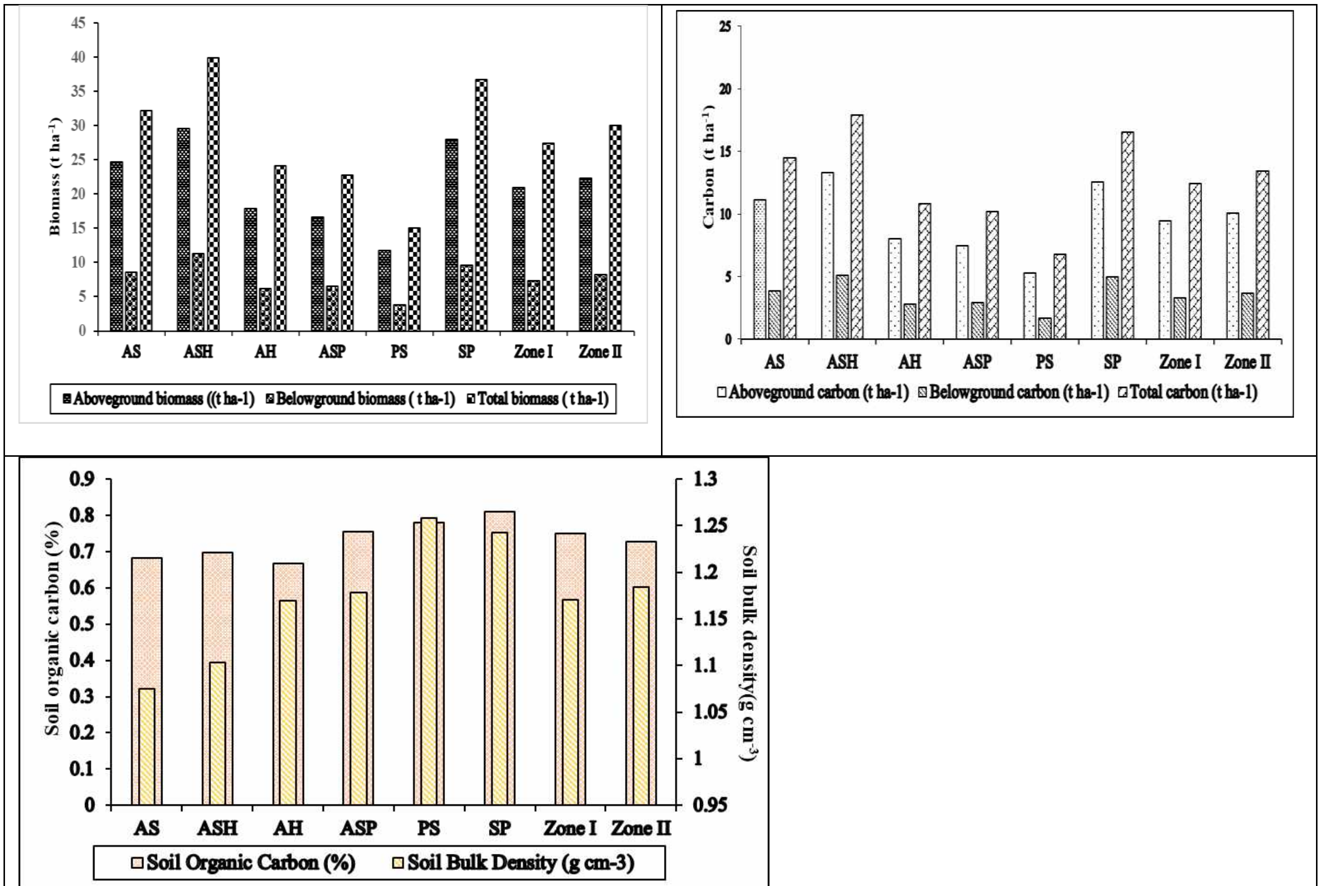

Figure 1: a) Above ground, below ground and total biomass (t ha^{-1}) of different agroforestry systems at two elevation zone; b) above ground carbon, below ground carbon and total carbon of different agroforestry systems at two elevation zone (t ha^{-1}); c) soil organic carbon (%) and soil bulk density (g cm^{-3}) of different agroforestry systems at two elevation zone. AS: agrisilviculture system; ASH: agrosilvihorticulture; AH: agrihorticulture; ASP: agrisilvipastoral; PS: pastoralsilviculture; SP: silvipastoral

Discussion

Agroforestry is a key component of climate change mitigation and livelihood security. Various agroforestry systems and their units have been studied in both the elevation zones. In this context, various researchers have recorded the same number of agroforestry systems with their respective units in the midhills of the northwestern Himalayas (Upadhyaya 1997; Goswami 2008). The multipurpose trees were recorded to exist in varied numbers on the bunds of agricultural fields, except for *P. deltoides* trees, which were regularly spaced all around the agricultural field. Trees of *D. sisoo, M. azedarach, C. fistula,* and *S. cumini* were found on bunds of agricultural fields, providing fuelwood, minor timber, and fodder for subsistence**.** Among the existing agroforestry systems, agrisilviculture, agrisilvihorticulture, and agrisilvipasture systems illustrate a greater diversity in their components.

In agroforestry, biomass accumulation and carbon sequestration are influenced by various factors, including climatic conditions, soil characteristics, phenology, and floristic diversity, which mainly occur through the absorption of atmospheric CO_2 during photosynthesis and the transfer of fixed carbon into vegetation, detritus, and soil pools for long-term storage in aboveground and belowground major segments (Baes *et al.* 1977; Nair *et al.* 2010). In the current study, the biomass and carbon stock were highest in agrisilvihorticulture, followed by the silvipasture system at elevation zone II. These findings are consistent with those of Singh (2017) and Bammanahalli (2016) in the subtropical region of Himachal Pradesh. Variations in biomass and carbon production are influenced by plant species diversity and genetic diversity interactions within dominant plant species (Crawford and Rudgers 2012). Goswami *et al.* (2014) found that agrisilvihorticulture and agrihortisilviculture systems produced higher biomass than the silvipasture system, as well as pure agriculture or grassland in the western Himalayan watershed. The higher biomass production observed at elevation zone II could be attributed to a greater number of tree species in the agroforestry systems, closer proximity to plant management practices, and variations in species composition. It is well established that incorporating trees into croplands and pastures enhances both aboveground and belowground carbon sequestration (Palm *et al.* 2004; Haile *et al.* 2008

The soil organic carbon content in the present investigation ranged from 0.66% to 0.81%, with the highest levels recorded in the silvipastoral system, followed by the pastoral silviculture system. Similar organic carbon levels have been reported by various researchers in agroforestry soils of the northwestern Himalayas (Rajput et al., 2015; Prenil, 2014; Singh, 2014; Bhutia, 2017). The higher soil carbon stock observed in silvopastoral systems may be attributed to enhanced organic matter input from tree litter and root exudates, which promote microbial activity and soil aggregation, thereby improving carbon retention. These findings highlight the significant role of agroforestry in climate change mitigation. Among various agroforestry systems, the agrisilviculture system exhibits high potential for carbon sequestration and food security, whereas the pastoral silviculture and silvipastoral systems store the highest soil organic carbon while also meeting the nation's fodder demand.

Therefore, it is concluded that in the midhills of the northwestern Himalayas, agrihortisilviculture followed by silvipastoral and pastoralsilviculture systems have a greater scope for climate change mitigation.

Table 1: Crop combination with tree components by different farmers s in terms of system units at elevation zone I and zone II.

Agroforestry systems	Agriculture/grass component		Tree components
	Kharif	Rabi	
Zone I			
Agrisilviculture	Zea mays (Maize), Capsicum annuum (Chilli), Abelmoschus esculentus (Okra), Solanum lycopersicon (Tomato) Solanum melogena (Brinjal), Oryza stavia (rice), Vigna mungo (Blackgram), Curcuma longa (Turmeric)	Triticum aestivum (Wheat), Hordeum vulgare (Barley), Brassica juncea (Mustard), Allium. cepa (Onion), Brassica oleracea (cauliflower), R. raphanistrum & Brassica juncea	Dalbergia sisso, Bahunia variegata, Bambax ceiba, Toona ciliata, Ficus palmata, Populus deltiodes, Grevia optiva, Morus alba, Melia azedarach,
Agrisilvihorticulture	Zea mays, Capsicum annuum, Abelmoschus esculentus, Solanum Lycopersicon, Solanum melogena, Oryza stavia, Curcuma longa & Vigna mungo	Triticum aestivum, Brassica juncea, Allium Cepa, Brassica oleracea oleracea, R. raphanistrum, Hordeum vulgare	Morus alba, Grewia optiva, Citrus limon, Mangifera indica, Psidium guajava, Melia azedarach & Cassia fistula

Pastoralsilviculture	**Grasses:** Simarounba glauca, Imperata cylindrica, Cercocarpus montanus, Haemonchus contortus, Cymbopogon martini, Apluda mutica, C. martini		Terminalia bellerica, Dalbergia sisoo, Albizia chinensis, Bahunia variegata, Ficus palmata, Grevia optiva, Acacia catechu & Bombax ceiba
Agrisilvipastoral	Zea. mays, Oryza stavia, Abelmoschus esculentus, Solanum melogena, Solanum Lycopersicon, Vigna mungo	Triticum aestivum, Brassica oleracea, R. raphanistrum, Hordeum vulgare, Allium cepa, Brassica juncea	Populus deltoides, Cassia fistula, Dalbergia sissoo, Terminalia bellerica, Toona ciliata, Grevia optiva, Albizia chinensis, Bombax ceiba
	Grasses: Imperata cylindrica, Haemonchus contortus, Apluda mutica, Cercocarpus montanus, Simarounba glauca, Cymbopogon martini		
Silvipastoral	**Grasses:** Cercocarpus montanus, Haemonchus contortus, Imperata cylindrica, Apluda mutica, Simarounba glauca, Cymbopogon martini		Melia azedarach, Terminalia bellerica, Toona ciliata, Bombax ceiba, Dalbergia sissoo, Bahunia variegata, Albizia chinensis
Zone II			
Agrisilviculture	Z. mays, C. annuum, A. esculentus, S. melogena, V. mungo, C. longa, S. lycopersicon C. annuum, A. esculentus	T. aestivum, R. raphanistrum, H. vulgare, B. juncea, A. sativum, H. vulgare, B. oleracea and A. cepa	G. optiva, A. chinensis, L. leucocephala, T. bellerica, M. alba, F. palmata, B. variegata, L. leucocephala, B. ceiba, Z. mauritiana & A. chinensis
Agrisilvihorticulture	Z. mays, C. annuum, A. esculentus, O. sativa, C. longa & S. lycopersicon,	T. aestivum, B. juncea, R. raphanistrum, H. vulgare, A. cepa	G. optiva, A. chinensis, L. leucocephala, C. limon, T. bellerica, M. alba, F. palmata, B. variegata
Agrisilvipastoral	Z. mays, A. esculentus, O. sativa,	T. aestivum, R. raphanistrum, B. nigra, B. oleracea, H. vulgare & B. juncea	L. leucocephala, M. alba, A. chinensis, B. ceiba, G. optiva, B. variegata M. indica, B. variegata + C. limon, F. palmata, T. belerica & Z. mauritiana
	Grasses: T. anathera, A. mutica, C. martinii, I. cylindrica P. maximum, D. stricta, C. longa, S. Lycopersicon, C. annuum, V. mungo, S. melogena, C. montanus, H. contortus & I. cylindrica		
Pastoralsilviculture	C. martinii, T. anathera, H. contortus, D. strica, A. mutica, P. maximum, I. cylindrica & C. montanus,		M. alba, B. ceiba, F. palmata, G. optiva, A. catechu, L. leucocephala, B. variegate, Z. mauritiana, T. belerica, A. chinensis, T. bellerica, A. catechu
Silvipastoral	A. mutica, H. contortus, I. cylindrica, P. maximum, C. martini, D. stricta, & C. montanus		G. optiva, M. alba, B. variegata, L. leucocephala, Z. mauritiana, T. belerica, B. ceiba, F. palmata, A. catechu, A. chinensis & F. palmata

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Developing a tool to assess soil carbon sequestration potential in the Northern Australian rangelands

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Abstract

We conducted a large research project to address knowledge gaps relating to how grazing management may affect soil organic carbon (SOC) in the northern Australian rangelands. 2257 soil cores over 908 sites were sampled to a depth of 120 cm, and SOC and other relevant soil parameters were determined at 5 cm intervals using spectroscopy. Additionally, in-situ information on land type, land condition and time-series observations of total biomass, vegetation cover, surface reflectance were collected from satellite sensors. The results showed a positive correlation between SOC and land condition. We integrated these results in a modelling tool which will allow us to identify the greatest opportunities for SOC sequestration in the rangelands and potential scenarios of improved grazing management.

Introduction

Increasing Soil Organic Carbon (SOC) by improving grazing management is being rapidly adopted by the livestock sector as an option for improving soil health and offsetting greenhouse gas emissions. The feasibility of significantly increasing SOC through improved grazing management in semi-arid regions remains less evident (Henry et al 2024, McDonald et al 2023, Bartley 2023). Changes in SOC often occur slowly over long periods, requiring resource intensive long-term monitoring to detect significant trends. Our goal is to develop a tool which integrates soil and vegetation sampling, remote sensing data and modelling to assess the dynamics of SOC in the rangelands. A critical step is to understand and account for the long-term effects of management (especially grazing) and SOC. We used an indirect way to account for grazing management: we assessed Land Condition (LC) and assumed that sites with the same land type (i.e. geomorphology and vegetation) but contrasting LC have had differences in grazing management in recent years. The underlying hypothesis that we tested is that sites with better LC will have higher SOC.

Methods

We sampled soil properties, vegetation type, LC and historical land management across the Australian Agricultural Company (AACo) cattle stations in the northern rangelands. We sampled the variability in land types using land mapping from Queensland and the Northern Territory. We also used a land type classification generated in house using digital soils mapping techniques (e.g. Minasny 2015), combining data inputs from the Landsat sensor including fractional and persistent green cover (JRSRP, 2022), and the Radiometric Grid of Australia (Wilford, 2019). We also identified locations with the same land type but contrasting LC scores across a fence. Additionally, we selected 15 paired sites either side of the fence between the cattle grazed Brunette Station and the Connells Lagoon Conservation reserve, which has been intentionally left unburnt and ungrazed since 1982 (Australian Heritage Database, accessed Dec 2024).

Soil sampling

Soil samples were taken to a depth of 120 cm. Five cores, 10 m apart linearly, were sampled per site in 2022. This was reduced to 3 in 2023 following analysis of the 2022 data (Figure 1). The cores were kept refrigerated at 5°C and transported to a laboratory where they were analysed using the SCANS system (Viscarra Rossel et al 2017). Soil and SOC mass for each 5cm sublayer in each core were calculated following DCCEEW (2024) for spectral modelling. Carbon mass was reported on specified soil masses rather than depth to avoid inaccuracies due to core compression, core recovery and changing bulk density in swelling clays. Results are reported for 3500 and 7000 t soil/ha. These masses represent sampling depths of approximately 30 and 56 cm.

Vegetation and Land Condition

Land condition (LC) is a relative measure of the health of grazing lands and is determined by simultaneously assessing indicators of soil and pasture condition, woodland thickening and the presence of weeds (Future Beef, accessed Dec 2024). Rangeland officers with experience in the AACo grazing lands performed a rapid visual assessment in each sampling site following the specific regional guidelines published by the Northern Territory or Queensland. To account for conditions which were intermediate between the four ABCD classes, the officers rated each site using a 7-class system including: A, A-B, B, B-C, C, C-D and D.

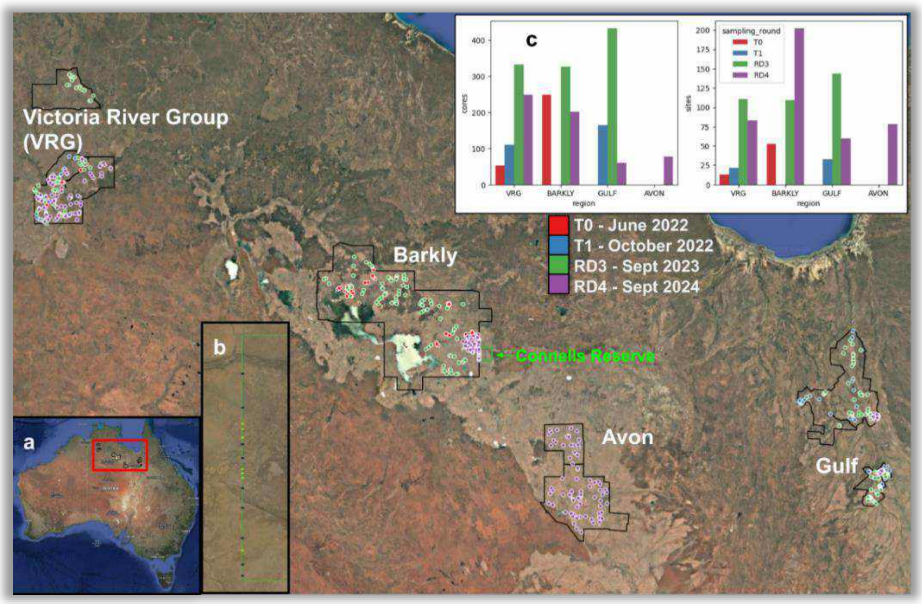

Figure 1: Location of the soil samples collected. Symbol colours correspond to the sampling round as: T0: May/June 2022, (5 cores per site); T1: September 2022, (5 cores per site); RD3: September 2023 (3 cores per site) and RD4: September 2024 (1 core per site). Inset a shows the location of the study area in Australia. Inset b shows the paired sites across the fence dividing Brunette Station (left) from the Connells Conservation Reserve (right). Black and green dots correspond to the clays and rises respectively. Inset c shows the number of cores (left) and the number of sites (right) per region and sampling round.

Landscape carbon model

The landscape carbon tool integrates a series of models with spatial data and spatially referenced databases for model parameters and management events. The key integrated models include a simple pasture growth model, which is coupled with an implementation of the RothC soil carbon model for Australian conditions (Janik et al., 2002, Skjemstad et al., 2004). LC can be incorporated as either a direct multiplier that affects pasture productivity (Net-Primary Productivity) or as a modifier of the soil cover setting in Roth-C. The final calibration of the integrated model is currently in progress utilising the extensive empirical dataset collected through this project. The initialisation of the SOC pools in RothC is taken from soil carbon baseline mapping, for which we employed a multi-layer perceptron (MLP) model (LeCun et al 2015), trained using soil sampling data collected in the project. Inert Organic Carbon could not be directly measured and was therefore estimated based upon the Soil and Landscape Grid of Australia (SLGA) (Wadoux et al 2022) data. The clay fraction is also determined from the trained MLP model outputs for the AACo estate. Where this more specific data is not available, the model can be run using SLGA data.

Results

We collected 2257 soil cores over 908 sites between June 2022 and September 2024 (Figure 1). Of these, 450 cores from 150 sites were taken at locations where Land Condition varied across a fence (75 pairs) and 30 cores (15 pairs) corresponded to paired sites in the Brunette Station – Connells Reserve.

Soil Organic Carbon and Land Condition

SOC mass was positively correlated with Land Condition (a), but the low Pearson's correlation (0.162) indicated that many other factors also determine SOC. Nevertheless, the low p-value from linear regression analysis showed a very low p value, indicating that the probability of finding these results if LC and SOC were not correlated are extremely low. The slope of the regression (1.95) suggests that by every point of improvement in LC (e.g. from C to B condition) results in an average increase in SOC of 0.65 ton C per ha. The 75 paired sites with contrasting LC had a mean difference of SOC of 0.25 ton C/ha (t-test p= 0.11) (b). SOC was, on average, 1.49 ton C/ha higher in the Connells Conservation Reserve (ungrazed) than in Brunette Station (grazed) (c) (t-test p= 0.015). The difference between the grazed and ungrazed SOC was much higher in the rises (mean = 2.53 ton C/ha) than in the clays (mean = 0.58 ton C/ha).

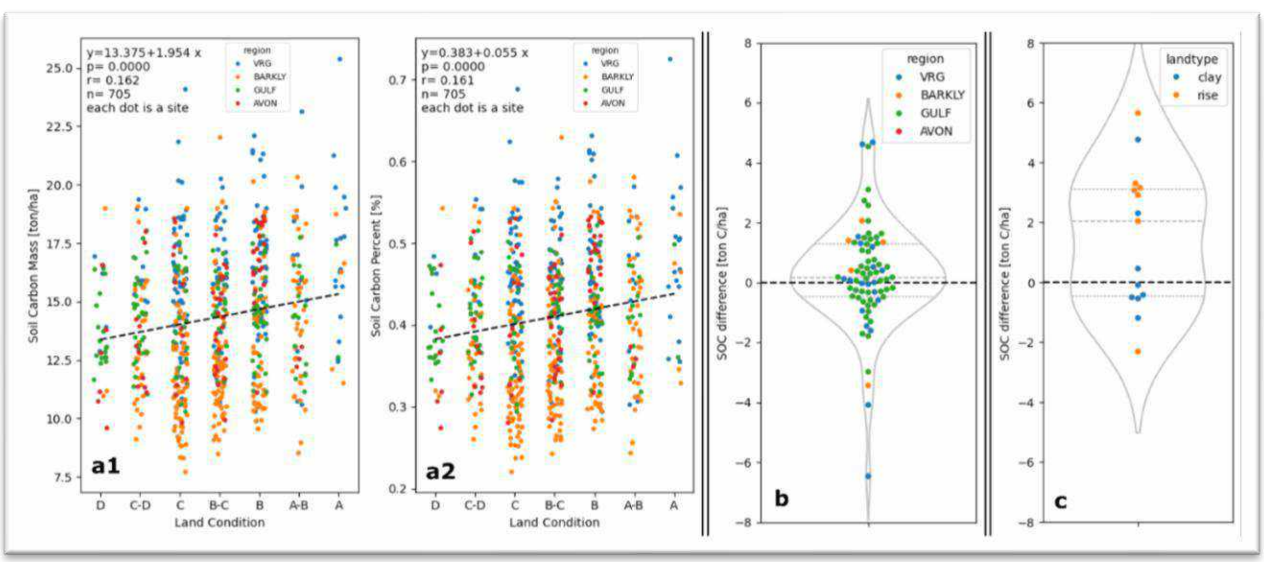

Figure 2: Soil Organic Carbon (SOC) and Land Condition (LC). Panels a1 and a2 show the relationship between SOC and LC over all sites in the study. The black dotted lines show the linear regression between SOC mass (a1) and SOC percent (a2) and LC, where LC was given an ordinal value ranging from 0 (D) to 1 (A). Panel b shows

a swarm plot and violin plot of the difference in SOC mass in the paired sites (n=75). The difference was calculated always as the mass on the better LC side minus the SOC mass in the worse LC side of the fence. Panel c shows the difference in SOC mass for each paired site between the Conells Conservation Area (ungrazed) and the Brunette Station (grazed).

Soil Organic Carbon Baseline and Landscape Carbon modelling

Figure 3a shows the baseline SOC map of the study area. Figure3b shows an example simulation based on preliminary model calibration. The simulation incorporates the time-series climate data, together with site specific soil properties. Two scenarios were simulated: business as usual, and an improved Land Condition. Both scenarios have the same historical data and assumptions, with the improved Land Condition, scenario only differing from 2025 with an assumed uplift in Land Condition. The interannual variation due to climatic variability, influencing both pasture growth and soil carbon decomposition, is obvious. As the scenarios move into a projection from 2025, both scenarios show the same underlying variability due to the cycled climate data, with a gradual build in the soil carbon mass for the improved Land Condition over the 20-year projection period compared to the business-as-usual scenario.

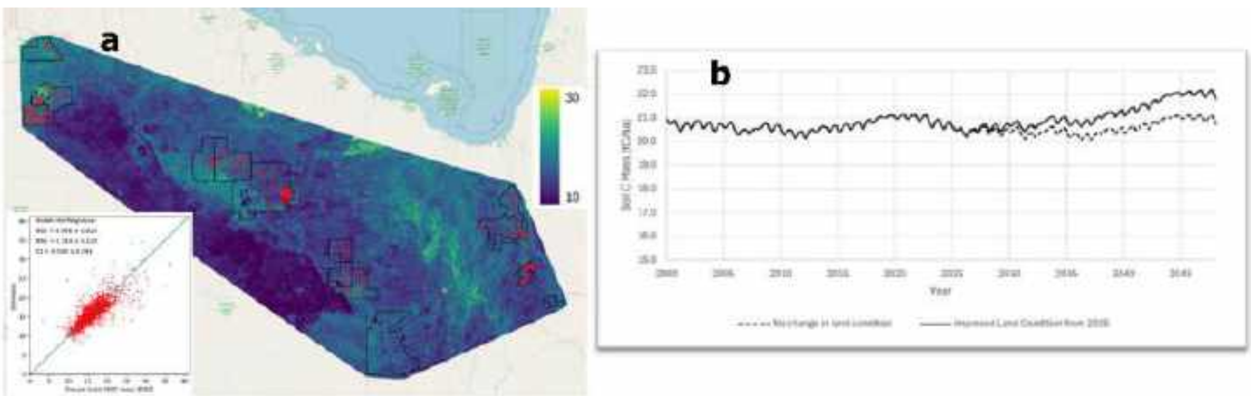

Figure 3: a: Soil Organic Carbon Baseline showing the SOC mass in the top 3500 tons of soil in ton SOC per ha. The red dots show the soil sampling locations. The inset scatterplots show the relationship between the measured SOC and the SOC value from the baseline. b) Example SOC Mass for top 3500t soil mass, historical trend, and projected scenarios from 2025 for a 'No change in Land Condition' and an 'Improved Land Condition scenario'

Discussion

With these comprehensive data we assessed the relationship between SOC and land management in 3 ways. In two of these we used Land Condition as a proxy for grazing management effects on the vegetation and soils with a space-for-time method. We found a noisy but positive and statistically significant relationship between LC and SOC. On average, the difference due to one LC class (e.g. class C vs B) resulted in a difference of 0.65 ton C per ha. When we compared contrasting LC states across a short distance over a cattle fence, however, the differences we found were more modest (0.25 ton C/ha higher on the better LC side). We speculate that LC is indeed a useful indicator of SOC in Australia's northern grazing land, and the experiments of Bray et al (2014) did not have the statistical power to find such results due to a more limited sampling size. As in all space-for-time methods we need to be cautious about the potential pitfalls of the approach. First, the correlation between SOC and LC does not conclusively prove a causal link. Second, these findings do not answer the question: if land condition is improved, how long it will take to see increases in SOC? Other studies suggest that in arid lands this could take at least 5 to 20 years (Bartley et al 2023). Our preliminary simulation results using the integrated model support this, with climatic variability remaining an important driver, with a gradual modest long-term increase in SOC. The results found in the Connells Reserve / Brunette Station fence further support the causal connection, and positive response of SOC to management change. There, the difference in SOC between the excluded and the grazed areas was on average 1.5 ton C/ha. We speculate that the increase in SOC under a better grazing strategy could potentially be even higher (Stanley et al 2024). Even though this study provides the most extensive sampling, and convincing evidence of the potential for SOC sequestration in the Northern Australian Rangelands, the establishment of long-term grazing trials would be invaluable. Using these results we produced a SOC baseline for the wider area under study and a process-based model that allows to simulate Carbon stocks and fluxes over time. Our tool is being refined and will enable us to accurately and affordably estimate soil and vegetation carbon in Australian rangelands.

Acknowledgements
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Carbon sinks in grazing systems

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XII INTERNATIONAL RANGELAND CONGRESS
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Wyoming sagebrush rangeland soils are a weak methane sink

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Key words: Dormant season; Soil carbon fluxes; Soil moisture; Cattle urine; Greenhouse gas

Abstract

Dryland ecosystems cover 41% of Earth's terrestrial surface while providing 60% of the world's food production, and 50% of the world's livestock. Drylands also account for 30% of global carbon while operating as a carbon sink, carbon neutral, or a carbon source depending on the season and availability of soil moisture. Within dryland soils, methanotrophs, methane (CH_4) consuming bacteria, are present and could aid in reducing methane from the atmosphere. However, the influence that methanotrophs have in the overall soil carbon flux of dryland soils is less known. To understand their influence, we established a soil flux experiment in a semi-arid Wyoming sagebrush (*Artemesia tridentata wyomingensis* Nuttall, Beetle & Young) plant community in western North America. We measured *in situ* CO_2 and CH_4 soil fluxes at 30-minute intervals for 16 days during the dormant season. For four days we established a soil flux baseline before adding 200-mL of cattle urine to a subset of plots to observe how cattle might influence soil carbon fluxes. We also added 200-mL of distilled water to the remaining plots as a control. We then measured all plots for an additional 12 days. We found that during the dormant season the sagebrush soils were consistently a weak CH_4 sink, while CO_2 was a weak source, and the addition of cattle urine only augmented those dynamics. We also found a diurnal pattern which coincided with increased surface air temperatures. During the nighttime, both soil CH_4 and CO_2 were carbon sinks, but between 0800 and 1600 hr soil CO_2 fluxes became a carbon source while CH_4 fluxes remained a carbon sink. These results suggest that our semi-arid Wyoming sagebrush rangelands can act as a methane sink even during the dormant season and the strength of the methane sink during the dormant season is based on soil moisture.

Introduction

Even though dryland ecosystems are considered neutral carbon sinks to atmospheric CO_2, dryland soil microbial communities include methanotrophs capable of consuming atmospheric CH_4, making drylands potentially very important in the global carbon cycle. The importance and magnitude of CH_4 consumption in drylands are still uncertain, as our understanding of the underlying mechanisms driving the microbial community activity are unclear (Song et al. 2024). Generally, warm and dry or warm and moist soils provide ideal conditions for methane-oxidizing bacteria to consume the greatest amounts of CH_4, while cold and wet soils reduce CH_4 consumption rates (Wen et al. 2024). Therefore, desert steppe drylands such as North American sagebrush steppe where soils experience prolonged drying regimes (ca. 5 months) coincident with warming temperatures provides potentially a consistent CH_4 sink for atmospheric CH_4.

Atmospheric CH_4 is the second most abundant greenhouse gas in the atmosphere and has more than tripled since preindustrial levels because of anthropogenic activities (Canadell et al. 2021). Globally, livestock account for ~30% of anthropogenic CH_4 emissions (Jackson et al. 2020). Methane emissions from livestock in the United States accounts for 4% of the overall CH_4 emissions in agriculture (Dillion et al. 2021), however it is estimated most of the emissions come from cow-calf production and stockers grazing on lower quality forage in drylands (Vargas et al. 2024). Drylands provide forage for 50% of livestock globally, suggesting soil processes in these drylands are likely impacted by livestock excreta such as urine. Livestock urine provides a high nitrogen deposit in liquid form which is readily available to soil microbes and has the potential to increase microbial activity which would result in higher soil respiration rates as well as higher CH_4 consumption in dryland soils. The objective of this study was to characterize how cattle urine influences soil respiration and methane consumption in the warm late-season plant dormant period of drylands soils. Specifically, we wanted to quantify if cattle urine deposition increased soil methane consumption and soil respiration because of the available nitrogen present in the urine. To address this, we added cattle urine to Wyoming sagebrush steppe soils and repeatedly monitored soil respiration and CH_4 consumption over a 14-day post-urine application period.

Methods

The study was conducted at the USDA-Agricultural Research Service Northern Great Basin Experimental Range (NGBER, 43.471507, -119.691100), located about 70 km west of Burns, OR, USA. The study site is situated in a Wyoming sagebrush (*Artemesia tridentata* subsp. *wyomingensis* Bettle & Young), Sandberg's bluegrass (*Poa secunda* J. Presl.), bluebunch wheatgrass (*Psuedorogenaria spicata* [Pursh] Á. Löve) and Idaho fescue (*Festuca idahoensis* Elmer) plant community at 1397 m asl. The soils at the study site were classed as a Vil-Decantel, Variant-Ratto complex which are well drained and have a duripan at 30-50 cm. Soil texture in the top 10 cm was determined to be a sandy clay loam using the hydrometer method.

We deployed two opaque soil respiration chambers connected to an LI-8250 multiplexer and LI-7810 CH_4 and CO_2 trace gas analyzer (LI-COR Environmental, Lincoln, NE USA). The chambers sat on PVC soil collars that were placed in the interspace between Wyoming sagebrush and native bunchgrasses over bare soil. Soil fluxes were sampled every 2 hrs from 07 September 2022 to 26 September 2022. On 12 September 2022 we applied 200 ml of Angus-Hereford cattle urine to one soil respiration chamber plot, and 200 ml of DI H_2O to the other soil respiration chamber plot. The amount of beef cattle urine applied to each soil respiration chamber plot equates to the average amount released during a urination event by a mature beef cow corrected for the volume of the soil respiration chamber plot (Yamulki et al. 1998, Misselbrook et al. 2016). Cattle urine was collected following FASS approved methodology (Canton et al. 2020).

Results

Even though both chambers were less than 2 m apart we observed the variability in soils in the separation between the two treatments, which was most pronounced in the CH_4 flux. Regardless of this difference we observed that soil CO_2 flux increased the most on September 12 when urine was added to the plot compared to water; incidentally there was also a small precipitation event that occurred the night prior to the urine and water additions (Fig. 1). The influx in available nitrogen from the urine did not alter the flux direction of CH_4, but subsequent precipitation events did increase the CH_4 flux closer to zero, indicating weaker CH4 sink activity. There was a small diurnal pattern observed for the soil CO_2 flux between 0800 hr to 1600 hr, while there was no diurnal pattern captured for the soil CH_4 flux with urine added to the soil, but a potential decrease in CH_4 flux strength where water was added to the soil between 1000 hr and 1600 hr (Fig. 2).

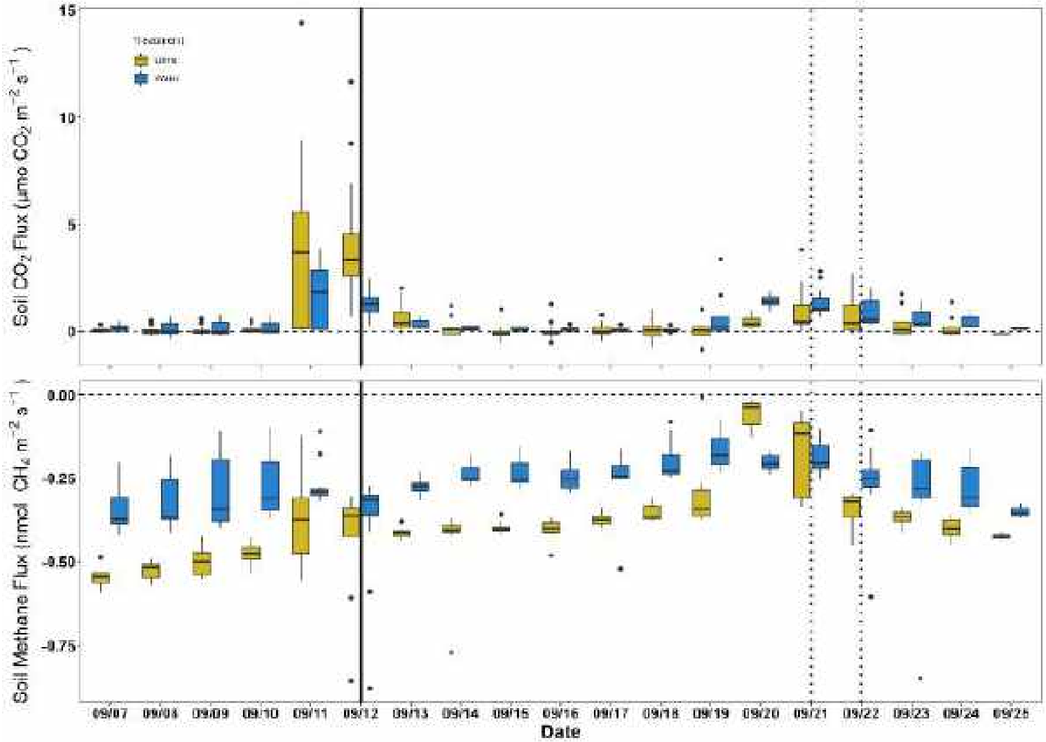

Figure 1. Daily average soil CO_2 (top panel) and CH_4 (bottom panel) fluxes from 07 September – 25 September 2022. Blue boxes are for water addition while yellow boxes are for urine addition. The black vertical bar represents the day water or urine was applied to the plots, and the dotted blue vertical line represents a day when it rained.

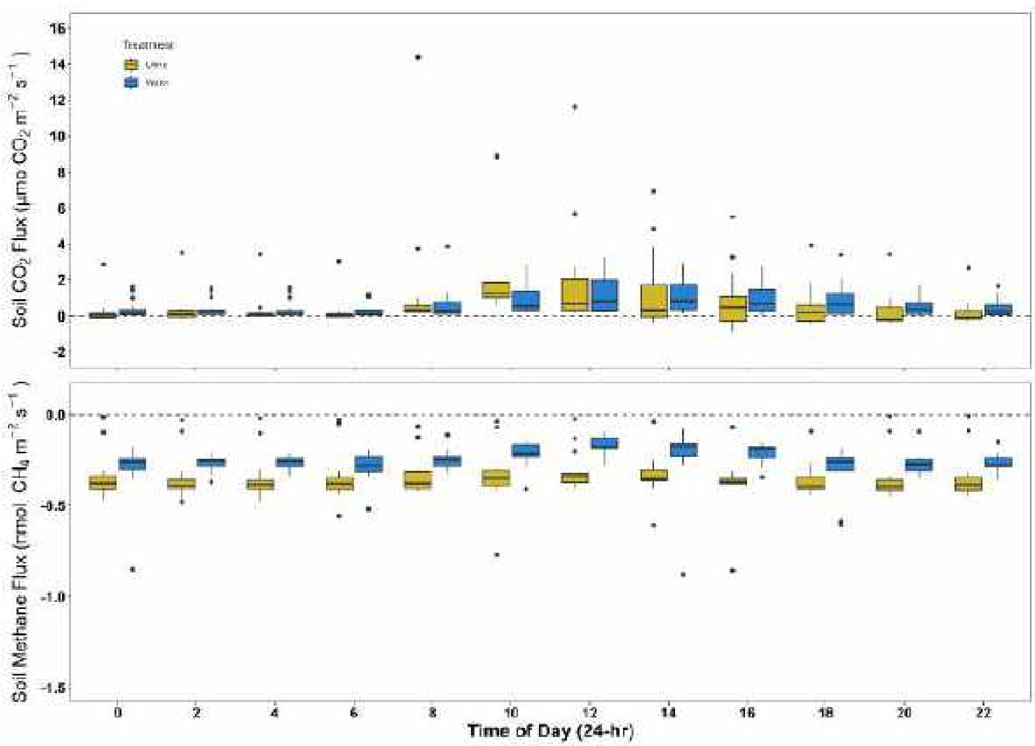

Figure 2. Diurnal soil CO2 (top panel) and CH4 (bottom panel) fluxes averaged across September 12 - September 25, 2022 observations. Blue boxes are for water addition while yellow boxes are for urine addition plots. Data were aggregated during their respective sampling times across the monitoring time.

Discussion

Our data suggests that Wyoming sagebrush steppe rangeland soils act as a weak CH_4 sink in the dormant season regardless of the addition of beef cattle urine or water. However, this soil sink strength is reduced when under moister soil conditions. Additionally, our diurnal data showed that from 10:00 to 16:00 CO_2 efflux increased, regardless of urine or water additions making these soils a weak source of carbon. Over these same periods, CH_4 flux was consistently negative, indicating they acted as a weak methane sink regardless of diurnal variation in soil conditions. Urine deposition possibly increased CH_4 uptake across the study period (Fig. 1), at least in part due to decreased diurnal variation in sink strength (Fig. 2), which likely reflects greater methanotrophic microbial activity. However, this pattern needs to have additional replication to parse out the heterogeneity of soil and the actual effect of cattle urine on the sink strength of CH_4. This project only demonstrates that more research is needed to study CH_4 dynamics in semi-arid Wyoming sagebrush steppe rangeland soil, and that it is critical to determine and how precipitation and livestock activity interact to influence seasonal CH_4 sink strength dynamics, and how these change across seasons and with plant community structure. Our findings and experience will be used to expand this research effort of understanding CO_2 and CH_4 dynamics to a larger spatio-temporal extent with beef cattle grazing in a native Wyoming sagebrush steppe plant community.

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XII INTERNATIONAL RANGELAND CONGRESS AUSTRALIA 2025

Enhancing carbon sequestration in western U.S. rangelands through responsible wool standard and regenerative sheep farming practices

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Key words: soils; carbon sequestration; rangelands; sheep farmers

Abstract

Little is known about soil carbon dynamics and the effects of regenerative grazing practices on sheep ranches in the United States. To address this knowledge gap, we established a soil carbon monitoring program across ten sheep ranches spanning over 1 million hectares of private and federal rangelands in the Western United States. Collectively, these operations manage over 47,000 sheep for meat and wool production. By adopting the Responsible Wool Standard (RWS), these ranches have implemented practices to improve grazing management, land health, and animal and social welfare. From 2020 to 2023, soil carbon levels were measured at a depth of 20 cm. Greenhouse gas emissions, including CO_2, CH_4, and N_2O, were also estimated using the COMET-Farm model at both individual and aggregate levels. Preliminary results indicate that one ranch showed an increase in soil organic carbon (SOC), while SOC levels on the remaining ranches remained relatively stable. COMET-Farm modeling estimates that these ranches have the potential to offset 91,444 metric tons of CO2 equivalents annually. This study provides a crucial baseline for understanding soil carbon dynamics on sheep ranches and highlights the potential of regenerative grazing and conservation practices to enhance carbon sequestration. It emphasizes the role sustainable sheep grazing systems can play in promoting ecological health while maintaining agricultural productivity.

Introduction

Recent efforts have focused on monitoring greenhouse gas (GHG) emissions and strategies to reduce them, with soil carbon sequestration emerging as a key solution. This process occurs when carbon capture through photosynthesis exceeds losses from respiration, transforming ecosystems into carbon sinks. Conservation practices like no-till farming, cover cropping, regenerative grazing, and optimized fertility management (mineral and organic amendments) not only enhance soil carbon but also improve soil health, reduce erosion, and promote sustainability (Havstad et al., 2007; Derner and Schuman, 2007). Rangelands, which cover vast areas, are particularly suited for carbon sequestration while providing critical ecosystem services like food production, water retention, and biodiversity (Follett and Reed, 2010; Davies et al. 2011; Pyke et al. 2015). Interest in sustainable practices among ranchers and farmers has grown due to the environmental concerns associated with livestock production. However, research on soil carbon impacts in sheep production, particularly on U.S. rangelands, remains limited. To address this, we developed a soil carbon monitoring program for sheep ranches in the Shaniko Wool Company Farm Group. These farms implement management practices that are deemed regenerative such as rotational grazing, no-till farming, and riparian restoration. Using field sampling and the USDA's COMET-Farm model, which assesses net GHG emissions, we estimate the carbon budget for individual farms and the group as a whole. We hypothesize that these practices will increase soil organic carbon, supporting the role of regenerative livestock production in sustainable land management.

Methods

The soil carbon monitoring program was conducted across ten ranches within the Shaniko Wool Company farm group. However, this study includes data from only seven farms, as three recently joined the group. Collectively, this group grazes across 2.6 million acres (1.05 million hectares) of private lands, Bureau of Land Management (BLM) allotments, and U.S. Forest Service (USFS) allotments. The USFS lands, located at higher elevations, experience cooler temperatures and greater moisture compared to the lower-elevation, drier BLM and private rangelands. Average annual rainfall ranges between 250mm in the drier areas up to 600mm in the higher elevation allotments. Soil types in the ranches present a very high variability as they are located on different areas, from sandy basins to loams and clayey soils. Altogether, the farm group raises over 47,000 sheep and produces approximately 225,000 kilograms of wool annually. The landscapes span diverse ecosystems, ranging from basin shrub-steppe to high-elevation mixed conifer forests and mountain meadows, reaching elevations of over 2,700 meters above sea level. For carbon monitoring, representative sampling sites were selected on each farm based on factors such as topography, soil characteristics, elevation, gradient, vegetation types, and land use. In total, 236 sampling points were established across the participating farms. At each sampling point, five soil cores were collected using a 2-inch bucket auger and combined into a single composite sample per site. Soil was collected at a depth of: 0–20 cm for all sites. Of the seven ranches evaluated in the project, one was sampled four times (2020, 2021, 2022, and 2023), while the other six were sampled three times (2021, 2022, and 2023). Samples were analyzed at the USDA-ARS Soil Laboratory in Corvallis, OR, USA, for soil organic carbon (SOC) using a LECO CN828 analyzer. Because the study sites are located in semi-arid regions, a preliminary "fizz" test (Lal, 2009; Whitlark, 2011) was performed on all soil samples to detect the presence of carbonates. Reactive samples were further analyzed for calcium carbonate content using a pressure-calcimeter (Fonnesbeck et al., 2013). Additionally, soil pH was measured using both a 1:1 soil-to-water ratio and a 0.01 M $CaCl_2$ solution. Bulk density values were obtained from the USDA Web Soil Survey. Soil carbon stocks were estimated using the following formula:

$$\text{Soil C (kg/ha)} = (\%C \div 100) \times BD\ (g/cm^3) \times D\ (cm) \times 100{,}000$$

where %C is the carbon content, BD is the bulk density, and D is the soil depth.

We used the COMET-Farm model for GHG modeling. Due to model limitations, only BLM public lands and private lands were included while USFS public lands were excluded as the model lacks soil data for forested sites. Operational boundaries were delineated and edited using ArcGIS Pro 2.8.0. To meet model size constraints, large shapefiles were divided into parcels smaller than 1,200 acres and imported into COMET-Farm as SHP files. Projects were limited to fewer than 50 parcels and no more than 200 soil units each. Each ranch was modeled separately for grazing land management, cropland management, and animal agriculture. Emissions from these categories were calculated individually and then combined to estimate total emissions for the operations. Historical (pre-1800s general management), baseline (2000–2020), and animal agriculture data were collected through interviews with land managers and incorporated into the parcels. For grazing lands, data collected included vegetation type (modeled as perennial grass), percent daily utilization, grazing periods, rest days, and management practices like fertilization, irrigation, or burning if applicable. For croplands, data included crop species, planting and harvest dates, tillage intensity, field operations, fertilizer or amendment applications, irrigation events, grazing events, and liming when necessary. For animal agriculture, data collected included class and number of animals, average daily feed, average liveweight, diets, housing, manure management, manure N content, total dry manure produced, and the percentage of pregnant animals.

Each ranch was analyzed separately, as comparisons between ranches were not conducted due to differences in management, history, location, climate, elevation, and soil types. For each ranch, we used a one-way ANOVA to compare the means of soil carbon and nitrogen across its total operations and by lease type (BLM, USFS, and private lands). Normality assumptions were tested by examining residual plots, identifying extreme outliers, and performing a Shapiro-Wilk test. ANOVA and normality analyses were conducted using RStudio (2021.09.0), while regression analyses and plots were generated with SigmaPlot version 15.1.1.26 (2023).

Results

Soil organic carbon

Changes in soil organic carbon (SOC) was not statistically significant ($P>0.05$) on six of the seven ranches (Figure 1a). Ranch D had an increase in SOC between 2021 and 2022 ($P<0.001$) as compared to 2020 and remained stable until 2023.

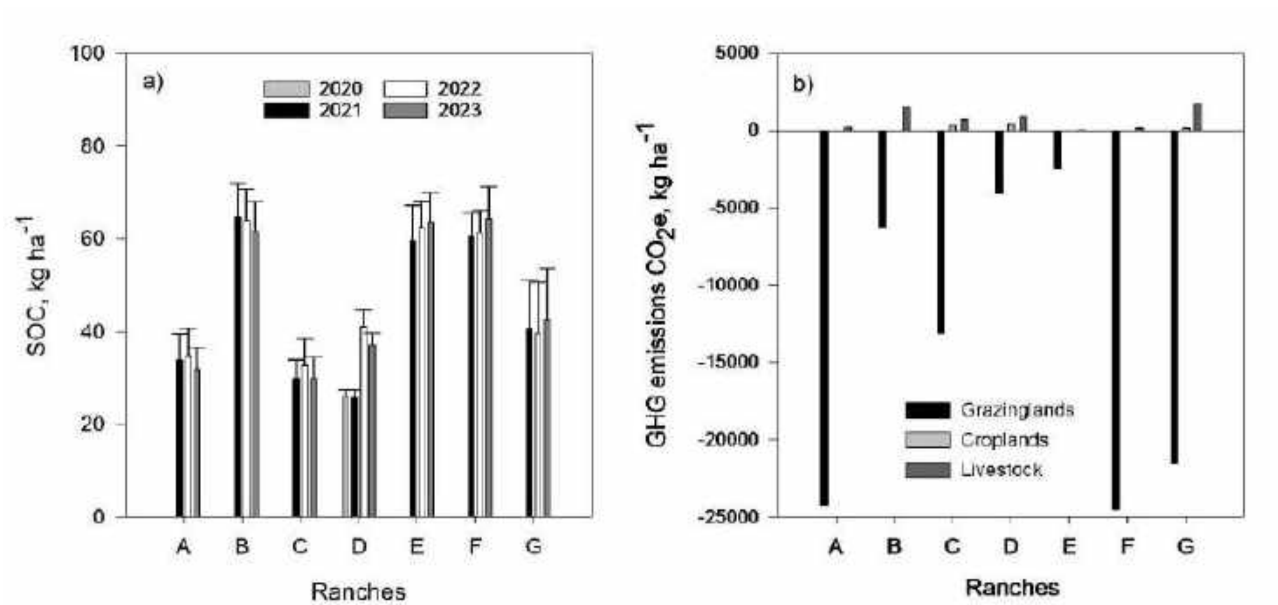

Figure 1. Average soil organic carbon (SOC, t ha^{-1}) change at 0-20cm depth from 2020 to 2023 (a) and GHG emission reduction potential of the ranches (A-G) (b). Bars represent standard error of the mean.

COMET-Farm GHG results

Each one of the ranches presented a large negative emission value in the grazing lands as compared to the smaller positive emissions from the croplands and livestock. The sum of the emissions from the three categories (grazing lands, croplands and livestock emissions) results in a negative emission value for the entire modeled operations. This negative value indicates the potential carbon that can be taken by the soil, demonstrating that all cropland and animal emissions from the ranches can potentially be sequestered by the soil under optimal conditions (Figure 1 b).

Discussion

Among the seven evaluated ranches, only one showed a significant increase in soil organic carbon (SOC) between 2020 and 2023. Three others displayed positive trends in carbon sequestration, while three showed negative trends. Such fluctuations in SOC are expected in the carbon cycle, especially in dry regions where low moisture limits soil organisms responsible for cycling carbon (Burke et al., 2019). In general, we found that soils high in sand content presented lowest soil carbon, as compared to soils with more silt or clay, highlighting the importance of soil texture in carbon sequestration. Particular attention to soil texture needs to be taken in consideration to better understand carbon sequestration and to better advise land managers. As lands with soils higher in clays will have a different potential to bank carbon as compared with drier sandy soils, common in many regions that are grazed. Longer-term sampling is likely needed to better understand SOC dynamics in these ranches.

COMET-Farm™ modeling suggests that, under current management practices, the ranches can act as carbon sinks, potentially offsetting 91,444 CO_2e kg ha^{-1} y^{-1}. However, these estimates assume "optimal" rangeland conditions, such as complete plant cover and average rainfall, meaning the results reflect potential sequestration under ideal circumstances. The analysis included only Bureau of Land Management (BLM) allotments and private lands. U.S. Forest Service (USFS) allotments, covering approximately 247,465 hectares (611,500 acres) of forested soils, were excluded due to limited data. Forested soils on USFS lands generally have higher SOC levels than drier rangeland soils, likely due to greater plant cover. This highlights the potential of agroforestry or silvopastoral systems on USFS lands to maintain higher carbon levels while sustaining livestock.

In summary, maintaining adequate plant cover is essential for increasing and sustaining soil carbon sequestration (Lal, 2004). Regenerative practices—such as adjusting livestock numbers, overseeding rangelands, and planting riparian trees—can create favorable conditions for plants to capture atmospheric carbon (Chen et al., 2009). COMET-Farm modeling is a useful tool to project the impacts of these practices over a ten-year period. At the same time, is important to understand that soil carbon sequestration has a limit or saturation point in which no more carbon can be banked in the soils regardless of carbon inputs. This saturation point is associated to the soil texture, soil structure and the biochemical complexity of the organic compounds (Stewart et al., 2007). Furthermore, maintaining adequate soil carbon levels in the upper layers of the soil can eventually assist to improve the vertical transfer of carbon to the deeper layers of soil as a result of the soil mineral properties, plant and microbial activity, favouring banking (sequestering) the carbon to ensure its permanence in the soil (Dwivedi et al., 2017). While current efforts promote healthy, carbon-sequestering ecosystems, further research is needed to determine when these soils might reach the carbon saturation point and avoid carbon loses.

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A review of the evidence linking management and soil carbon sequestration in rangelands

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Key words: soil organic carbon, grazing management, climate change, carbon offsets

Abstract

While the agronomic benefits of organic matter in soils have long been established, debate continues regarding the potential for increasing carbon storage in soils to help combat anthropogenic climate change. Of all the world's biomes, rangelands have arguably the highest expectations, and the greatest uncertainty, for soil organic carbon (SOC) sequestration, i.e. removing carbon dioxide from the atmosphere via photosynthesis and securely storing the assimilated carbon in soil. Our review of evidence for persistent increases in SOC stocks following implementation of new management strategies showed significant methodological limitations and inconsistencies in reported outcomes. A major challenge is that detection and attribution of management impacts are difficult in low productivity, high diversity rangelands where 90% or more of sampled differences in SOC stocks may be determined by climate and soil factors. Caution is needed in interpreting results, but strategies with more consistent evidence for SOC sequestration include over-sowing forage legumes into grass pastures, conversion from cropping to permanent pasture and avoiding prolonged high grazing intensity. Our analysis did not find evidence for significant, persistent increases in SOC stocks with the implementation of other livestock management options (e.g. rotational grazing). We conclude from the available evidence that the potential for SOC sequestration in rangelands is likely modest. However, uncertainty is high, and we recommend research priorities to improve data and understanding of SOC in rangelands for production and environmental benefits.

Introduction

The mass of carbon (C) in soils is very large, estimated at three times that in the atmosphere, and 80% of the total C stored in terrestrial ecosystems (IPCC 2023). Of this C pool, the organic component is more responsive to management than inorganic C, and 25−75% of soil organic carbon (SOC) has been lost globally since 1850 largely through inappropriate agricultural practices (Sanderman et al. 2017). There is strong interest in the prospects for improved management to restore SOC in degraded lands for agricultural productivity, ecosystem services and food security benefits and increasingly as a climate change mitigation strategy since permanent increase in SOC storage (i.e., sequestration) represents a net removal of CO_2 via photosynthesis from the atmosphere (Bossio et al. 2020). Rangeland, as the most extensive biome, spanning 79.5 M sq km (ILRI et al. 2021), and holding a third of global soil organic matter (SOM), theoretically represents a substantial climate change mitigation potential, but there is considerable uncertainty in the achievable SOC sequestration.

The value of SOM for soil condition and functionality is well-established from centuries of agronomic research but how long-term increase in SOC in stable forms is affected by different pasture and grazing management practices is less well-understood (Rumpel et al. 2023, Salley and Brown 2023). To mitigate climate change by offsetting greenhouse gas (GHG) emissions, C sequestration must meet internationally recognised integrity standards for C removals, including additionality (whether management activities go beyond business-as-usual), evidence-base (scientific evidence linking human activity and SOC sequestration), permanence (persistence of stored SOC), and quantification (accurate, conservative measurement or modelling of SOC stock changes) (Dupla et al. 2024). Uncertainty is high for rangelands, due to their diversity and generally limited data. Here we present: (i) an overview of data and evidence for management-induced SOC sequestration in global rangelands; (ii) a case-study of management impacts on SOC sequestration in Australia's rangelands; and (iii) recommendations for research to reduce uncertainty for agriculture and climate policy.

Methods

Scope: The review covered published papers and reports on field trials, soil sampling surveys, and credible modelling studies with SOC data for grazed rangelands. For the global overview we did not undertake a new comprehensive literature search but drew on published reviews, meta-analyses and recent papers (e.g., Reinhart et al. 2021, Sanderson et al. 2020, Salley and Brown 2023). For the Australian case study, we expanded on recent reviews of the impacts of management on SOC stock changes in Australian rangelands (McDonald et al. 2023, Henry et al. 2024) to summarise the sequestration potential of strategies for: (i) grazing management; (ii) pasture improvement; and (iii) land conversion.

Data selection and analysis: Studies on SOC storage in rangelands have used a range of methods for experimental design, SOC quantification and management interventions. Based on recent scientific understanding and measurement protocols (Batjes et al. 2024, Zhang et al. 2024), a set of criteria was developed to select SOC stock change data and management strategies for evaluation (Table 1). Overall, few publications provided adequate information to reliably assess data quality and enable valid comparisons. Inconsistencies between studies affected the strength of evidence and were used to identify data and knowledge needs in rangeland systems.

Results

Global review: Our review revealed that few studies had credible data able to meet minimum requirements for quantifying the impacts on SOC *sequestration* of management strategies appropriate for implementation in rangeland production systems. The impacts reported for similar strategies were marked by inconsistencies in the magnitude (and, in some cases, direction) of SOC stock change, but there was some evidence of robust trends in response: (i) no clear effects of various rotational grazing practices; (ii) positive effects when more productive species were over-sown into grass pastures; (iii) negative impacts of prolonged high grazing intensity on SOC stocks; (iv) positive impacts of conversion from crop production to permanent pasture; (v) limited potential for SOC sequestration, and probable adverse impacts on ecosystem services, of conversion of grasslands to forest (Briske et al. 2024).

Table 1. Summary of criteria used to select credible SOC sequestration data from publications reviewed for analysis, and constraints for rangeland monitoring.

Criterion	Data requirement	Rangeland context
Consistent with SOC sequestration definition	SOC stock change relative to initial or baseline reference	Few long-term trials with SOC and bulk density measured (baseline, project) across the diversity of rangeland soils, climate, production systems
Baseline	SOC stocks under business-as-usual management.	Representative initial SOC stock measurements, preferably dynamic baseline monitored over multi-decadal periods, accounting for variance and climate
Management strategy	Details of baseline and new management	Poor/no data limits the evidence-based attribution and comparisons for SOC change due to new management
Measurement (in-field; lab. or proximal sensors)	Depth ≥30 cm; bulk density; sampling protocols; variance	Vast areas, high spatial and temporal variability and low Net Primary Production (NPP) mean small/slow rates of change that are hard to detect and costly to monitor
Measure – model approaches	Calibrated and verified models	Few data across rangelands for calibration; model representation of C and N dynamics often inadequate
Monitoring periods	Monitor at 5-10 year intervals for decades/ centuries (>10 years)	Dominant impacts of rainfall and soil type, high risks of reversal under low/unreliable rainfall mean detection and attribution of change need longer monitoring

Australian rangeland study: The Australian rangelands cover around 75% of the continental area, with a range of management systems across diverse climates, soils and landscapes. Results of the literature review and analysis of data extracted from studies (field trials, surveys or credible simulations) meeting criteria for monitoring SOC stock changes were broadly consistent with the global observations. While data were insufficient to reliably quantify the potential for SOC sequestration under different initial soil conditions (e.g., nutrient status) and management options, some strategies provided indicative values (Table 2). For example, over-sowing native grass pastures with more productive grasses or with forage legumes provided consistent evidence of sequestration (up to 0.1 t C ha^{-1} yr^{-1}; ~0.3 t C ha^{-1} yr^{-1}, respectively), and conversion from cropping to permanent pasture increased SOC stocks (median value ~0.2 t C ha^{-1} yr^{-1}). Conversely, data from long-term studies indicated that implementing rotational or other grazing strategies had negligible persistent impacts on SOC stocks. Across all studies, the permanency of any SOC sequestration could not be assessed.

Table 2. Summary results from Australian rangeland SOC studies quantifying SOC sequestration (0-30 cm depth). (Adapted from Henry et al. 2024.)

Management strategy	Number of studies[1]	Estimation period (yr)	Baseline[2] C (t C ha^{-1})	SOC seq. range (median) (t C ha^{-1} yr^{-1})
Grazing management				
Lower grazing intensity	2	16 –26	13 – 19	0 – 0.09 (0.03)
Destocking or exclosure	7	7 –58	5 – 80	0 – 1.68 (-0.03)
Rotational vs continuous	4	5 –10	5 – 75	-0.11 – 0.01 (0.08)
Pasture improvement				
More productive grasses[3]	5	Various	>10 – 50	0.02 – 0.11 (0.06)
Oversowing with legumes[3]	3	22 – 50	19 – 52	0.27 – 0.45 (0.38)
Water ponding	1	20 – 25	19	0.28 (0.28)
Fire management	1	58	33	0.03 – 0.04 (-0.07)
Land conversion				
Cropland to grassland	3	15 – 20	23 – 121	0.06 – 0.48 (0.16)
Forest to grassland[4]	7	<11 – 73	20 – 121	-2.42 – 0.72 (-0.22)
Grassland to forest[4]	1	10 – 58	16 – 76	0 (0)

[1] Studies included field trials, field surveys and models; [2]Reported as either *Initial* or *Control* site C stocks; [3]Results include modelled data; [4]Results include data from a survey of 45 sites in northern Australia.

Discussion

Assessment combining an overview of global studies and analysis of Australian research indicated that the potential for management-induced SOC *sequestration* in rangelands is uncertain, variable and unlikely to contribute substantially to climate change mitigation or income for livestock producers C offsets. Other recent publications have reached similar conclusions (Don et al. 2023, Dupla et al. 2024, Reinhart et al. 2021). The analysis is also consistent with evidence that the dominant drivers of SOM inputs and losses, and of the long-term net SOC stocks, are rainfall, temperature, and the soil properties that determine SOC stabilisation and persistence. The challenges of maintaining and increasing SOC stocks are exacerbated in rangelands by typically infertile soils and high seasonal variations in NPP (Cotrufo and Lavallee 2022). At a property scale, in rangelands the large areas and low and reversible rates of storage make accurate and cost-effective quantification of SOC stocks and stock change a barrier to 'C farming' (Derner et al. 2019, Batjes et al. 2024, Dupla et al. 2024). Measurement uncertainty adds to the difficulty in attributing changes in SOC to implementation of a new practice when management may be responsible for as little as 10% of measured differences between sites (Allen et al. 2013, Salley and Brown 2024). These factors contribute to the lack of consistency in results from published rangeland trials (Sanderson et al. 2020, Henry et al. 2024). Additionally, studies have varied in whether emissions of other GHGs arising from a management change were counted in the estimated climate change mitigation benefit of SOC sequestration and whether standards for integrity of C offsets, particularly additionality and permanence, were adequately established. To improve understanding of the potential for SOC sequestration, investment is needed in long-term trials using best practice experimental design, multi-decadal monitoring of control and treatment sites for SOC stocks to >30cm with sufficient replicates for statistical analysis of spatial and temporal variance supported by site information on historic management, baseline soil condition and initial SOC stocks. Based on our review, we caution against over-expectation for the environmentally and economically achievable quantity of SOC sequestration in rangeland soils. However, while C farming market opportunities are likely modest, there is value in expanding investment in well-designed, long-term field and modelling studies over spatial and temporal scales representative of the diverse rangelands to better quantify the potential for maintaining or increasing SOC stocks and to understand the value for rangeland resilience now and under future climatic conditions.

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Enhancing carbon sequestration in drylands through silvopastoral systems

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Key words: Sustainable land management; Climate change mitigation.

Abstract

Drylands, spanning over 40% of the Earth's surface, sustain two billion people, half the global livestock population, and rich biodiversity. They are crucial carbon reservoirs but are highly susceptible to land degradation, emphasizing the need for sustainable management. Silvopastoral systems (SPS) present a promising approach to balance productivity with environmental gains. However, the carbon sequestration potential of SPS in drylands remains underexplored.

To address this knowledge gap, the FAO, in partnership with the Alliance of Bioversity International and CIAT, has launched a comprehensive global assessment on enhancing carbon sequestration in drylands through SPS. This initiative aims to provide evidence-based strategies for sustainable planning, management, and restoration of drylands. This study encompasses an integrative methodology combining literature reviews, case studies, and scenario modelling to evaluate current carbon reserves and forecast future potential under varying intensification, climatic, and policy contexts. Outputs include a guide to best practices and a robust monitoring framework.

These efforts will culminate in a detailed report offering actionable recommendations for policymakers, government bodies, and institutions. Collaboration with the FAO's Committee on Forestry (COFO) will ensure the development of tailored, country-specific strategies to maximize the sequestration potential of drylands via SPS. Countries will receive targeted support for designing and implementing SPS as tools for Sustainable Land Management, contributing to climate mitigation, resilience, and livelihood enhancement.

This paper highlights the findings so far, emphasizing evidence, best practices, and lessons learned. It underscores the potential of SPS to enhance carbon sequestration while supporting sustainable management and restoration. By focusing on practical strategies for leveraging SPS, it will underpin actionable recommendations to address climate adaptation and mitigation challenges, fostering the rejuvenation of these critical ecosystems and strengthening global resilience against climate change.

Introduction

Drylands cover about 41% of the Earth's surface, according to the Thornthwaite classification, and face increasing pressures from climate change and population growth (Yan et al., 2024). The livestock sector, a significant driver of land degradation, contributes 9% of anthropogenic carbon dioxide (CO_2) emissions globally, largely due to deforestation and land use changes for pasture and feed crops (Mohammed and Naqvi, 2011; Singh et al., 2017). Additionally, livestock account for 35–44% of anthropogenic methane emissions (Yusuf et al., 2012).

Carbon sequestration has emerged as a critical strategy to offset rising atmospheric CO_2 levels. SPS, multifunctional systems combining herbage, shrubs, trees, and grazing animals, present a promising sustainable land management approach. These systems not only boost productivity but also deliver ecosystem and climatic benefits by enhancing carbon storage in biomass and soil organic carbon (Aryal et al., 2019). Compared to open grasslands, SPS are particularly effective in increasing carbon storage and fostering ecosystem resilience (Feliciano et al., 2018).

Globally, SPS cover approximately 450 million hectares, accounting for 28% of agroforestry systems (Nair, 2012). Their adaptability to diverse environmental conditions and socio-economic needs makes them valuable tools for climate adaptation and sustainable development. These systems integrate diverse practices, such as grazing under tree cover, live fences, and protein banks, enabling tailored applications across regions.

This study explores the potential of SPS to enhance carbon sequestration in drylands. It aims to provide evidence-based strategies for sustainable planning, management, and restoration while addressing knowledge gaps. By evaluating current reserves and forecasting future potential, the study offers the evidence-base for designing actionable recommendations to support global climate resilience and sustainable land stewardship.

Methods

A systematic review was conducted following the methodology of Tranfield et al. (2003), comprising three stages: planning, conducting, and reporting. Studies were screened based on abstracts, full texts, and additional literature identified through snowballing methods.

To identify studies on the carbon sequestration potential of silvopastoral systems in drylands, the following search strings were used: ("silvopastoral*" OR "silvo-pastoral*" OR "agrosilvopastoral*" OR ("grazing*" AND "tree*") OR ("agroforest*" AND "livestock") OR ("pasture*" AND "tree*")) AND ("dryland*" OR "arid" OR "semi-arid" OR "desert") AND ("carbon*" OR "greenhouse gas emission*" OR "GHG*" OR "mitigation"). Boolean operators combined terms to refine searches.

Searches included published journals, bibliographic databases, conference proceedings, industry trials, and grey literature. Key sources included ScienceDirect, Web of Science, Dimensions Research, Google Scholar, and ResearchGate. Grey literature was further identified through manual reference checks, Google Scholar's cited-in function, and targeted searches. Duplicate records were manually removed.

Inclusion criteria required studies to provide quantitative carbon sequestration data for above-ground, below-ground biomass, or soil organic carbon in silvopastoral systems within drylands (annual rainfall <900mm) or areas classified as Hyper-arid, Arid, Semi-arid, or Dry sub-humid (AI <0.65) (Zomer et al., 2022). Publications needed to be recent (2003–2023), peer-reviewed, or reliable grey literature with English-language abstracts. Populist publications and inaccessible records were excluded.

Studies underwent a three-tier screening process—title, abstract, and full text—to ensure only the highest quality evidence informed the review.

Results

The systematic review has so far analysed 62 publications, highlighting diverse SPS arrangements and their contributions to carbon sequestration. Dispersed trees and shrubs in pastures were the most frequently studied arrangement, followed by grazing in timber systems, traditional SPS[10], and live fences. (Ibrahim et al., 2005; Nahed-Toral et al., 2013). These configurations vary in their structure and functionality, yet all contribute to carbon storage in above-ground biomass, below-ground biomass, and soil organic carbon. The adaptability of these arrangements allows them to thrive in diverse ecological conditions while addressing local socio-economic needs.

Dispersed trees and shrubs in pastures demonstrated a broad capacity for carbon sequestration, with total carbon stock values ranging from 60 to 183 Mg C/ha. This variation in carbon stocks is influenced by multiple factors, including soil properties, climate, tree species composition, and grazing intensity.

These systems truly bolster above-ground biomass, which ranged from 9 to 47 Mg C/ha across SPS arrangements, with grazing in timber systems often contributing to the higher end of this spectrum. Below-ground biomass, a critical component of carbon storage in SPS, ranged from 5 to 66 Mg C/ha, with traditional SPS and live fences providing notable contributions to below-ground carbon pools.

Soil organic carbon, often the largest carbon pool in SPS, ranged from 13 to 195 Mg C/ha, with systems integrating trees and shrubs, such as dispersed configurations and live fences, showing high values. Annual carbon accumulation spanned from 0.3 to 8 Mg C/ha/year, with live fences and grazing in timber arrangements contributing to dynamic carbon cycling. CO_2 sequestration rates across all arrangements were substantial, averaging approximately 1 Mg CO_2 eq/ha/year, with some systems, particularly those with denser tree components, peaking at 3.5 Mg CO_2 eq/ha/year.

Discussion

This study highlights the critical role of SPS in addressing global challenges such as climate change, land degradation, and food security. By integrating trees, shrubs, herbaceous vegetation and livestock, SPS create multifunctional ecosystems that deliver environmental and socio-economic benefits. Beyond their capacity for carbon sequestration, SPS contribute to biodiversity conservation, soil health, and water quality, making them essential components of sustainable land management strategies. Furthermore, SPS adoption has shown to improve livestock productivity by reducing heat stress, improving water availability and enhancing feed quality, contributing to higher milk yields and weight gains and reducing greenhouse gas emissions (López-Santiago et al., 2024; Rivera et al., 2024)

A critical insight from this research is the versatility of SPS configurations in achieving region-specific goals. Dispersed trees and shrubs in pastures, grazing in timber systems, and live fences are adaptable arrangements capable of thriving across diverse ecological conditions while increasing carbon storage. These variations influence carbon sequestration potential, with humid environments typically storing more carbon due to increased biomass productivity, while arid regions depend on drought-resistant species for below-ground carbon accumulation (López-Santiago et al., 2019). The influence of soil type is also critical, as finer-textured soils retain more organic carbon, whereas sandy soils require additional organic inputs to enhance sequestration potential. Additionally, moderate grazing supports soil structure and nutrient cycling, making SPS viable under varying grazing intensities (Howlett et al., 2011).

There are, however, several barriers to widespread adoption of SPS adoption. Financial constraints, limited technical knowledge, unsuitability of land to host trees, incompatible livestock management practices and land tenure issues impede their scalability. Addressing these requires targeted policies, adapted financial tools (such as

[10] Traditional silvopastoral systems integrate native trees, shrubs, and pastures with grazing livestock, often following low-input management techniques and natural regeneration. Unlike intensive SPS, traditional systems rely more on native vegetation, less on external inputs, and foster a balance between production and ecosystem services.

subsidies and low-interest loans), market-based incentives like carbon credit programs, and capacity-building initiatives tailored to local needs. Bessi et al. (2024) emphasized the importance of integrating SPS into national policies to maximize their impact on both environmental restoration and socio-economic development.

In conclusion, silvopastoral systems exemplify the convergence of ecological restoration, integrated climate mitigation and adaptation, and agricultural productivity enhancement. By integrating carbon sequestration with food security and ecosystem restoration, SPS offer a viable solution for mitigating climate change and fostering socio-economic resilience. Their strategic implementation, particularly in dryland regions, will play a pivotal role in global sustainable development efforts.

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Long-term impacts of rabbit and cattle grazing on carbon sequestration in arid rangelands

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Key words: above-ground biomass; woody cover; trees and shrubs; remote sensing

Abstract

One of the claimed multifunctional characteristics of degraded pastoral landscapes is their ability to sequester carbon in woody biomass. But what is the actual potential for this, and at what rate may this occur over time? Due to slow growth rates, intermittent droughts, and heterogeneous landscapes, it may require many years of data collection from across multiple site locations to answer such questions. For an arid calcareous landscape in central Australia that had been degraded through overgrazing by cattle and rabbits, we used multiple, disparate, data sources to estimate change in above-ground woody biomass over 40 years. From a very low density of live trees and shrubs in 1981, regeneration occurred in 1-ha plots when protected from grazing by rabbits and large herbivores (‘rabbit-exclosed’). There was lesser regeneration in adjacent plots that excluded only cattle grazing (‘cattle-exclosed’) and minimal establishment in control plots that were grazed. Hyper-spatial satellite images available from Google Earth were classified to estimate multi-temporal woody canopy cover for each plot between 2004 and 2023. Plot-based above-ground biomass (AGB, dry weight) of live trees and shrubs was estimated from the density and cover data using allometric functions from studies conducted elsewhere. Finally, AGB was accurately estimated in all plots in late 2022 using ground-based allometry data. AGB increased by 1.92 tonnes / ha within the rabbit-exclosed plots between 1981 and 2022, with lesser increases on the cattle-exclosed and control plots (0.69 and 0.63 tonnes / ha, respectively). Although maximum AGB after 40 years was still small (1.97±0.303 tonnes / ha), separate analysis of satellite data has shown that woody canopy cover elsewhere in this recovering landscape has reached ~50%, equivalent to ~4 tonnes / ha AGB. Such woody thickening can potentially reduce herbage growth and adversely impact beef production, bringing to focus the multifunctional balance between pastoralism and carbon sequestration.

Introduction

Altered grazing management to facilitate carbon sequestration, above- and below-ground, is progressively being implemented in parts of the Australian rangelands, both demonstrating their multifunctional value (Stringer et al. 2012) and providing an additional income stream for pastoralists (Hacker and McDonald 2021). The potential to sequester carbon may be greatest where formerly productive landscapes have been degraded through loss of perennial vegetation and erosion (Baumber et al. 2020, Henry et al. 2024).

Owen Springs pastoral lease near Alice Springs, Northern Territory (NT), is an exemplar of variably degraded rangeland in arid central Australia. The area has a summer-dominant mean annual rainfall of ~280 mm but with high interannual variability (minimum, 67 mm; maximum, 782 mm; 84-year record, Alice Springs Airport). The lease was first stocked in 1873 with grazing by cattle continuing until 2002 when the lease was resumed and all cattle and feral horses removed. Part of the lease became the Old Man Plains (OMP) research station (522 km^2) which was progressively restocked from 2005 at between three and six animal equivalents (AE) / km^2. Prior to that, cattle grazing pressure on calcareous shrubby grasslands, the most preferred pastoral land type, was estimated at ~12 AE / km^2 (Bastin et al. 2023). Feral horses (unknown number) and rabbits (densities as high as 20 / spotlight km, Foran et al. 1985) added to total grazing pressure. This sustained grazing pressure, particularly during drought, had caused extensive degradation (Pickup and Chewings 1994, see also Fig. 4 in Bastin et al. 2023) including widespread death of browsed shrubs (Fig. 1), a phenomenon previously described by Friedel (1985). High rabbit densities are especially pernicious during drought because rabbits will ringbark stems in their search for water. They will then browse seedlings that may germinate following high rainfall preventing the successful regeneration of woody vegetation.

Figure 1. Extensive shrub death on an OMP calcareous shrubby grassland associated with cattle and rabbit browsing. The 1982 photo also shows a rabbit warren in the foreground and part of a netted rabbit exclosure. Photo: Barney Foran, CSIRO.

The continuing security on present-day OMP of replicated rabbit- and cattle-proof exclosures constructed in 1981 and archived tree- and shrub-density data from that time (Foran et al. 1985) have provided the opportunity to retrospectively monitor change in woody biomass over the past four decades. In this paper, we combine multiple, disparate, data sources to estimate change in above-ground woody biomass since the early 1980s.

Methods

Three 1-ha plots (netted to exclude rabbits, fenced to exclude cattle and open to all grazing) were replicated at six sites in 1981 on calcareous shrubby grasslands approximately ~40 km south west of Alice Springs. The density of shrubs and trees (dead, mature or juvenile) was collected annually in four belt transects (10 m by 50 m) at each plot between 1982 and 1988 (see Foran et al. 1985 for further detail).

Individual stem diameters (at 10 cm) and crown area (as an ellipse) were measured for all trees and shrubs within all exclosures in October 2022. The same data were collected in adjacent 1-ha grazed plots (which may have been different to the original 'controls' as their precise locations were unknown). Health scores of the canopy and stem wood for all individuals were also recorded (Piper, pers. comment). Above-ground biomass (AGB, kg dry weight per individual) was calculated using the generalised shrub allometry of Paul et al. (2016). Plot-level canopy cover was calculated by summing the individual crown areas corrected for health divided by the plot area. Individual AGBs corrected for health were summed and divided by plot area to calculate plot-level AGB. These data were combined with those collected from another 430 sites in the Australian rangelands to develop generalised stand-level canopy cover – AGB relationships (by structural vegetation class) (Pasut, pers. comment) with the shrub equation used to calculate plot-level AGB (tonnes / ha) for the OMP sites in years where canopy cover was estimated using remote sensing.

Publicly available, high spatial-resolution satellite images available between 2004 and 2023 on Google Earth were saved as red-green-blue (RGB) composites with a nominal pixel size of 0.25 m for each site area. Twenty classes were generated for each site-time using ISO Cluster unsupervised classification. Those classes best representing identifiable tree and shrub canopies, plus associated shadow, were grouped to estimate multi-temporal percent canopy cover. Plot-level AGB was then estimated as above.

Results

From a notional low level of woody biomass in the 1980s*, AGB increased by a factor of 12 (cattle-exclosed) to 75 (grazed) by the early 2000s. The rabbit-exclosed treatment had consistently higher biomass, followed by cattle-exclosed (Fig. 2). Remotely-sensed estimates of AGB in 2021 and 2023 were higher for all treatments than the more accurate estimates in late 2022 using ground-based allometry data.

Assuming a consistent increase in AGB between 2004 and 2023, linear regressions fitted to the data suggested an annual increase of 34 kg / ha for the rabbit-exclosed plots ($R^2 = 0.77$, $P<0.01$), 21 kg / ha for the cattle exclosed treatment ($R^2 = 0.21$, ns) and 17 kg / ha for grazed plots ($R^2 = 0.28$, ns).

Discussion

The field-measured AGB of trees and shrubs in 2022 was low compared with other studies in the arid rangelands (e.g. Williams et al. 2023, Pasut, pers. comment). Nevertheless, the other data sources used here indicate that woody AGB started from a very low base on degraded land in the 1980s and may have accumulated at an annual rate of up to 34 kg / ha from the early 2000s onwards. The 'grazed' rate of 17 kg / ha / year extrapolates to an annual AGB accumulation of ~288 tonnes between 2004 and 2023 for the 169 km^2 of calcareous shrubby grassland on OMP. We acknowledge these increases are small and may have large estimation errors due to limited spatial sampling and no validation of the remote sensing analyses.

Initial establishment and growth of seedlings was only successful within rabbit exclosures (Foran et al. 1985, and 1988 data in Fig. 2). Successful regeneration of shrubs in cattle-exclosed and grazed plots probably dates from about 1996 when the rabbit population was substantially reduced, and subsequently maintained at a low level, through rabbit haemorrhagic disease (Edwards et al. 2002). Exceptional rainfall in 2000-2001 combined with destocking promoted vegetation growth (Bastin et al. 2023) and likely facilitated further successful shrub establishment. Thereafter, resumed grazing at a more conservative stocking rate combined with periodic spelling, and further years of above-average rainfall help to explain the gradual increase in remotely-sensed canopy cover and derived AGB.

* There was an initial low density of mature shrubs (predominantly Acacia kempeana, see Table 3 in Foran et al. 1985) and individuals were given a notional AGB of 35 kg (dry weight). Juvenile shrubs were similarly allocated a biomass of 1 kg each.

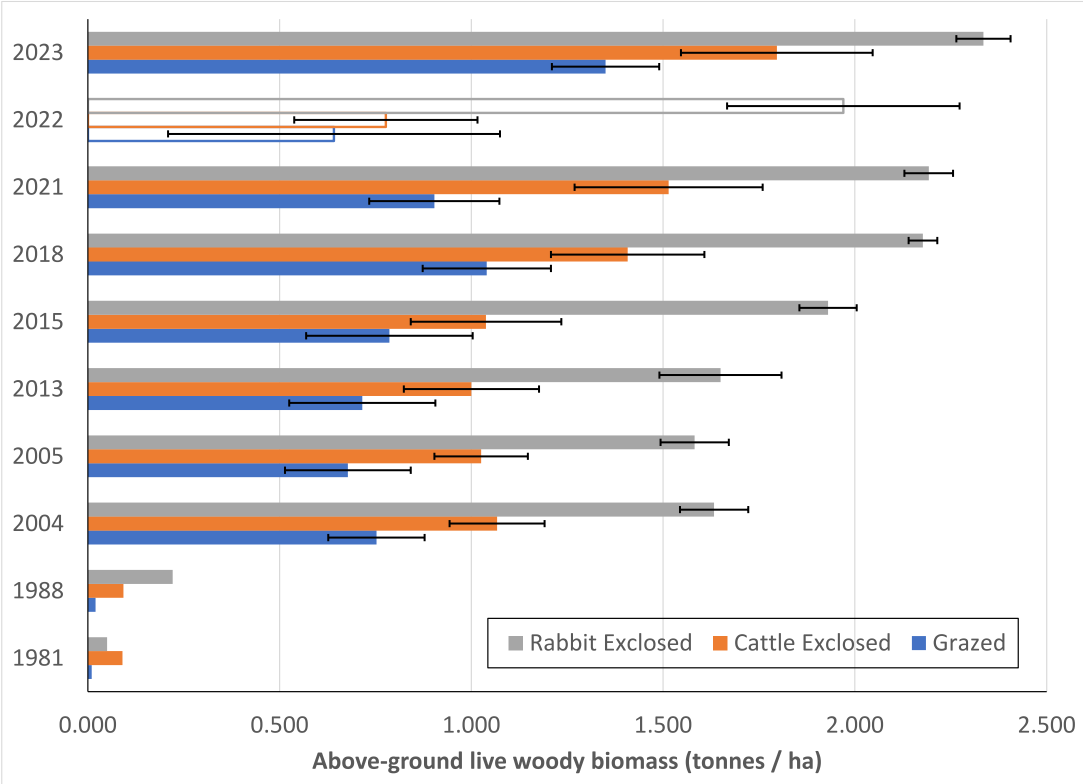

Figure 2. Estimated mean above-ground biomass of trees and shrubs for grazed, and rabbit- and cattle-exclosed treatments at six sites on Old Man Plains between 1981 and 2023. The standard error of each mean from 2004 onwards is also shown. Solid columns between 2004 and 2023 show remote sensing-based estimates with the open columns representing the 2022 field data.

The monitored increase in AGB, excluding the 2022 field data, is indicative rather than absolute due to the assumed relationship between density and AGB in the 1980s and probable errors associated with image processing in accurately discriminating canopy cover. The notional AGB of 35 kg assigned to each of the very few mature *A. kempeana* was based on the mean dry weight of 254 similar individuals harvested in a neighbouring paddock in 2012 (Bastin 2014). The density of juvenile shrubs in the rabbit-exclosed treatment increased through the 1980s but we argue their contribution to woody AGB was minimal regardless of their assigned small biomass value. The RGB images saved from Google Earth had reduced radiometric resolution compared with their source data. Further, we did not radiometrically calibrate the multi-temporal images to correct for different sensors, and sun-angle and atmospheric effects. Woody canopies were best discriminated when there was good spectral contrast between their grey-green foliage and the background soil and a senescent herbage layer; actively growing (green) pasture confounded successful classification. Despite these limitations, the Google Earth images did provide a free and convenient method for retrospectively monitoring change in canopy cover.

Regeneration of trees and shrubs across this calcareous landscape varies according to the nature and severity of past degradation (Stafford Smith and Pickup 1990). Woody canopy cover in some areas has reached ~50%, equivalent to ~4 tonnes / ha AGB. Such woody thickening can potentially reduce herbage growth and adversely impact beef production, without substantially contributing to carbon sequestration. This brings to focus a probable imbalance between the multifunctional values of continued successful pastoralism and meaningful long-term removal of carbon dioxide from the atmosphere.

Acknowledgements
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Know your numbers: Soil carbon sequestration has potential to support carbon neutral red meat and wool production in semi-arid rangelands

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Key words: Greenhouse gas emissions (GHGe); soil organic carbon (SOC); carbon neutrality; grazing management

Abstract

There is growing global pressure for agriculture, in particular red meat production, to reduce net greenhouse gas emissions (GHGe). A greenhouse gas (GHG) estimate is useful to benchmark and measure emissions and is useful to inform strategies to reduce or offset farm emissions. The average annual net farm emissions for two extensively grazed rangelands properties (Property A and B) in the semi-arid rangelands of southeastern Australia were calculated using the Primary Industries Climate Challenges Centre (PICCC) Greenhouse Gas Accounting Framework (GAF) tools over 5 years. Property A is 19,794 ha, has an average annual rainfall (AAR) of 390 mm and grazes cattle, sheep and goats for red meat production. Property B is 11,831 ha, has an AAR of 290 mm and grazes cattle and sheep for red meat and wool production. The average annual net farm emissions were 2,233 t CO_2-e/farm for Property A and 1,078 t CO_2-e/farm for Property B. As expected, in these low input systems, methane from livestock was the largest source of emissions for both enterprises.

Carbon neutrality within a farm business can be achieved when GHGe are balanced by carbon sequestered in soil and vegetation on farm. Soil is an important and large store of carbon in the landscape. Using Property A as an example, our calculations demonstrate that even a conservative increase in SOC through grazing management could increase SOC concentration by 0.05 % (e.g. from 0.53 to 0.58 % SOC; 0 to 100 cm) over a 25-year period (one of two permanence periods under the Carbon Credits (Carbon Farming Initiative) Act 2011). Calculated at property scale, this equalled 18,497 t CO_2-e per year sequestered in soil which could offset the average annual emissions produced.

Introduction

Greenhouse gases (GHG) are gases in the earth's atmosphere that trap heat. GHG reported under the Australian National GHG Inventory (National inventory report) include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other gases. There is currently very little documented evidence of emissions profiles of rangelands grazing enterprises in Australia. A farm carbon account is useful to benchmark and understand farm emissions, by accounting for sources and sinks of GHG within a farm business. The Australian red meat industry (in particular, MLA) has set the target to be carbon neutral by 2030 (CN2030). To achieve the goal of carbon neutral by 2030 producers must be able to reliably quantify and benchmark GHGe, as well as carbon stored and sequestered in trees and soils. By benchmarking GHG emissions, producers can then determine strategies to reduce emissions and identify opportunities to sequester more carbon in soil or trees. This study aimed to benchmark GHGe over five years for two extensive grazing properties in the semi-arid rangelands of southeastern Australia and identify the potential to offset emissions via soil carbon sequestration.

Methods

A whole farm carbon account and an annual average GHGe estimate (total tonnes of CO_2-e per property) was calculated for two extensive semiarid rangelands properties in New South Wales Australia using the Primary Industries Climate Challenges Centre (PICCC) Greenhouse Gas Accounting Framework (GAF) tool (specifically the SB-GAF and Go-GAF tools, developed by the University of Melbourne). A five-year baseline (~2018-2022) was calculated, as would be typical for a soil carbon project under the following methodology: Carbon Credits (Carbon Farming Initiative - Estimation of Soil Organic Carbon Sequestration using Measurement and Models) Methodology Determination 2021 (referred to as 'the Method'). Emissions intensity (i.e, the amount of CO_2-e per kilogram of product) was also calculated for each property and each commodity. Property A is 19,794 ha, has an average annual rainfall (AAR) of 390 mm and grazes cattle, sheep and goats for red meat production. Property B is 11,831 ha, has an AAR of 290 mm and grazes cattle and sheep for red meat and wool production.

Results

Annual net farm emissions & annual emissions intensity

The average annual net farm emissions for Property A were 2,233 t CO_2-e/farm, ranging across the five years from 1,776 t CO_2-e (2019-20 FY) to 4,396 t CO_2-e/property (2022-23 FY) (Figure 1). The average annual net farm emissions for Property B were 1,078 t CO_2-e/property ranging from 528 t CO_2-e (2018-19 FY) to 1,335 t CO_2-e/farm (2021-22 FY) (Figure 2). Not surprisingly, methane from livestock was the largest source of emissions for both farms. Emissions intensity varied over the five-year period and varied by farm enterprise (Table 1).

Discussion

Globally, we are seeing a growing expectation that agriculture, amongst other industries, should work to reduce its net emissions. This is a whole of supply chain effort and red meat businesses have a part to play.

Soil is an important and large store of carbon in the landscape. There are well known benefits of increasing soil organic carbon (SOC) for agricultural productivity and landscape function. In the rangelands, well-managed grazing animals are important tools in the landscape to build soil organic matter (the driver or the first step towards accumulating SOC) by stimulating plant growth, influencing plant composition, herbage mass and ground cover, nutrient redistribution, and breaking down vegetation and litter through trampling (McDonald et al., 2023, Orgill et al. 2017, Waters et al. 2015). Gray et al (2021) estimated a carbon sequestration rate of 0.17 t C/ha/yr in the 0 to 30 cm soil layer (over 20 years) in the Western Division of NSW if a relative increase of 10 % groundcover could be achieved. However, increasing and sustaining SOC through management in Australian rangelands can be a challenge (Henry et al. 2024). Therefore, management practices which focus on livestock productivity, pasture biomass and composition, and ground cover promotion will support producers to improve their overall emissions intensity, and protect and potentially build soil carbon in Australian rangeland landscapes.

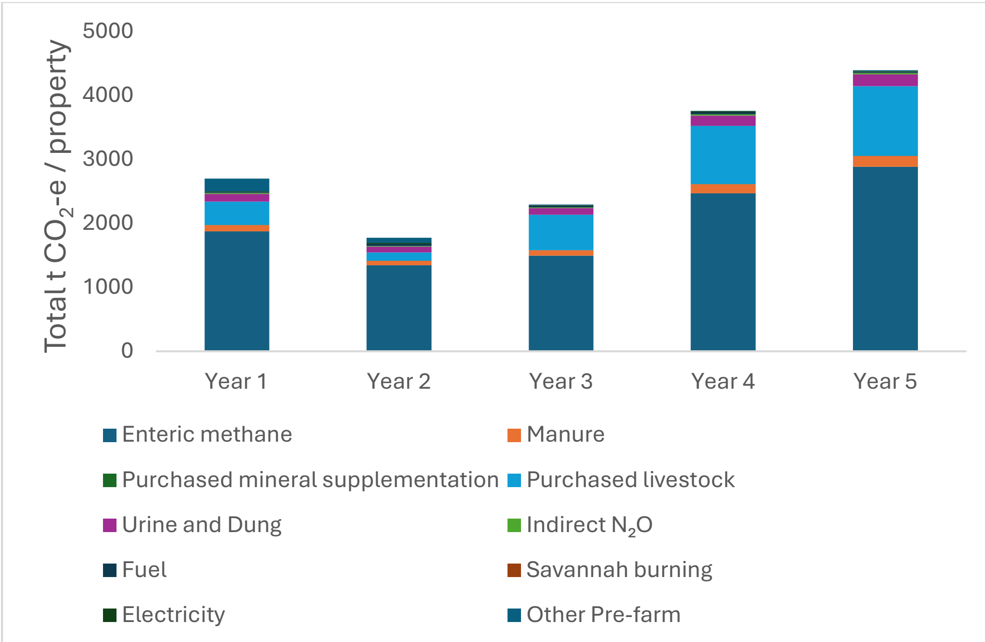

Figure 1. Annual net farm emissions (total t CO_2-e/ property) for Property A. Total emissions are the sum of all livestock enterprises on Property A including Sheep and Beef (SB-GAF) and Goat (Go-GAF). Year 1 was the start of June 2018 to end of May 2019, year 2 was the start of June 2019 to the end of May 2020, year 3 was the start of June 2020 to the end of May 2021, year 4 was the start of June 2021 to the end of May 2022 and year 5 was June 2022 to May 2023. Electricity, fuel and diesel were apportioned to each enterprise (therefore, not double counted). The category 'other Pre-farm' includes fertiliser, purchased feed, herbicides and pesticides lime and livestock away on agistment.

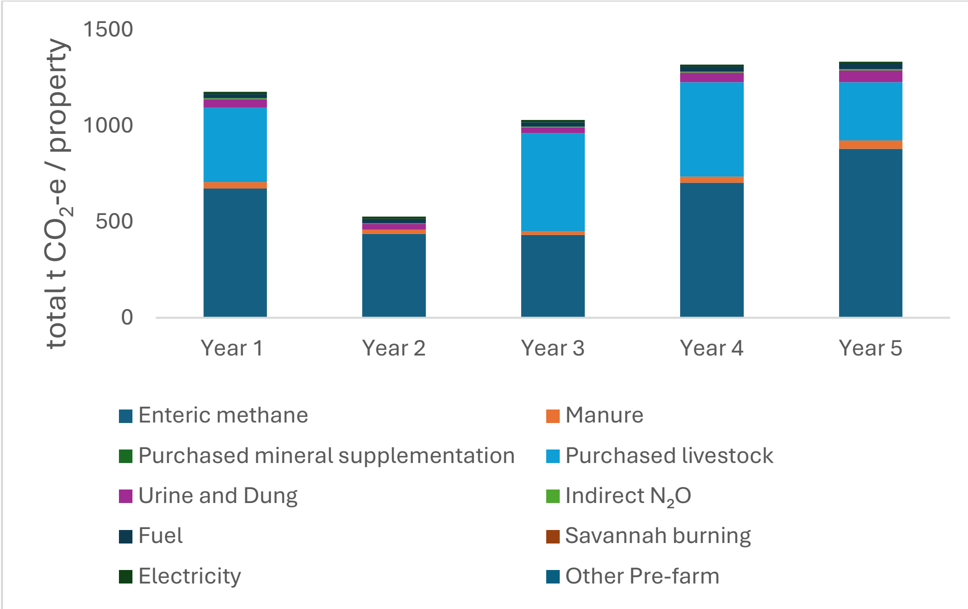

Figure 2. Annual net farm emissions (total t CO_2-e/ property) for Property B. Total emissions are the sum of all livestock enterprises on Property B including Sheep and Beef (SB-GAF). Year 1 was the 2017-18 financial year (FY), year 2 was the 2018-19 FY, year 3 was the 2019-20 FY, year 4 was the 2020-21 FY and year 5 was the 2021-2022 FY. Electricity, fuel and diesel were apportioned to each enterprise (therefore, not double counted). The category 'other Pre-farm' includes fertiliser, purchased feed, herbicides and pesticides, lime and livestock away on agistment.

Table 1. Emissions Intensity (kg CO_2-e / kg live weight (LW)) for Beef, Sheep and Goat enterprises for Property A and for Beef, Sheep and Wool enterprises on Property B over the 5-year period. The year 3 result for beef emissions intensity was artificially high (and therefore data not shown) for Property A. Beef emission intensity could not be calculated for years where there were no sales or purchases (year 2 to 4) for Property B.

Property	Enterprise	Emissions Intensity (kg CO_2-e / kg LW)				
		Year 1	Year 2	Year 3	Year 4	Year 5
A	Beef	10.6	9.0	-	29.2	15.8
	Sheep meat	49.2	15.6	16.0	15.4	13.3
	Goat	5.8	45.5	25.2	27.5	6.73
B	Beef	24.5	-	-	-	-
	Sheep meat	8.0	9.1	30.6	10.9	17.2
	Wool	25.9	28.9	95.1	34.7	53.4

Using the Property A case study as an example (average annual net emissions of 2,233 t CO_2-e), even a conservative increase in SOC sequestration could potentially offset the average annual emissions produced by the property. Assumptions and calculations to determine this are as follow:

- Grazing management increasing SOC concentration (SOC % equivalent to g/100 g) by 0.05 % (e.g. increase from 0.53 to 0.58 % SOC) over 100 cm over a 25-year period.
- Assuming a bulk density (BD) of 1.4 g/cm^3
- This equals an annual sequestration rate of 1.03 CO_2-e / ha/ year
- At the property scale, this is equivalent to 18,497 t CO_2-e per year sequestered in soil under 18,000 ha of grazed country.

This hypothetical soil carbon sequestration rate offsets even the highest annual GHGe for the 5-year baseline period. Whilst only carbon sequestration in *planted* trees is included when using the MLA GAF tools, carbon sequestration in regenerating vegetation and soil in rangeland systems may be an important consideration and, in some situations, may outweigh annual GHG emissions for a rangeland enterprise.

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Grazing management – plant-animal interface

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Effects of herbivore species and season and intensity of grazing on the steppe rangelands in an adaptive management system

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Key words: Livestock; Residual height; Standing dead; Nutrient resorption; Compensatory growth

Abstract

Effects of three herbivore species, four grazing seasons and three grazing intensity levels on a semi-arid rangeland in an adaptive management system were investigated using a 7-year grazing experiment in the Xilingol region of Inner Mongolia, China. The region experiences a semi-arid climate, with a mean annual temperature of -0.5°C, and a mean annual precipitation of 315 mm, which mainly falls during the plant growing season from May to September. The rangeland is a typical steppe dominated by *Stipa grandis* and *Leymus chinensis*. A rotational grazing management with grazing duration controlled on the basis of grassland residual height was applied to adapt to the inter-annual variation in plant production. The results showed that cattle, sheep and goats had different preferences for plant species, and grazing by these herbivores at moderate grazing intensity drove divergent changes in species composition of vegetation. Grazing in different seasons at moderate intensity affects plant community structure and production mainly through altering the seasonal pattern of plant standing dead and litter, which impacts soil moisture capture and retention, and thus soil nutrient availability for plant growth; and by changing plant nutrient resorption and remobilisation, with autumn grazing having the least plant nutrient resorped in autumn thus negatively affecting plant growth in subsequent spring. Autumn grazing had the biggest adverse effect on plant community structure and production, while winter and early spring grazing promoted plant growth. Grazing intensity and precipitation jointly shape the compensatory growth and ANPP of the rangeland, with the highest ANPP occurring at relatively high grazing intensity and under high precipitation. Our results provide insights into the rangeland vegetation dynamics under different grazing regimes, and suggest that adjusting livestock composition can be used as a tool in rangeland management. Winter and early spring grazing was better than complete animal exclusion for grassland health, and an adaptive grazing management based on residual vegetation height is efficient for coping with the large inter-annual variation in climate and vegetation production in semi-arid rangeland regions. This paper collates and summarises findings from the study.

Introduction

Plant production in arid and semi-arid rangeland areas varies widely across years driven by large inter-annual fluctuation in precipitation. The vast steppes in Inner Mongolia region of Northern China have been used as rangeland for thousands of years to graze livestock (sheep, goats, cattle and horses) using a nomadic system at low grazing intensity. With the privatization of land use rights in the rangeland region and associated reduction in livestock mobility, one of the major challenges in livestock management is to cope with the uncertainties in climate, to provide sustainable livestock production and other ecosystem services. We have proposed a grazing management strategy to set on and off livestock on the rangeland paddocks in the use-right privatized rangeland farms based on vegetation (residual) height, so as to keep the livestock-forage relations balanced and prevent rangeland from degradation. This management adjusts the summer grazing rangeland areas and the animal numbers at the end of plant growing season. It is essential to understand the effects of livestock grazing strategies in this adaptive grazing management system on plant and soil systems, including grazing season, intensity and livestock species for developing and improving rangeland management.

Methods

We conducted three interrelated grazing experiments to examine the effect of three livestock species, four grazing intensity levels and four grazing seasons on plant community composition and production, and soil properties over a 7-year period in a semi-arid rangeland, located in the Maoden farm, 45 km northeast of Xilinhot city, in Inner Mongolia of China (44°10′N, 116°28′E, 1101m asl). The region experiences a semi-arid climate, with a mean annual temperature of -0.5°C, and a mean annual precipitation of 315 mm, which mainly falls during the plant growing season from May to September. The rangeland is a typical steppe on a sandy loam chestnut soil dominated by tall grasses *Stipa grandis* and *Leymus chinensis,* with other important species of *Cleistogenes squarrosa, Carex korshinskyi* and several forbs.

The experimental rangeland was set up in 2016, with 36 paddocks of 50m×50m, to arrange 9 grazing treatments, replicated by 4 blocks. The nine treatments include no-grazing (NG), summer sheep grazing at three intensity levels of light (LG), moderate (MG) and heavy (HG) grazing; summer cattle (Cattle) and goat grazing (Goat) at moderate intensity, and sheep grazing in early spring (Spring), later autumn (Autumn) and winter (Winter). Summer sheep grazing at moderate intensity (MG) was also used when comparing the grazing season or grazing animal species effects (i.e., MG in grazing intensity experiment = 'Summer' grazing in grazing season experiment = 'Sheep' grazing in animal species experiments). The grazing treatment was conducted from 2017 to 2023 inclusive, two-year old Mongolian sheep with an average initial bodyweight of approximately 33 kg were used for grazing treatments. The number of sheep for NG, LG, MG and HG were 0, 3, 6 and 9 respectively. The sheep were set on the grassland in paddocks in summer period of June, July and August each year, and set off when residual vegetation height decreased to about 6 cm at MG. The same sheep grazing days (i.e., sheep unit × grazing days) in the MG treatment was applied for all grazing treatments in grazing season experiment and animal species experiment. Plant species composition and biomass, and animal bodyweight before and after each grazing rotation were determined, soil properties were monitored each year, and animal daily intake was estimated. Potential plant aboveground biomass (AGBp) at peak plant biomass time was determined by setting up three grazing-exclusion cages of 1.2 m length × 1.2 m width × 1.0 m height in each paddock before the start of summer grazing in all the grasslands subject to grazing at different intensities. Grassland aboveground net primary productivity (ANPP) was determined as the sum of herbage accumulation consumed by animals during grazing season and the residual biomass of grassland at the end of grazing season, including the small amount of detached litter produced in the current year. Please refer to Shi et al. (2022, 2023) and Li et al. (2018, 2021, 2022, 2024) and Yan et al. (2024) for the details in grazing management and monitoring. Here we summarize the major findings from these interrelated experiments, and discuss their management implications.

Results

Grazing intensity effects: grazing promoted grassland productivity, and the promotion varied with precipitation, grazing intensity and plant species.

The realised grazing intensity in the experiment was around 20%, 40% or 60% of the ANPP being consumed at LG, MG and HG, with actual stocking rate controlled at 138 ~ 240 sheep grazing days per year at MG over the 7 years. A comparison of the AGBp and ANPP revealed that grazing at LG and MG promoted plant production, that is, generated compensatory growth (ANPP>AGBp), and the promotion was the highest for dominant grass *L. chinensis*; while the promotion at HG occurred only in wet years, and highest promotion was for *C. squarrosa* and annual species. The grazing enhanced nutrient cycling by defoliation and excreta deposition, accelerated decomposition of plant litter with animal dung (Wang et al 2023), and increased nutrient resorption, can be a major mechanism for grazing promotion of ANPP (Zhang et al. 2020).

Grazing season effects: grazing in winter or in early spring improved, while autumn grazing reduced grassland growth, compared to complete exclusion of animals from grassland.

With moderate grazing intensity applied, under which around 40% of ANPP was consumed by animals during the plant growing season, plant community height and aboveground biomass were higher under spring and winter grazing than that under autumn, summer or no- grazing. The divergence in plant community structure was mainly mediated by grazing-induced variation in the seasonal patterns of plant standing dead and litter mass across the grazing season treatments. A high plant standing dead and litter mass benefited soil moisture by enhancing accumulation of snow in winter and reducing soil evaporation during the plant growing season, benefiting plant growth; also, the removal of plant litter before the plant growing season increased the reception of solar radiation, thus improving soil temperature and plant production. Seasonal grazing, especially autumn grazing reduced plant nutrient resorption in autumn, thus negatively affecting plant growth in the coming year (Zhang et al. 2020).

Animal species effects: Forage preference differed among sheep, cattle and goats. Sheep preferred *L. chinensis* and forbs, cattle preferred *S. grandis* and forbs, and goats preferred *C. squarrosa* and *C. korshinskyi* (Li et al. 2018). Consequently, sheep grazing reduced *L. chinensis* and forbs, but increased *S. grandis*; cattle grazing decreased *S.grandis,* but increased *C. korshinskyi* and forbs; goat grazing reduced *C. squarroa* and *C. korshinskyi*, but increased forbs. However, dominant plant species of *L. chinensis* and *S. grandis* were still dominant over the 7-year period though their dominance changed. These results imply that animal species or population structure can be used as a tool to manipulate grassland communities, and the adaptive grazing of all three livestock species at MG to consume 40% of ANPP can sustain the grassland.

Discussion and conclusion

Our results show that adaptive grazing management by removing grazing animals based on grassland residual height can prevent grassland degradation. Grazing intensity and precipitation jointly determine the ANPP or compensatory growth of grazing grassland, and grazing can promote ANPP by accelerating nutrient cycling. Grazing season affects ANPP by changing the seasonal patterns of plant litter mass that modulate soil physical conditions, and by altering the nutrient resorption efficiency differently. Winter or spring grazing is better than no grazing for grassland restoration and improvement. Grazing by different animal species drives divergent changes in plant community, with cattle grazing preferring dominant tall bunch-grasses and leading to better plant diversity then sheep/goat grazing.

The results do not support the policy to have a grazing ban for preventing grassland degradation in the region. Instead, it suggests that light or moderate grazing (consuming up to 40% of ANPP) is beneficial to plant production. In addition, grazing in winter or early spring before plants starting to grow is better than complete animal exclusion for recovery of degraded grassland or prevention of grassland degradation. The reduction of grazing in autumn to allow more resorption of plant nutrient to belowground is important to keep the viability and production of grassland plants in the coming year. These grazing management strategies should be incorporated in grassland management systems.

Our findings suggest encouraging the farmers to raise 'more cattle and less sheep' in the region, as cattle grazing in our adaptive management system can achieve a higher species diversity (Yan et al. 2024) and total ecosystem services (Shi et al. 2023), but with less damage than sheep production. The needle-like fruit of *S.grandis* is a nuisance in sheep grazing system, as it damages sheep skin and throat. Intensive cattle grazing in the early period of the reproductive stage of *S. grandis* is recommended before sheep grazing to prevent its negative effects on sheep production. Plant residual height-based adaptive grazing system with the rotation of different/mixed livestock species are expected to achieve the dual goal of pastoral production and ecosystem sustainability.

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Grazing management effect on mineral content of grasses: Case of two veld types of the Eastern Cape, South Africa

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Key words: Forage quality; herbaceous biomass; management practice; mineral concentration; veld type.

Abstract

This study examined the impact of three distinct grazing management strategies on the mineral composition of bulked native herbaceous forages within the sourveld and sweetveld ecosystems of South Africa's Eastern Cape province. The grazing management treatments examined were communal continuous (CC), holistic planned grazing (HPG), and commercial rotational (CR), each implemented across both veld types. Herbaceous forage samples were harvested from transects distributed along the lower, middle, and upper slopes of each site. Bulked, ground herbaceous forages were analysed for macro-elements (K, Ca, Mg, and P) and micro-elements (Fe, Zn, Mn, and Cu). Results highlighted notable differences between sourveld and sweetveld forages, with sourveld exhibiting higher macro-nutrient levels while sweetveld displayed elevated micronutrient concentrations, except for Mn. In sourveld areas, grazing management significantly affected ($P < 0.05$) the concentration of both macro and micro-elements except Zn. Additionally, the year (season) exerted significant effects ($P < 0.05$) on levels of Ca, K, Mg, Cu, Fe, and Zn, though not on P and Mn. Noteworthy interactions were observed, such as the influence of management practice by year by landscape position on P levels, and management by year on Zn and Mn levels. In sweetveld areas, management practices significantly impacted ($P < 0.05$) the levels of Ca, K, Mg, Cu, Zn, and Mn. Overall, grazing management practice and yearly (seasonal) variations emerged as the primary factors influencing forage mineral status. The analysis indicated deficiencies in P and Cu across both veld types, implying insufficient levels to meet ruminant animal requirements. Moreover, other elements potentially displayed marginal to deficient supplies, particularly in areas with continuous grazing. Consequently, supplementation may be necessary in both veld types. Future research could explore animal blood serum mineral levels to devise practical supplementation regimes aimed at averting potential deficiencies.

Introduction

There are two main types of rangeland tenure and usage in South Africa: communal land, which is owned by the government but managed through the chief, and the title deed land, which is mainly private ranching. Two major grazing systems have been practiced, namely continuous grazing (mostly practiced in communal tenure), and rotational grazing (mainly practiced in the commercial ranching and conservation farms). Over the last few decades, holistic planned grazing (HPG) has been introduced in a few commercial farm and communal areas in an attempt to maintain the natural balance between the livestock and rangeland resources for sustaining livestock production and associated values. Recent studies suggest that vast communally used rangelands in South Africa have degraded (Kwaza *et al*. 2020; Mlaza *et al.* 2023) with implications on mineral provision, both in time and space. However, the changes in forage minerals in the communal land in relation to other management (including rotational or HPG) have not been investigated. The objectives of this study were to determine the mineral content of bulked herbaceous forage samples in three grazing systems along a landscape gradient over time.

Methods

The study was conducted in two rangeland types across a precipitation gradient, sweetveld and sourveld in the Eastern Cape, South Africa. Sweetveld sites in Enock Mgijima local municipality experience a relatively dry climate with sourveld sites in Raymond Mhlaba local municipality receiving ~1000mm mean annual rainfall. Three communal - continuous grazing camps (CC), three communal - holistic planned grazing camps (CHPG) and two commercial ranches with rotational grazing (CR) were selected in the sweetveld. In the sourveld, two CC grazing lands, two CR grazing and two commercial ranches with HPG (CRHPG) were selected. Each camp or farm was divided into three major landscape positions (upper, middle and lower), and two 100 m x 10 m permanent plots ~50 m apart for data collection were established in each landscape unit. Forage samples were collected over two years; in the first year, during end of the dry season (sweetveld – 2016; sourveld – 2017), and towards the end of the growing season the following year. Forage samples were taken from ten 0.25 m^2 quadrats per plot, harvested at stubble height, bulked and oven-dried. The samples were milled and mineral elements were analysed using dry ashing (Method 6.1.1) (ALASA, 1998) at Western Cape Department of Agriculture, Enselberg Laboratories, South Africa. The experimental design consisted of nine treatment combinations in each rangeland type (3 camps/farms and 3 landscape positions). Data were analysed separately for the two rangeland types using the Mixed Model procedure of SAS (2007) testing the effects of grazing management, landscape position and seasonal variation.

Results

Effect of grazing management practices on mineral concentration

All forage mineral contents except Zn were significantly influenced by grazing management (Table 1). Forage Ca and P were higher ($P < 0.001$) in CR and CRHPG farms, K ($P < 0.01$) in CR farms and Mg ($P < 0.001$) in CC farms. Of the micro elements, forage Cu and Fe contents were highest in CR farms and Mn had the order of CR > CC > CRHPG farms. In the sweetveld, grazing management significantly influenced ($P < 0.001$) Ca, K and Mg concentrations. Forage Mn, Cu and Zn were highest in CC camps (Table 1).

Table 1: Mineral concentrations of forage samples from three grazing management systems in the sourveld and sweetveld study areas.

Mineral	Sourveld			Sweetveld		
	CC	CRHPG	CR	CC	CHPG	CR
Ca (%)	0.26±0.01^{b}	0.32±0.01^{a}	0.32±0.01^{a}	0.25±0.01^{b}	0.24±0.01^{c}	0.32±0.01^{a}
P (%)	0.06±0.01^{b}	0.11±0.01^{a}	0.13±0.01^{a}	0.11±0.01^{a}	0.10±0.01^{a}	0.11±0.01^{a}
K (%)	0.69±0.04^{b}	0.69±0.04^{b}	0.86±0.04^{a}	0.59±0.04^{b}	0.48±0.04^{c}	0.84±0.04^{a}
Mg (%)	0.13±0.00^{a}	0.08±0.00^{b}	0.10±0.00^{b}	0.10±0.00^{b}	0.08±0.00^{c}	0.12±0.01^{a}
Mn (mgkg^{-1})	169.6±10.9^{b}	58.8±10.9^{c}	229.1±10.9^{a}	50.2±1.62^{a}	43.4±1.62^{b}	46.1±1.99^{ab}
Cu (mgkg^{-1})	2.16±0.12^{b}	2.24±0.12^{b}	2.66±0.12^{a}	2.88±0.09^{a}	2.59±0.09^{a}	2.51±0.11^{a}
Fe (mgkg^{-1})	281.8±27.3^{b}	263.8±27.3^{b}	442.7±27.3^{a}	667.6±44.38^{a}	585.1±44.38^{ab}	499.4±54.4^{b}
Zn (mgkg^{-1})	28.0±1.26^{a}	27.0±1.26^{a}	26.9±2.16^{a}	36.0±1.68^{a}	28.9±1.68^{b}	32.1±2.06^{ab}

Means with different superscripts differ significantly (*P < 0.05*)

Effect of year (season) on mineral concentration
Significant differences (P < 0.0001) in forage mineral concentrations of Ca, K, Mg, Fe, Cu and Zn were found between years in both sourveld and sweetveld. Sourveld forages had lower concentrations in Year 1 (2017) compared to Year 2 (2018) (Table 2). Phosphorus and Mn were not influenced by year, but P showed a significant interaction of management practice x year x landscape position (P<0.05). In the sweetveld, all macro elements (Ca, P, K and Mg) were greatly influenced (P < .0001) by year with higher P, K, Ca and Mg in Year 2 (Table 2)

Table 2: Mean concentration of macro and micro-minerals by year in sweetveld and sourveld forages.

Mineral	Sourveld			Sweetveld		
	Year 1	Year 2	SE	Year 1	Year 2	SE
Ca (%)	0.27	0.33	0.01	0.24	0.30	0.01
P (%)	0.09	0.11	0.01	0.07	0.14	0.05
K (%)	0.56	0.94	0.03	0.43	0.84	0.03
Mg (%)	0.09	0.11	0.00	0.08	0.12	0.04
Mn (mgkg^{-1})	15.05	39.53	1.76	47.70	45.42	1.43
Cu (mgkg^{-1})	1.71	3.00	0.10	1.87	3.46	0.77
Fe (mgkg^{-1})	249.44	409.48	22.26	496.67	671.35	39.14
Zn (mgkg^{-1})	148.94	156.05	8.90	20.26	49.43	1.48

Effect of landscape position on mineral concentration
Landscape position significantly affected (P < 0.001) K, Cu and Zn concentrations in the sweetveld, with higher levels found in the upper slopes. Management and landscape interactions influenced mineral concentrations, with upper slopes of CR farms having higher K, Mg, Cu, Zn and Mn, while CC and CHPG had highest Zn concentrations in the lower slopes, and K, Mg and Mn highest in CHPG middle slopes.

Discussion
Phosphorus concentration was inadequate for grazing animals in both veld types, and across all management systems. This was likely due to the stage of plant maturity, as P levels typically decrease with advancing maturity (Beyene and Mlambo 2012), particularly when forages are harvested in the dry season and towards the end of the rainy season. The slight increase in P content in Year 2 may have been caused by more seed in the forages harvested

towards the end of the growing season. A study by Kwaza (2018) in the sourveld also found inadequate P levels in the forages of the same veld. The deficiency of P in forages of South African rangelands was previously recorded by Drewes *et al*. (1999). Calcium deficiency may be of concern in CHPG camps, as forages should contain at least 0.27 % for beef cattle (NRC, 2000). The K concentration in sourveld forages exceeded the recommended level for grazing animals (McDowell 1996; NRC 2000), a similar finding to that of Kwaza (2018). Magnesium levels were deficient for grazing animals in both veld types, especially in holistic managed camps and farms. Previous studies, such as Drewes *et al*. (1999), noted Mg deficiencies in Eastern Cape rangelands. The deficiency in Mg could be due to soils with higher amounts of K (Prabowo *et al*. 1991). High soil K can compete with Mg for uptake, reducing Mg availability and causing Mg deficiency in forages. Variations in Mg levels in the different management systems could be partially clarified in terms of the proportion of leaf and stem fractions that were collected for mineral analysis, especially during the dry season where a higher proportion was stem. Beyene and Mlambo (2012) found that most grass species generally meet micro-nutrient requirements, but Zn levels in CHPG were inadequate. In the communal rangelands especially where sheep are grazed, supplementation of Zn needs to be kept under review. The levels of forage Zn did not vary by season, unlike Ramirez *et al*. (2001) who reported variations in forage Zn by season.

The concentration of Cu levels in the forages were below the required 6-12 $mgkg^{-1}$ (NRC, 2000) potentially leading to deficiency. This may be due to the high levels of Fe in the soil as the forages had above the recommended levels of Fe for grazing animals (NRC, 2000). Grazing pressure and grazing systems (CC and CHPG) in sweetveld may have contributed to low Cu levels, potentially due to high Fe and Mn levels. Beyene and Mlambo (2012) found elevated Fe concentrations in bulked range forages harvested from a variety of soil types. Complex interactions between soil properties, land management practices, landscape position, grazing intensity, and seasonal changes affect both the soil's mineral content and the plant's ability to absorb and accumulate these nutrients.

Conclusion

It can be concluded that the forages in the two veld types generally meet ruminant mineral requirements, except for P and Cu. Forage Ca, Fe, Mn and Zn are sufficient. However, K and Mg in communal holistic managed rangelands need monitoring. Supplementation may be required, and further studies on animal blood mineral levels are recommended to ensure animals have the right nutrients and to detect potential health issues.

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Overgrazing of buffel grass pasture in the Brigalow Belt bioregion of central Queensland, Australia, led to invasion by Indian couch

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Key words: *Bothriochloa pertusa*; Brigalow Catchment Study; grazing land management; land condition; safe long-term carrying capacity

Abstract

Overgrazing, or failing to adjust stocking rates to match annual forage production, traps land in a cycle of degradation. From 2015 to 2024, two adjacent catchments in the Brigalow Belt bioregion of central Queensland were grazed by beef cattle. One catchment was stocked at or below the safe long-term carrying capacity. The other was stocked at the recommended stocking rate for newly established buffel grass pasture on recently cleared and developed brigalow land, which made no allowance for pasture productivity decline over time resulting in overgrazing.

The minimum ground cover in the catchment stocked at the safe long-term carrying capacity was 82% and end of dry season pasture biomass was always greater than 780 kg/ha. The proportion of buffel grass in this pasture averaged 93% throughout the study. In comparison, the overgrazed catchment had a minimum ground cover of 72% and end of dry season pasture biomass was as low as 46 kg/ha. At the commencement of this study, 88% of the overgrazed pasture was comprised of purple pigeon, buffel, and Indian couch grasses (54%, 27% and 7%, respectively). However, after 10 years, purple pigeon grass was almost absent and the proportion of buffel and Indian couch grasses in the pasture was 1% and 92%, respectively.

Overgrazing resulted in a decline in biomass, changed species composition, and the loss of the perennial, palatable and productive purple pigeon grass. Although ground cover initially declined as the tussock grasses disappeared, it recovered with Indian couch invasion. Previous research has shown that overgrazing also substantially altered catchment hydrology, with runoff and erosion more than tripling in the first five years. Conceptually, as runoff increases, the amount of rainfall stored in the soil for plant growth decreases, leading to lower ground cover and pasture biomass. Unless an intervention such as a reduction in stocking rate is undertaken, pasture utilisation will continue to exceed pasture production, and land degradation will continue.

Introduction

The Fitzroy Basin, in the Brigalow Belt bioregion of central Queensland, Australia, has been extensively cleared for agriculture. The dominant land use in the catchment is beef cattle grazing, accounting for 25% of the state cattle herd and 11% of the national herd. Land degradation in the Fitzroy Basin has occurred as a result of continuous heavy grazing, just as it has in up to 35% of permanent pastures globally (Thornton and Elledge 2021). Reducing sediment loss from degraded grazing land in the Fitzroy Basin was a priority under the Reef 2050 Water Quality Improvement Plan (The State of Queensland 2018). Under the plan, the effects of hillslope grazing management on land condition and water quality were monitored at the Brigalow Catchment Study. This paper presents the longitudinal changes in ground cover, pasture biomass, and species composition under heavy grazing pressure compared to conservative grazing pressure.

Methods

This study ran from 2014 to 2024 (hydrological years), utilising two catchments of the Brigalow Catchment Study in central Queensland, Australia. The site has a semi-arid, subtropical climate with a long-term (1965 to 2023) average annual rainfall of 643 mm. Rainfall data prior to the commencement of the Brigalow Catchment Study was obtained from SILO (Queensland Government 2019). Soils in both catchments were dominated by Vertosols which supported native brigalow (*Acacia harpophylla*) woodland prior to clearing and development for improved pasture. The first catchment was a long-term conservatively grazed buffel grass (*Cenchrus ciliaris*) catchment of 12.7 ha. The second was a commercially grazed purple pigeon (*Setaria incrassata*) and buffel grass catchment of 12 ha that was subjected to heavy grazing from October 2014 onward. Both catchments were grazed by *Bos indicus* beef cattle breeds. Conservative grazing stocking rates were at or less than the safe long-term carrying capacity of the landscape, being 3.5 ha/adult equivalent animal. Heavy grazing stocking rates were about 2 ha/adult equivalent, which was the recommended stocking rate for newly developed brigalow land with no consideration for a decline in pasture productivity since clearing. Pasture biomass and species composition were estimated using the BOTANAL method of Tothill *et al.* (1978). Ground cover was assessed using VegMachine® (Beutel *et al.* 2019). A comprehensive description of the study and its associated data sets can be found in Thornton and Elledge (2021).

Results

The extreme variability of central Queensland's rainfall was experienced prior to and during this study. From 2010 to 2014, rainfall was above average, including the wettest (2011) and third wettest (2010) years on record at the Brigalow Catchment Study. From 2015 to 2021, rainfall was below average and included the driest year on record (2017). From 2022 to 2024, rainfall alternated between above and below average.

As a result of consistent above average rainfall from 2010 to 2014, both catchments had high biomass at the commencement of the study, with about 7,600 kg/ha in the long-term conservatively grazed catchment (Figure 1) and 6,900 kg/ha in the heavy grazing catchment (Figure 2). Ground cover was 92% in both catchments. Under conservative grazing, pasture biomass and species composition were dominated by buffel grass in all years (Figure 1). Purple pigeon grass was only observed on one occasion, and Indian couch grass (*Bothriochloa pertusa*) was commonly observed but averaged only 3% of total pasture biomass. Pasture biomass under conservative grazing always exceeded that under heavy grazing.

At the commencement of heavy grazing, purple pigeon grass accounted for more than 50% of the pasture biomass while buffel and Indian couch grasses accounted for 27% and 7%, respectively (Figure 2). Within three years, pasture biomass dropped to less than 10% of the starting biomass and averaged 9% for the remainder of the study. Three major shifts in species composition occurred over time: 1) the dominant purple pigeon grass was replaced by buffel grass; 2) buffel grass became co-dominant with Indian couch grass; and 3) Indian couch became the dominant grass (Figure 2).

Under conservative grazing, ground cover averaged 90% (82% to 94%), while under heavy grazing ground cover averaged 87% (72% to 97%). Periods of low ground cover in the heavy grazing catchment were associated with a shift in the dominant tussock grass, from purple pigeon grass to buffel grass, whereas the highest ground cover was during the dominance of Indian couch in the near absence of tussock grasses.

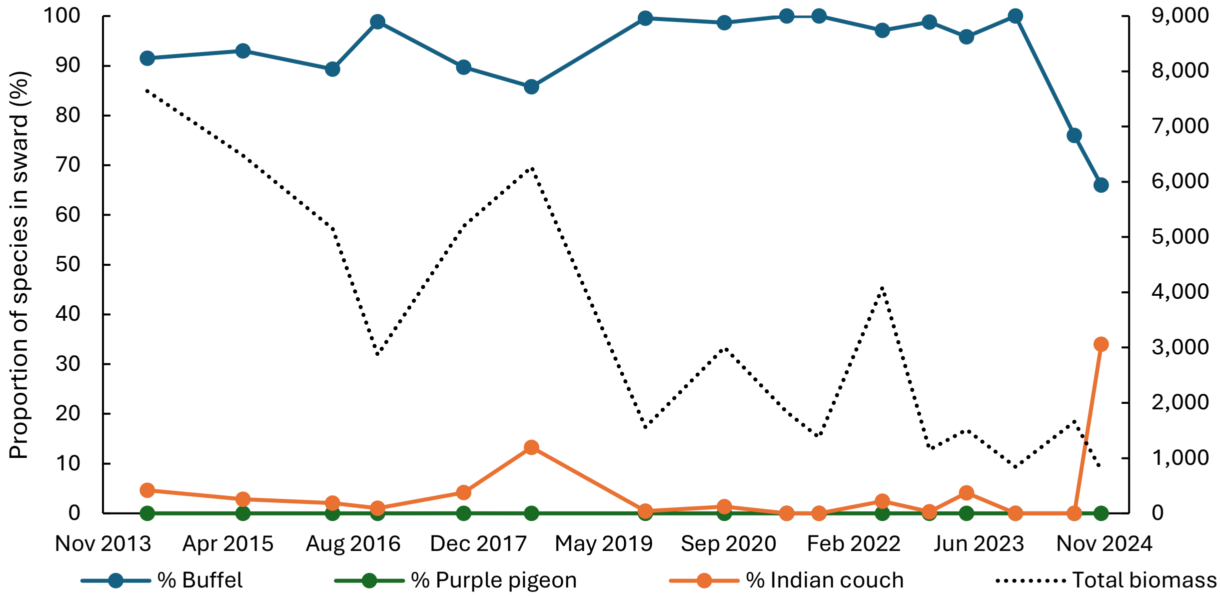

Figure 1. The proportion of buffel grass, Indian couch grass, purple pigeon grass and the total biomass of pasture under conservative grazing.

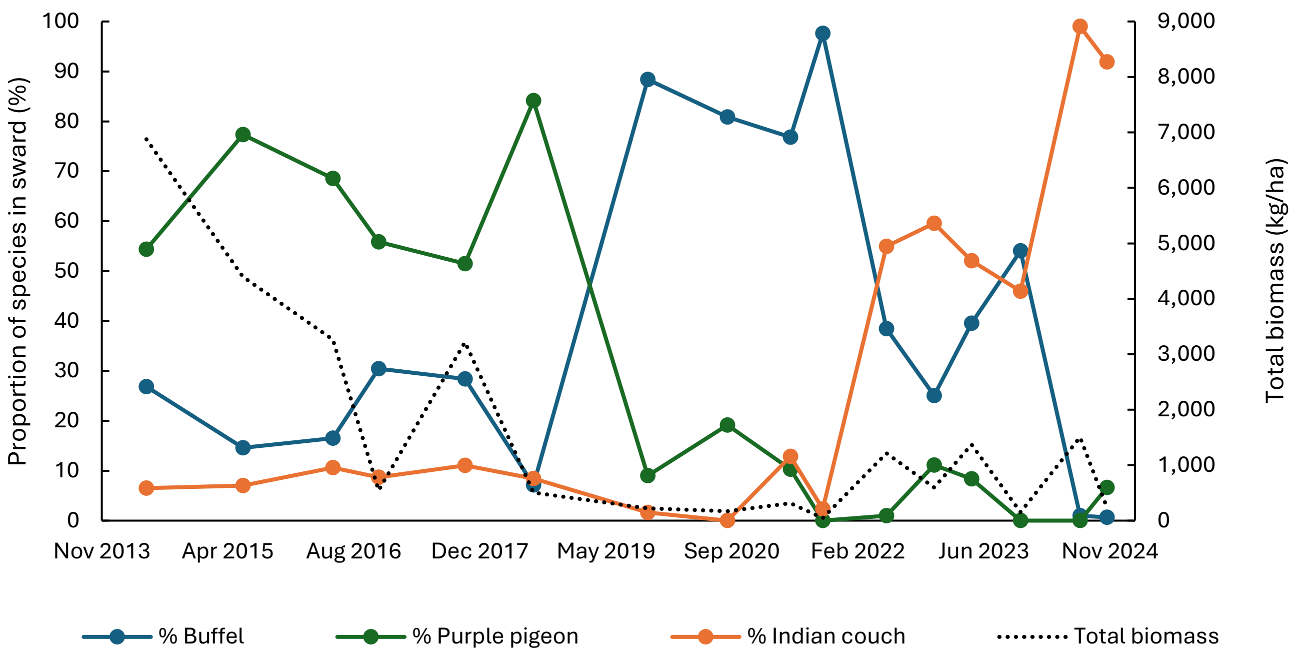

Figure 2. The proportion of buffel grass, Indian couch grass, purple pigeon grass and the total biomass of pasture under heavy grazing.

Discussion

This study was conducted during one of the driest periods in European history. Seven years of below average rainfall is atypical in the observed record, only happening twice since 1890. The previous occurrence was the Federation Drought which totalled an additional 100 mm of rainfall compared to the drought during this study. Drought was a substantial stressor to the pastures, as shown by the decline in yield under conservative grazing well below the 3,000 to 4,000 kg/ha typically seen in that catchment (Radford *et al.* 2007). Failure to lower grazing pressure from 2023 onward likely accounts for the rapid decline in buffel grass, and the corresponding increase in Indian couch due to reduced competition.

The three shifts in species composition under heavy grazing likely occurred because of the cumulative stresses of drought and overgrazing, given that purple pigeon and buffel grasses have contrasting responses to these stressors. Purple pigeon grass is intolerant of continuous heavy grazing and will not survive (Scattini 2008). Conversely, buffel grass is very tolerant of regular grazing and will withstand considerable grazing once established (Skerman and Riveros 1990; Cook 2007). The two species also have quite different rainfall requirements. Purple pigeon grass is considered drought tolerant, but not as much as buffel grass which is considered the most drought tolerant improved pasture species (Cook and Clem 2000; Cook 2007; Scattini 2008). Purple pigeon grass is recommended for regions with annual rainfall greater than about 450 to 500 mm (Skerman and Riveros 1990; NSW Government 2012). In contrast, buffel grass is recommended for regions with annual rainfall greater than about 300 to 350 mm (Humphreys and Partridge 1995; NSW Government 2012). Annual rainfall was marginal for purple pigeon grass in three of the study years, whereas it was only marginal for buffel grass in one year.

The effect of heavy grazing was evident in the declining biomass of all three pasture species over time. While purple pigeon grass was no doubt stressed by record below average rainfall in 2017, it was able to respond to rainfall the following year and maintain a high proportion of the total pasture biomass. However, the combined effects of overgrazing and drought in 2019 to an already stressed plant caused a substantial decline in the proportion of purple pigeon grass in the pasture. The decline of purple pigeon grass likely provided buffel grass a competitive advantage, with buffel grass increasing to average more than 80% of pasture composition until 2021. At this point the proportion of buffel grass in the pasture dropped substantially, prior to a partial recovery, becoming co-dominant with Indian couch grass prior to the dominance of Indian couch grass.

Differences in palatability between purple pigeon and buffel grass may explain differences in initial pasture composition but are unlikely to have had substantial influence on the final pasture composition. Purple pigeon grass is typically considered less palatable than buffel grass, so may have received less grazing pressure, and hence accounted for more of the total pasture biomass during the high biomass period at the start of the study. However, when the proportion of purple pigeon grass in the paddock dropped abruptly in 2019, there was only about 220 kg/ha of feed on offer in a paddock stocked at about 1 ha/adult equivalent, which suggests palatability would have been a substantially lower concern for animals compared to simply finding enough forage to maintain intake.

Interpretation of ground cover without consideration of biomass and species composition provided an incomplete assessment of catchment and pasture condition. The decline in biomass and change in species composition when tussock grasses were dominant was reflected in low ground cover observations. Counterintuitively, the highest ground cover observation of 97% was the final sampling period, which yielded only 230 kg/ha of biomass from a sward containing greater than 90% Indian couch. This suggests that ground cover alone is a poor metric for assessing land condition when Indian couch is the dominant pasture species.

In contrast to changes in pasture composition and cover that occurred under heavy grazing, there was little change in pasture composition and cover under conservative grazing. This demonstrates that drought alone was not responsible for the changes in species composition under heavy grazing, as both catchments were subjected to the came climatic sequence. Heavy grazing was a key driver in the loss of valuable improved pasture species and the subsequent dominance of Indian couch in that catchment. This mechanism was illustrated under conservative grazing in 2024, when failure to lower grazing pressure resulted rapid decline of buffel grass, and a corresponding increase in Indian couch due to reduced competition.

The implications of heavy grazing extend beyond decreased biomass, changed species composition and the dominance of Indian couch in a formerly productive tussock pasture, as all these factors contribute to a decline in beef production (Stokes *et al.* 2023). Furthermore, from 2015 to 2018, heavy grazing more than tripled runoff, peak runoff rate and total suspended solids lost in runoff compared to conservative grazing (Thornton and Elledge 2021). Total nitrogen lost in runoff increased by a factor of 1.6 while total phosphorus loss increased by a factor of 2.6 (Thornton and Elledge 2021). The increased loss of rainfall as runoff and the subsequent loss of nutrients undermines the resilience of pastures to overgrazing and the invasion of Indian couch. Management practice change towards conservative grazing with consideration of safe long-term carrying capacity is essential to halt land degradation and begin improving land condition.

Acknowledgements
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Genetic environment interaction on percent juniper in the diet of goats divergently selected for high or low juniper consumption

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Key words: restoration ecology; diet preferences; targeted grazing; animal breeding

Abstract

Diet selection by grazing animals is determined by genetic and environmental factors that interact and affect their efficacy for managing vegetation as targeted grazers and developing animals adapted to local grazing environments. The effect of rearing environments on the percentage of dietary juniper (*Juniperus* spp.) of goats, that for 15 years were divergently selected for high (J+) or low (J-) juniper consumption, was investigated using a factorial design 2 × 2 (rearing environment × selection line). Eighty pregnant does from both selection lines were grazed on either juniper-infested (JIR) or juniper-free (JFR) rangelands until their kids were weaned at about 75 days of age. Faecal samples were analysed with faecal near-infrared reflectance spectroscopy to determine the percent juniper in the diet. After weaning, kids from both rearing environments grazed JIR. The J+ does always consumed more ($P < 0.001$) juniper than J- does, demonstrating different maternal role models for kids reared in the JIR environment. The percentage of juniper in J- kid diets (7%) was the same regardless of the rearing environment. However, the rearing environment affected the percentage of juniper in the diet of J+ kids, resulting in a gene-environment interaction (P=0.022). The percentage of juniper in the diet of J+ kids reared in JFR (16%) and JIR (24%) were about two and three times higher than J- kids, respectively, indicating that genetics and the rearing environment contributed about equally to the increase in the percentage of juniper in the J+ kid diets. Regardless of the rearing environment, the J+ kids had a higher percentage of dietary juniper than J- kids (P<0.001). The ability to select animals with specific dietary preferences and proper rearing environments holds promise for targeted grazing strategies to restore degraded rangelands, with potential applications in conservation and ecosystem management.

Introduction

Livestock are valuable ecosystem engineers whose selective grazing habits affect the botanical composition and biodiversity of grazed ecosystems. There is much interest in methods for influencing grazing livestock botanical preferences to manage an ecosystem's trajectory. Diet selection and preference by grazing animals are determined by the genome, gene expression (epigenetics), and complex and variable learning environments of animals, and there is interest in using the variation within breeds to select animals that can utilize poor quality forages high in plant secondary compounds (PSC) that are common in arid environments. Determining to what extent foraging behaviour and diet preferences are genetically and environmentally determined and the interaction of these two factors will aid in selecting animals better suited for use in conservation schemes, whether by employing different breeds or animals from different backgrounds.

Junipers are chemically defended woody plants that have encroached in the western U.S. rangelands. For 15 years, Texas A&M AgriLife Research divergently selected goat populations for increased (J+) or decreased (J-) juniper consumption (Mulim et al., 2024). This study aimed to determine the gene-environment interaction on preference for juniper (*Juniperus ashei* and *J. pinchotii*) by goats from the two selection lines. To accomplish this, J+ and J- does were reared from the end of breeding until weaning on rangelands with or without juniper, and the percentage of juniper in kid diets was compared post-weaning, when goats were grazing in the juniper-infested rangelands (JIR).

Methods

The experiment was conducted following a completely randomized 2 × 2 factorial design (selection lines × rearing environment), and individual animals were replicates. The study was conducted on rangelands in west central Texas, USA. The predominant ecological site for the JIR is a Low Stony Hill in an Oak/Mixed-brush Shortgrass seral state. The JFR is predominantly a Clay Loam ecological site in a Shortgrass Mesquite/Mixed brush Savannah ecological seral state.

Does from the two selection lines were joined to bucks of their respective selection line in separate JIR pastures in the fall of 2021. At the end of the breeding season, 20 does from each line were randomly selected and transported to a JFR, while similar does remained on JIR. Does from the two selection lines in both rearing environments remained in separate pastures until their kids were marked according to their selection line at 30 days of age. Then, they were combined to graze on a common pasture in their respective rearing environments. After weaning, goats from the two selection lines (J+ and J-) and from both rearing treatments (JIR and JFR) grazed common but different JIR pastures for does and kids (Figure 1).

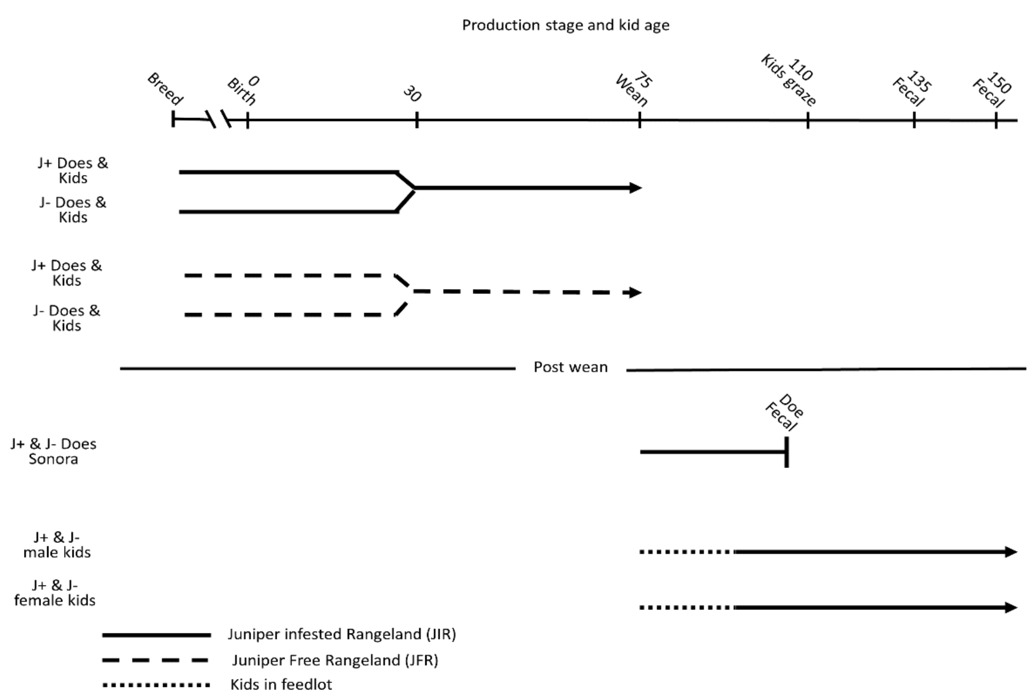

Figure 1. Diagram depicting rearing and grazing environment periods and fecal sample collections for goats divergently selected for high (J+) and low (J-) juniper consumption.

The percent juniper in the diet was determined on faecal samples (fNIR) using near-infrared spectroscopy (Walker et al., 2007). To document that does provide different maternal role models for their offspring faecal samples from does grazing JIR were collected when kids were 30 days old, at weaning, and 30 days post weaning. Post weaning following a 21-day adaptation period, 110-day-old kids from both rearing environments were grazed on JIR. Faecal samples were collected two or three days apart in the same pasture for does and kids, respectively, and averaged before statistical analysis because these samples were considered subsamples. Analysis of variance using the MIXED procedure of SAS 9.4 was used to determine treatment effects and their interactions. Tukey's test was used for mean separation when there were more than 2 means.

Results

When grazing JIR, the J+ does always had a higher percentage of juniper in their diets (P < 0.001) compared to J- does (Table 1). There was no effect of rearing environment (P = 0.488) or rearing environment × selection line interaction (P = 0.096) when does grazed a common pasture.

The percent juniper in the J- kid diets was the same regardless of rearing environment, and J+ kids raised on JFR had twice as much juniper in their diet, while J+ kids raised on JIR had three times as much juniper in their diet compared to J- kids, resulting in a significant selection line x rearing environment interaction (P = 0.022; Figure 2). Regardless of the rearing environment, the J+ kids had a higher percentage of juniper in their diets than J- kids (P < 0.001; Table 2). Compared to males, female kids had a higher percentage of juniper in their diets (P = 0.002).

Table 1. Percentage of juniper in the diet of goat does divergently selected for high (J+) or low (J-) juniper grazing juniper infested rangelands (JIR) or juniper free rangelands (JFR).

Doe treatment	JIR		JIR & JFR
Forage type	JIR	JIR	JIR
Days postpartum	30	75	110
Selection line			
J+	43	67	71
J-	-3	4	26
SEM	NA[1]	13	10
P-value	NA	<0.001	<0.001

[1] Because does grazed different pasture statistical comparisons were not made.

Table 2. The effect of selection line and sex on percentage juniper in the diets of post-weaned kids grazing juniper infested rangelands.

	Selection line		Sex	
	J-	J+	M	F
Juniper (%)	7	19	12	17
SEM	1		1	
P-value	<0.001		0.002	

Discussion

To our knowledge, these two lines of goats are the only livestock that have been selectively bred to change the botanical composition of their diet. The genetic-environment interaction, while often hypothesized (Rook et al., 2004), has little supporting empirical research on free-grazing ruminants. However, the rearing environment did affect the percentage of juniper in the diet of J+ kids, resulting in a genetic-environment interaction. The percentage of juniper in the diet of J+ kids raised in the JFR and JIR environment were about two (16%) and three (24%) times higher than J- kids, respectively, indicating that genetics and the rearing environment contributed about equally to the increase in the percentage of juniper in the J+ kid diets. However, this study cannot explain the cause of the interaction. The rearing environment can cause epigenetic changes that increase an animal's ability to metabolize or eliminate xenobiotics (Zhu et al., 2023), and their ability to learn to sequence meals to mitigate PSC (Villalba et al., 2004). The rearing environment did not affect percentage juniper in the diet of J- kids, indicating that it is limited by their ability to metabolize PSC that act as feeding deterrents (Villalba et al., 2015).

The importance of the genetic influence on diet preference was shown by the higher percent juniper in the diets of J+ compared to J- kids and does regardless of rearing environment. The heritability estimates for the percent juniper in the diet of the goat lines used in this study was 43% (Mulim et al., 2024). Similar to this study in human twin studies the heritable of preference for vegetables that like juniper have a lower preference than other foods is about 45%, and the remaining variation is shared and nonshared environmental (Breen et al., 2006; Fildes et al., 2014). The need to use individual variation in diet preferences within breeds or species to develop animals more aligned with the botanical composition of the rangelands they are grazing has been recognized, and this study demonstrated that there is adequate variation and heritability within breeds to help accomplish this goal.

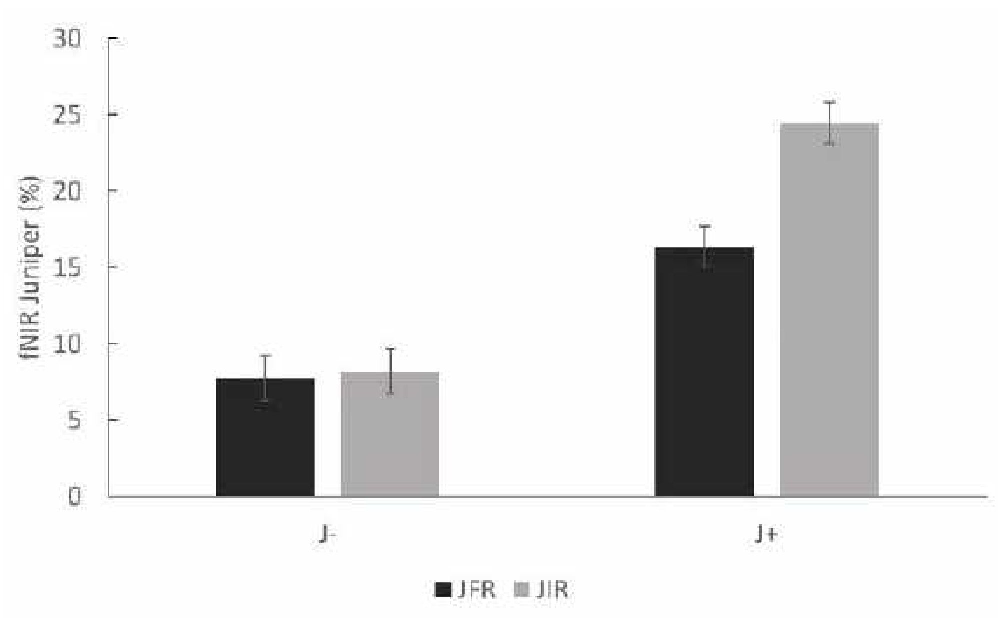

Figure 2. Selection line × rearing environment interaction (P = 0.022) for percent juniper in the diet of weaned kid goats divergently selected for high (J+) and low (J-) juniper consumption and reared on juniper-free rangelands (JFR) or juniper infested-rangelands (JIR) free grazing a JIR.

Acknowledgements
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All experimental protocols adhered to guidelines for the ethical and humane use of animals for research according to the Guide for the Care and Use of Agricultural Animals in Research and Teaching (FASS, 2010) and were approved by the Texas A&M AgriLife Institutional Animal Care and Use Committee (AUP 2022-008A).

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Species asynchrony as the key driver of reduced temporal stability in typical grassland community productivity

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Key words: grazing intensity; temporal stability; species asynchrony; semi-arid steppe

Abstract

Livestock grazing is a key factor influencing structure, functioning and stability of grassland ecosystems. However, the effects of grazing intensity on the temporal stability of plant community aboveground net primary productivity (ANPP) and the driving mechanisms remain poorly understood in typical steppe ecosystems. In a 6-year experimental study, we investigated how varying grazing intensities (light, moderate, heavy, and no grazing) affect the temporal stability of ANPP in plant communities and functional groups. Our findings revealed that both plant community ANPP and species richness increased significantly under all grazing intensities. Moderate and heavy grazing also led to a significant reduction in the temporal stability of ANPP of community and dominant species. Structural equation modelling further identified species asynchrony as the primary driver of community productivity stability across different grazing intensities in semi-arid grasslands.

Introduction

Grasslands, covering 40% of Earth's terrestrial surface, are critical for biodiversity and livestock production (Wen *et al.* 2011). However, they have suffered significant biodiversity loss, ecosystem degradation, and reduced stability, largely due to livestock grazing (White *et al.* 2000; Shan *et al.* 2011). Grazing alters plant community structure, diversity, and productivity, thereby impacting ecosystem stability (Filazzola *et al.* 2020; Li *et al.* 2022; Sun *et al.* 2023). Maintaining grassland stability is crucial for sustaining ecosystem services, necessitating a better understanding of how grazing influences these systems.

Temporal stability, defined as the consistency of aboveground biomass over time, is vital for sustaining multiple ecosystem functions (Tilman and Clark 2014; White *et al.* 2021). It is influenced by species diversity (Hautier *et al.* 2015), species asynchrony (Hautier *et al.* 2014), and the stability of dominant species (Hillebrand *et al.* 2008). Species diversity enhances stability by promoting species asynchrony, where different species respond differently to environmental variability, buffering productivity fluctuations (Wang and Loreau 2016; Xu *et al.* 2021). Grazing, a widespread land-use practice, impacts grassland stability by altering species richness and asynchrony (Blüthgen *et al.* 2016). Moderate grazing may enhance stability, whereas heavy grazing often reduces it by decreasing species richness (Li *et al.* 2018; Ren *et al.* 2018).

The temperate grasslands of Inner Mongolia, including meadow steppe, typical steppe, and desert steppe, have historically supported traditional grazing due to their unique ecological characteristics (Zhu *et al.* 2023). However, these grasslands have degraded in recent decades due to overgrazing, human activities, and climate change (Bai *et al.* 2015). Overgrazing has led to severe ecosystem degradation in the semi-arid steppe. Understanding how grazing intensity affects productivity stability is critical for developing sustainable grazing management strategies in these regions. In this study, we conducted a six-year field experiment in the Inner Mongolian grasslands to examine how grazing intensity influences productivity stability. Specifically, we addressed two key questions: (1) How do different grazing intensities affect the temporal stability of aboveground net primary productivity (ANPP)? (2) What are the key drivers of temporal stability under different grazing intensities? Our findings aim to clarify the mechanisms regulating productivity stability in semi-arid grasslands and provide a scientific basis for sustainable grazing management in temperate steppes.

Methods

Study site and experimental design

The study was conducted at the Grassland Ecosystem Research Station of Inner Mongolia University, 60 km northeast of Xilinhot city, Inner Mongolia, China (116°31′18″ - 116°32′28″E, 44°15′24″ - 44°15′41″N, 1146 m a.s.l.). In 2016, a grazing experiment was initiated in a level grassland area, with 16 experimental paddocks (0.25 hm^2 each). Four grazing treatments—nil grazing (NG), light grazing (LG), moderate grazing (MG), and heavy grazing (HG)—were randomly assigned, each replicated in four blocks. Grazing intensities were achieved by introducing 0, 3, 6, or 9 sheep to the respective paddocks, using a rotational grazing system. Sheep were introduced in June, July, and August, and after each grazing event, they were removed, leaving a residual grass height of about 6 cm in MG paddocks (approximately 60 g dry matter/m^2). The experiment ran from 2017 to 2022 to assess the long-term effects of grazing intensity on grassland ecosystem structure and function.

Sampling and measurements

Three moving cages of 1.2 m in length, 1.2 m in width, and 1.0 m height were randomly placed in each paddock to protect the grassland from grazing before each animal grazing rotation in June, July, or August. Plant aboveground biomass (AGB) was determined by harvesting (clipping) plant materials species by species from the ground surface at the end of each grazing rotation, both inside and outside each moving cage, using the quadrat of 1 m × 1 m, and then these cages were moved to other places for excluding animal grazing in next rotation. The harvested plant biomass was oven-dried at 65°C for 48 h and weighed.

(1) Aboveground Net Primary Productivity (ANPP): ANPP was determined as the total aboveground biomass produced by plants during the growing season, which included both livestock feed intake during the grazing rotations and the residual plant biomass remaining at the end of the final grazing rotation. The total ANPP for each paddock was measured at the end of each grazing season.

(2) The daily forage intake of grazing sheep (DI): in each grazing rotation was determined as the difference between plant AGB inside (AGB_i) and outside (AGB_g) of the moving cages after each grazing rotation:

$$DI = (ABG_i - ABG_g) \times 2500\ m^2 / N_L / D_g$$

Where DI was in $g \cdot head^{-1} \cdot d^{-1}$; AGB_i and AGB_g were in $g \cdot m^{-2}$; N_L is the number of sheep in grazing, and D_g is the number of grazing days.

(3) Species richness in each paddock was defined as the total number of species detected in the three quadrats.

(4) The temporal stability of ANPP was defined for each paddock as μ/σ (i.e., the inverse of CV), where μ is the temporal mean of community-level ANPP from the paddock over 6 years period and σ is the temporal standard deviation over the same period. Temporal stability is unitless.

(5) The species asynchrony was quantified using the community-wide asynchrony index by species biomass (Loreau and de Mazancourt 2013a).

$$1\text{-}\varphi=1 - \frac{\sigma^2}{\left(\sum_{i=1}^{s}\sigma_i\right)^2}$$

Where φ is species synchrony, and σ^2 is the temporal variance of community aboveground biomass of species i in a community with S species.

Statistical analysis

In this study, we used the Shapiro-Wilk normality test for the normality of variance for each data set. Repeated-measures ANOVAs were performed to test the effects of grazing treatments on ANPP, species richness, stability and asynchrony. One-way ANOVAs with Duncan's multiple range tests were used to determine the significance of difference among the grazing treatments. Structure equation modeling (SEM) was used to estimate the strength of direct and indirect relationships between grazing treatments, species asynchrony, species richness, functional groups stability and community temporal stability.

Results

Effect of grazing on plant community ANPP

Compared to the ANPP of total and function groups in the ungrazed grassland, the total ANPP and the ANPP of subordinate species significantly increased under increasing grazing intensity ($P < 0.05$, Fig. 1a, c). The ANPP of dominant species significantly increased under LG and MG, but not under HG ($P < 0.05$, Fig. 1b).

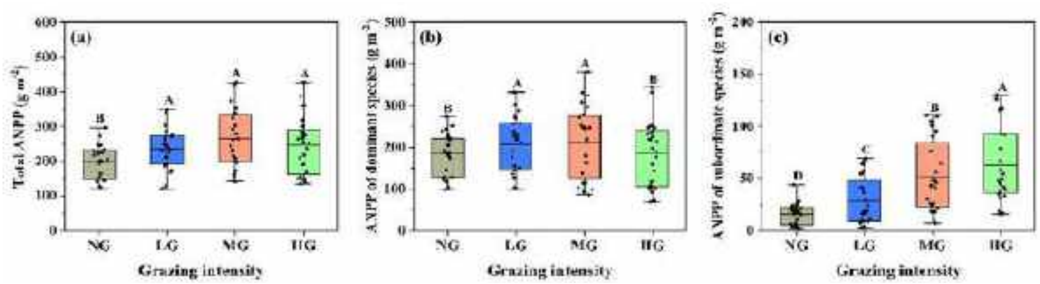

Fig. 1 Effects of different grazing intensity on ANPP of total (a) and function groups (b, c) in a typical steppe grassland. Different uppercase letters indicate significant differences between grazing treatments ($P < 0.05$).

Effects of grazing on temporal stability of ANPP and species asynchrony

Compared with no grazing, the stability of ANPP of community and dominant species significantly decreased under the MG and HG ($P < 0.05$, Fig. 2a, b), and the stability of ANPP of subordinate species significantly increased under moderate grazing ($P < 0.05$, Fig. 2c). Compared with no grazing, the species asynchrony significantly decreased under HG, but the species richness significantly increased under MG and HG ($P < 0.05$, Fig. 2d, e).

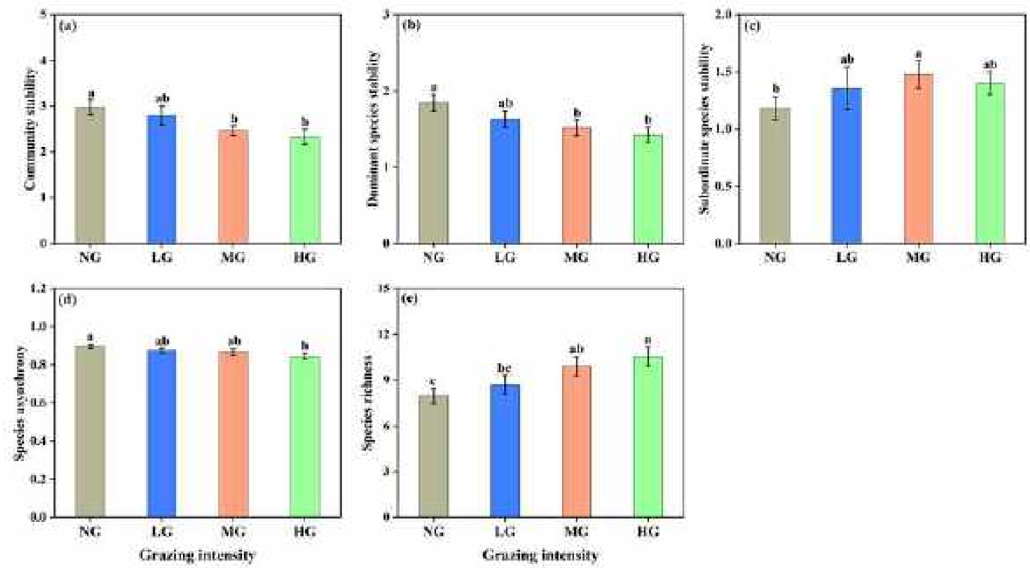

Fig. 2 Effects of different grazing intensity on productivity stability, species asynchrony and species richness in a semi-arid steppe.

Pathways through which grazing intensity influenced community stability

The SEM analysis demonstrated that grazing intensity indirectly reduces temporal stability of community ANPP by reducing dominant species stability and species asynchrony. Additionally, grazing intensity also indirectly reduced community temporal stability through its positive effects on species richness and ANPP. Species asynchrony was the primary factor influencing community temporal stability.

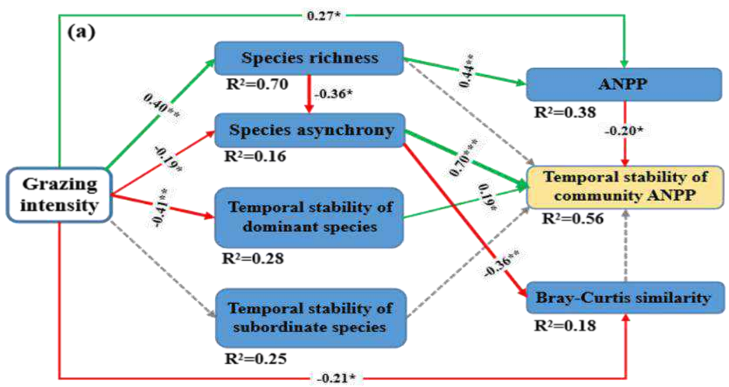

Fig. 3 Structural equation modeling (SEM) depicting the direct and indirect effects of different grazing management on productivity stability in a semi-arid steppe. Red and green arrows indicate negative and positive relationships ($P < 0.05$) respectively, with path coefficients shown on the paths, and dashed gray lines indicating non-significant relationships. Arrow width indicates the strength of the relationship.

Discussion

Our results indicate that grazing intensity increases community ANPP compared to no grazing, primarily due to higher ANPP of subordinate species and, to a lesser extent, dominant species. Previous studies suggest that moderate grazing enhances plant productivity through compensatory growth, while heavy grazing generally reduces productivity (Hilbert *et al.* 1981; Mcnaughton 1983). In our study, however, grassland productivity still increased under heavy grazing, likely for two reasons. First, the grazing intensity may not have been sufficient to cause significant damage, allowing compensatory growth to persist. Second, increased trampling and grazing pressure reduced biomass of dominant species, potentially altering competitive interactions (Sternberg *et al.* 2000).

In alignment with our expectation that livestock grazing can change productivity stability in temperate grassland, our results show that grazing intensity decreased community and dominant species productivity stability. This is consistent with other studies that have shown that community productivity stability decreases with increasing grazing intensity (Qin *et al.* 2019; Han *et al.* 2023). Summer is a season of vigorous plant growth, and grazing activities can alter the competition for resources (i.e., light and nutrients) among vegetation species (Eskelinen *et al.* 2022), resulting in dynamic changes in the plant community and decreased productivity stability. Grazing reduces the dominant species stability, largely owing to selective feeding by livestock. In general, herbivores prioritize tall and palatable plants (Lv *et al.* 2020), dominant species are highly favored by domestic animals owing to their generally larger size and high proportional abundance (Mariotte *et al.* 2013), whereas compensatory growth after ingestion also induces ANPP instability in the community (Zhu *et al.* 2021).

Species asynchrony, arising from differential species responses to environmental conditions, is a common feature of communities (Muraina *et al.* 2021). Our results show that heavy grazing reduces species asynchrony. Under heavy grazing, the relative biomass of annuals and biennials increases, while dominant species like *Leymus chinensis* and *Stipa grandis* decrease, leading to less asynchronous population dynamics. Studies have shown that increased species asynchrony enhances community productivity stability (Tilman and Downing 1994; Loreau and de Mazancourt 2013b; Zhou *et al.* 2019). In line with this, our findings suggest that grazing reduces ecosystem stability mainly by decreasing species asynchrony, rather than by affecting species richness. This negative impact on species asynchrony undermines its stabilizing effect, causing a decline in community stability with increasing grazing intensity (Liang *et al.* 2021). Species asynchrony, but not species diversity, are the main driver influencing community productivity stability in semi-arid grassland grazing ecosystems.

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How does the forage utilisation during winter of a native grassland pasture affect the subsequent dry matter on offer in spring?

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Key words: carry-over effects; native grasslands; forage utilisation

Abstract

Excessive forage utilisation over winter, resulting in short residual sward heights (SH), may compromise spring production of native *Campos* grasslands. To assess the relationship between end-of-winter SH and subsequent spring dry matter (DM) on offer, an experiment was carried out in 2020 and 2021 to describe forage dynamics for swards clipped at 2, 4, 6, 8 and 10 cm as winter residual SH during five sampling dates throughout spring. Each year, 150 homogeneous plots (0.2 x 0.5 m) were arranged in a complete random block design experiment with six replicates (blocks). In both years, residual end-of-winter SH affected spring forage DM on offer but only had a small effect on net DM accumulation. The magnitude and extent of this response differed between years (interaction year* treatment, $p<0.001$). The main climatic difference between years was less rain in 2021 compared to 2020, yet, there was a greater DM on offer and greater net increase in DM accumulation in 2021. Average minimum temperature was greater in 2021 and may account for these year effects. There was little effect of low residual SH at the end of winter on subsequent spring DM production, but the extra DM within the system, by planning to have a greater SH at the end of winter, provided a buffer to render the whole system more weather-resilient.

Introduction

Native *Campos* grasslands are the main nutrition basis for meat and wool production systems in Uruguay, especially for extensive production (Jaurena et al. 2021). Since these pastures are grazed directly all year round and each season provides different amounts of forage dry matter (DM) productivity, with the lowest productivity observed during winter and the highest typically in spring (Orcasberro et al. 2021), it is difficult to properly manage livestock production considering these differences. Thus, it is common to observe excessive forage utilisation in winter, resulting in short residual sward heights (SH) by the end of this season. This shorter initial spring SH may compromise spring forage production.

Stockpiling native grassland forage from a season with a rapid growth rate (such as autumn) in order to be consumed in a season with very little growth (such as winter, when growth is temperature limited - Forde et al. 1975) is a common practice of certain farmers in the Pampa Biome (Jaurena et al. 2021). Thus, during winter, only animal consumption (demand) and virtually no new forage growth (offer) is expected. The question arises as to whether there is any subsequent impact on spring DM production depending on the pasture remaining at the end of winter. The objective of this study was to determine if forage utilisation (final winter SH) of native pastures affects the subsequent dry matter production in the following spring.

Methods

The trial was carried out at “Glencoe” Research Station (INIA Tacuarembó, Uruguay), with average annual rainfalls of 1200 mm, a subtropical humid climate with no dry season, and mean temperatures of the coldest and warmer months being -3 and 18ºC, respectively (Panario & Bidegain, 1997).

Five hectares of native rangelands were stockpiled during autumn from 28th and 25th March on 2020 and 2021, respectively, being intensely grazed before the accumulation period aiming to remove dead material from the summer. This initial autumn stockpiling period aimed to imitate what some farmers do before winter begins.

After the stockpiling period, at the end of the winter (date 0, on 7th and 14th September in 2020 and 2021, respectively), five SH treatments were applied to 150 plots of 0.5 x 0.2 m, with an initial SH of 10±2 cm, by clipping as follows: 2 cm, 4 cm, 6 cm, 8 cm and 10 cm above ground SH. No cattle grazed the site over the duration of the experiment.

Treatments were arranged as a split plot design with assessment date as the main plot and initial SH as subplot treatments, with six replicates each. The dates and treatments were allotted randomly within its corresponding main plot (date) and subplot (SH). The assessment dates (described in Fig. 1) were fixed beforehand and estimated as the summation of degree days (DD) using a base temperature of 8 °C, every 165 DD after the treatment application (date 0).

Forage DM on offer and SH were analysed using a mixed model approach, while simple linear regressions were applied to calculate growth rates (GR). Weather variables between years were analysed using ANOVA. All statistical analysis was performed using Infostat programme (Di Rienzo et al. 2015).

Additionally, GR were calculated as the average DM of each treatment on the final date minus the initial DM value divided by the number of days between sampling.

The DM and SH lab and field evaluations were conducted following the same methods as Cazzuli et al. (2023). Weather data was collected from an automatic station near the trial area.

Table 1. Weather variables during the pre-trial period (stockpiling during autumn and winter) and during the trial (spring) for both years

Weather variable	**2020**	**2021**	**p-value**
	Period: stockpiling pre-trial (autumn-winter)		
Average maximum temperature (°C)	20.6	14.5	< 0.001
Average minimum temperature (°C)	7.4	13.4	< 0.001
Average temperature (°C)	13.7	13.9	0.68
Average rainfall (mm/day)	8.4	4.6	0.10
	Period: trial (spring)		
Average maximum temperature (°C)	26.0	20.3	< 0.001
Average minimum temperature (°C)	10.7	18.9	< 0.001
Average temperature (°C)	18.4	19.6	0.06
Average rainfall (mm/day)	4.6	0.7	> 0.001

Pre-trial dates: 2020 = 28th March 2020 – 7th September 2020 (163 days); 2021 = 25th March 2021 – 14th September 2021 (173 days).
Trial dates: 2020 = 7th September 2020 – 9th December 2020 (93 days); 2021 = 14th September 2021 – 16th December 2021 (93 days).

Results

There was less rain in 2021 compared to 2020 but only during the trial period, and the minimum overnight temperature in spring was much higher in 2021 (Table 1). There were slightly more frosts during the stockpiling period of 2021 compared to the same period of 2020 (53 and 36 frosts for 2021 and 2020, respectively), and no differences between number of frosts during the trial period (5 frosts for both years).

In both years, residual end-of-winter SH affected spring forage DM on offer, but the magnitude and extent of this response differed between years (interaction year * treatment, $p<0.001$) (Fig. 1).

There was a significant year effect (2021 > 2020, $p<0.05$, Table 2) on net DM GR. Even though GR was not affected by treatment, a trend could be observed for greater GR for 10cm in both years.

Final SH reflected initial SH, although there was a trend for 10cm initial sward height to have higher growth rates (double) than all shorter start SHs.

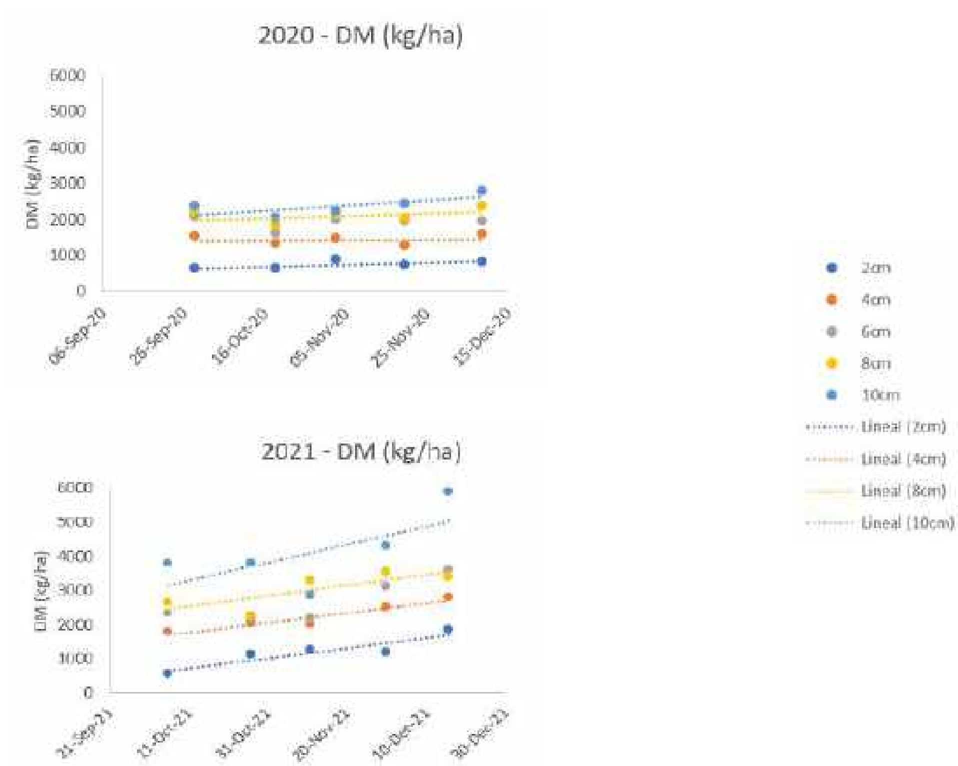

Fig. 1. Dry matter (DM) on offer on each of the 5 sampling dates of a native *Campos* grassland during spring, evaluating either 2, 4, 6, 8, or 10 cm final winter sward heights, for two years. The dotted lines are the regression of DM on offer over time.

Table 2. Daily dry matter (DM) growth rate and sward height (SH) of a native *Campos* grassland during spring, evaluating either 2, 4, 6, 8, or 10 cm final winter SH treatments, for two years.

Treatment SH	Final SH (cm)				Daily DM Growth Rate (kg/ha/day)	
	2020		2021		2020	2021
	Mean	SE	Mean	SE		
2cm	7.1	0.42	9.0	0.98	2.7	18.2
4cm	9.3	0.42	8.6	0.98	1.0	15.6
6cm	9.5	0.42	11.6	0.98	-1.5	18.2
8cm	11.8	0.42	11.5	0.98	3.0	13.9
10cm	13.3	0.42	14.6	0.98	6.2	29.0

Growth rates were calculated as the average DM of each treatment on the final date minus the initial DM value divided by the number of days between sampling. This is why there is a negative value.

Discussion

Residual sward height at the end of the winter affected spring forage-on-offer in both years but there was no effect on net DM accumulation nor on changes in SH (Fig. 1 and Table 2). High utilisation over winter with a low residual SH will have little effect on subsequent spring DM growth but low forage utilisation (high residual SH) may be used as a forage bank if spring DM production is compromised as illustrated in 2020 here. This has important management implications (Claramunt et al. 2018, Orcasberro et al. 2021).

There was a marked year effect, in agreement with Royo Pallarés et al. (2005) who concluded from their 19-year data on similar pastures that there was great inter-annual variability of forage production. On average, these authors found maximum GR of 25 kg/ha/day (between summer and autumn), and minimum GR of 5.5 kg/ha/day (winter months), the latter being above our spring GR data. The values of DM from 2021 were always greater than those from 2020 despite less rain over the period and no difference in the number of frosts in spring. The one difference was that average minimum temperature in 2021 (18.9C) was greater than 2020 (10.7C) and C4 plants are sensitive to minimum temperature to initiate and promote growth (Forde et al. 1975, Ivory & Whiteman, 1978). *Campos* grasslands have a high proportion of C4 plants and this may account for the differences between years in net DM accumulation and SH. Our DM on offer values are similar to the highly variable estimates of the native *Campos* grasslands during spring (e.g. Claramunt et al. 2018 with 1000 and 1500 kg/ha depending on the year, or Orcasberro et al. 2021 with 4147 kg/ha at 11.6 cm and 2910 kg/ha at 6.8 cm).

When analysing production systems as a whole, the higher the pre-drought herbage allowance and herbage accumulation rate, the lower the risk of a negative impact of a drought on the whole system (Modernel et al. 2019). Thus, having a relatively high end-of-winter SH provides a buffer of forage within the system and may have some advantage in not limiting subsequent DM growth over spring. However, the minimum temperature over spring appears to have a major effect on spring DM growth which requires further research in the heterogenous C3 and C4 plant systems such as these.

Implications

Weather conditions play a very significant role on overall forage on offer, even though their interactions are not always thoroughly understood. Minimum temperature in spring appears to be important in the growth response of Campos grasslands.

Nonetheless, there are some principles that apply if the aim is to optimise overall system productivity. Whilst the low residual end-of-winter SH has little effect on net DM accumulation in spring, there is no buffer DM present.

A higher residual SH would make the system more resilient to management strategies and between year variation in temperature and occurrence of frosts. Alternatively, although not statistically different in this study, further research may be warranted to investigate whether the observed trend of greater growth rates with 10cm is a real effect, as this would have implications for recommended end of winter target sward height to maximise spring forage growth and available dry matter.

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Exploring the nutritional composition of fodder resources utilized by transhumant Gaddi shepherds in the western Himalayas, India

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Keywords: Fodder, Gaddi Shepherds, Nutritional Composition and Western Himalayas

Abstract

The Gaddi shepherds of the northwestern Himalayan region practice transhumance, migrating their sheep and goats to alpine pastures in summer and lower Shiwalik hills in winter. These animals graze on various vegetation during migration, whose nutritional value remains largely unstudied. Therefore, this study aimed to assess the nutritional quality of key fodder resources (including trees, shrubs, herbs, and grasses) crucial for small ruminant feeding. Gaddi farmers were interviewed using a semi-structured questionnaire to gauge their preferences for these fodder resources. Representative samples 20 most important fodder species (in triplicate) were hand plucked to mimic the diet selection by migratory small ruminants from the Bharmour block of District Chamba and were subjected to nutritional evaluation. The study revealed significant variation in nutritional attributes among the different preferred fodder species. The DM % was highest in *Quercus semecarpifolia* (61.80 ± 0.77) and lowest in *Buddleja crispa* (32.40 ±0.26) [p<0.05]. The CP% (DM basis) was highest in *Indigofera heterantha* (22.03± 0.27) and lowest in *Quercus semecarpifolia* (9.93± 0.17) [p<0.05]. EE % was higher in *Quercus leucotrichophora* (3.26 ±0.20) and lowest in *Morus serrata* (1.33 ± 0.25) [p<0.05]. The CF, NDF, and ADF (%) were greater [p<0.05] in *Quercus semecarpifolia* and lowest in *Trifolium pratense* (37.00 ± 0.31, 53.13 ± 0.39 and 47.66 ± 0.29 vs. 21.23 ± 0.42, 36.13 ± 0.36 and 25.16 ± 0.58, respectively). The TA (%) was found highest in *Populus deltoides* (8.06±0.39) and lowest in *Indigofera heterantha* (2.56 ± 0.30) [p<0.05]. AIA (%) was highest in *Salix alba* (4.66 ± 0.21) and lowest in *Oxyria digyna* (0.66 ± 0.23) [p<0.05]. The NFE (%) was highest in *Festuca arundinacea* (57.13±0.40) and lowest in *Populus deltoides* (43.30 ±0.27) [p<0.05]. Based on farmer preferences and nutritional analysis, the study identified the most preferred species for Gaddi farmers feeding small ruminants in the Bharmour block of District Chamba, including *Desmodium elegens*, *Indigofera heterantha*, *Rubus saxatilis*, *Buddleja crispa*, *Trifolium pratense*, *Festuca arundinacea*, *Salix alba*, *Robinia pseudoacacia*, *Pyrus pashia*, and *Morus serrata*.

Introduction

Himachal Pradesh, located in the North-Western Himalayas of India, is divided into four distinct zones: dry temperate–alpine, moist temperate, sub-temperate, and sub-tropical. The Chamba district, which lies deep within Himachal Pradesh, has a significant tribal population (Rana et al. 2014). Within Chamba, two tribal regions—Pangi and Bharmour—are home to the Gaddi tribe. This tribe primarily resides in the Bharmour and Holi areas of

Chamba district, as well as in parts of Kangra district. In these regions, Gaddi farmers predominantly raise sheep and goats to meet their household nutritional needs. The Gaddis practice transhumance, migrating with their flocks to different parts of the state: they move to the lower Shiwalik hills in winter and to the alpine pastures during the summer. A major challenge for livestock farming in Himachal Pradesh is the seasonal availability of green fodder. While fodder is abundant during the monsoons, it becomes scarce in the winter and peak summer months, prompting nomadic farmers to migrate to find enough nutrition for their animals. This shortage of green fodder has increased the reliance on fodder trees and shrubs during these scarcity periods. A study by Vashist and Pathania (2001) revealed that there was a 59 (%) and 37 (%) shortfalls in dry and green fodder, respectively, in Himachal Pradesh. Due to a lack of research on the nutritional content of both conventional and non-conventional feed used by the Gaddi tribe for their sheep and goats, the present study titled "Exploring the Nutritional Composition of Fodder Resources Utilized by Transhumant Gaddi Shepherds in the Western Himalayas, India" was conducted in the Bharmour block of Chamba district, Himachal Pradesh.

Methods

To evaluate the nutritional content of fodder resources the samples were collected between July-September 2020 from Bharmour region of Himachal Pradesh, which is situated at an elevation of 7,000 feet above sea level. The region is located between 32˚ 11'–33˚ 13' N latitude and 76˚ 22'–76˚ 53' E longitude. The climate is generally temperate, with cool winters characterized by heavy snowfall and temperatures dropping below 0ºC. Summers are pleasant, with temperatures ranging from 15ºC to 25ºC. The mean annual rainfall is 1,500 mm, and the average annual temperature ranges between 3ºC and 30ºC. As per the information received from the gaddi farmers the important fodder species (fodder trees, shrubs, herbs, legumes and grasses) were collected from pastures, farm bunds in Bharmour block by random sampling. The fodder tree species was hand plucked with a mix of all edible parts (leaves, flower, fine stem and pods), while for herbs and other grasses were harvested at about 5cm above the ground level. After harvesting, individual species sample were separated and a total of three composite samples of 1kg each were collected for individual fodder species. Hence in this manner, samples were collected for 20 species consisting of total 60 representative samples.

The collected leaf samples were then dried in hot air oven at temperature 60±5°C until a constant weight was achieved. The dried leaf samples were then crushed in a mechanical grinder fitted with stainless steel blades to form fine powder which was used in the determination of the leaf nutritional composition. The estimation of DM, CP, EE, CF, TA, and NFE was done by employing the methods devised by Association of Official Analytical Chemist (A.O.A.C., 2000). The procedures of (Van Soest et al. 1991) were adopted for the estimation of ADF and NDF. The AIA was also determined. Data analyzed by one way classification as per the procedure suggested by (Gomez and Gomez 1984) wherever the experimental effects exhibited significance per cent level of probability, the critical difference was calculated.

Results

The overall average of DM in fodder tree leaves was 49.58 ± 0.56%. The mean percentage DM was highest in *Quercus semecarpifolia* (61.80 ±0.77) and lowest in *Salix alba* (38.38 ±0.55). The overall mean DM of shrubs was 40.05 ± 0.34% (Table 1). The overall DM (%) in herbs was 38.33 ± 0.21 %. The mean DM (%) was highest in *Rumex nepalensis* (40.13 ± 0.57) and lowest in *Aconogonum molle* (35.70 ± 0.45). The DM % followed a downward trend as *Rumex nepalensis* (40.13 ± 0.57) > *Oxyria digyna* (39.16 ±0.49) > *Aconogonum molle* (35.70 ± 0.45). The overall means of DM (%) in legumes and grasses was 36.63 ± 0.26. The mean DM (%) was greatest in *Festuca arundinacea* (39.16 ± 0.53) and least in *Trifolium pratense* (34.10 ± 0.59). The overall means DM of shrubs was 40.05± 0.34%. The overall DM (%) in herbs was 38.33 ±0.21. The mean DM (%) was highest in *Rumex nepalensis* (40.13 ± 0.57) and lowest in *Aconogonum molle* (35.70 ±0.45) (Table 1).

The mean CP (%) was higher in *Prunus spinosa* (16.53 ± 0.33) and lowest in *Quercus semecarpifolia* (9.93 ± 0.17). The overall mean of CP in leaves of shrubs was 17.49 ±0.70%. The average CP (%) was highest in the leaves of *Indigofera heterantha* (22.03 ± 0.27) and lowest in *Elaeagnus angustifolia* (14.46 ±0.32) (Table 1). The overall mean of CP in herbs was 13.51 ±0.49% where the CP (%) in *Aconogonum molle* was highest (15.20 ± 0.23) and lowest in *Oxyria digyna* (11.86 ±0.42). The overall mean of CP % in legume and grasses was 15.15± 0.32 (Table 1). The findings of the present study revealed that the mean CP (%) was 18.70± 0.41 and 11.60 ±0.31 in the leaves of *Trifolium pratense*, *Festuca arundinacea,* respectively.

The overall means of EE in tree leaves was 2.63± 0.46%. The mean EE (%) was highest in *Quercus leucotrichophora* (3.26 ± 0.20) and lowest in *Morus serrata* (1.33 ± 0.25). The overall means of EE in leaves of shrubs was 3.17 ± 0.40%. The mean EE (%) was highest in *Indigofera heterantha* (3.66 ±0.44) and lowest in *Rubus saxatilis* (2.50 ± 0.21). The overall means of EE in herbs was 1.14±0.46%. The overall means of EE in legumes and grasses was 2.87 ± 0.16%. The mean EE content (%) was greatest in *Trifolium pratense* (2.40 ± 0.30) and least in *Festuca arundinacea* (1.90 ±0.19) (Table 1).

The overall mean CF in tree leaves was 31.62 ±0.35% (Table 1). The mean CF (%) was highest in *Quercus semecarpifolia* (37.00 ±0.31) and lowest in *Robinia pseudoacacia* (25.46 ±0.40). The overall mean of CF in shrubs was 25.38 ± 0.60%. The maximum CF (%) was exhibited by *Desmodium elegans* (28.36 ±0.39) and the minimum in *Buddleja crispa* (22.00 ± 0.28). The total mean of CF in herbs was 22.69 ±1.04%. Mean CF (%) was highest in *Rumex nepalensis* (25.60 ± 0.31) and lowest in *Oxyria digyna* (23.16 ± 0.18). The CF (%) followed a downward trend, as *Rumex nepalensis* (25.60 ±0.31) > *Aconogonum molle* (23.33 ± 0.27) > *Oxyria digyna* (23.16±0.18). The overall mean of CF in legumes and grasses was 22.63 ± 1.40% (Table 1). The mean CF (%) was highest in *Festuca arundinacea* (24.03 ± 0.35) and lowest in *Trifolium pratense* (21.23 ±0.42) (Table 1). The overall mean NDF in tree leaves was 44.22 ±0.73%. The average NDF (%) was highest in *Quercus semecarpifolia* (53.13 ± 0.39) and lowest in *Salix alba* (31.83 ±0.25) (Table 1). The overall means of NDF in shrubs was 40.14 ± 0.30%. The mean NDF (%) was highest in *Desmodium elegans* (43.86 ± 0.33) and minimum in *Buddleja crispa* (40.46 ±0.54). The overall mean of NDF in herbs was 37.61 ± 0.75%. The mean NDF (%) was highest in *Aconogonum molle* (38.40 ± 0.44) and lowest in *Rumex nepalensis* (36.33 ± 0.35). The overall mean of NDF in legumes and grasses was 36.73±0.69%. The mean NDF (%) was highest in *Festuca arundinacea* (37.33 ± 0.42) and lowest in *Trifolium pratense* (36.13 ± 0.36) (Table 1). The overall mean of ADF in tree leaves was 36.13 ± 0.57% (Table 1). The ADF (%) was highest in *Quercus semecarpifolia* (47.66 ±0.29) and lowest in *Salix alba* (23.50 ± 0.37). The overall averages of the ADF in shrubs leaves were 28.60 ± 0.49%. Mean of ADF (%) was highest in *Desmodium elegans* (38.16 ±0.45) and the lowest in *Buddleja crispa* (25.17 ± 0.33). The overall means of ADF in herbs was 27.27 ±0.47%. The mean ADF (%) was highest in *Aconogonum molle* (28.80±0.51) and lowest in *Oxyria digyna* (25.66 ± 0.36) (Table 1). The overall means of ADF in legumes and grasses was 26.43 ± 1.02%. The mean ADF (%) was maximum in *Festuca arundinacea* (27.70 ±0.44) and minimum in *Trifolium pratense* (25.16 ± 0.58).

The overall mean TA content in the tree leaves was 3.98 ± 0.19%. The mean TA (%) was recorded highest in *Populus deltoides* (8.06 ±0.39) > and lowest in *Pyrus pashia* (2.57± 0.24). The mean TA content in shrubs was 4.17±0.70%. The overall mean of TA content (%) in herbs was 4.29 ±0.75. The mean TA (%) was observed highest in *Rumex nepalensis* (5.13± 0.23) and lowest in *Aconogonum molle* (2.80± 0.36) (Table 1). The trend followed in TA content (%) was as follows, i.e. *Rumex nepalensis* (5.13± 0.23) > *Oxyria digyna* (4.93 ± 0.24) > *Aconogonum molle* (2.80 ± 0.36). The overall mean of TA in legumes and grasses was 4.48 ± 0.95%. The mean TA (%) was highest in *Festuca arundinacea* (5.43 ± 0.35) and lowest in *Trifolium pratense* (3.53 ±0.31). The overall mean of AIA in tree leaves was 2.27 ± 0.44%. The mean AIA (%) was highest in *Salix alba* (4.66± 0.21) and lowest in *Quercus leucotrichophora* (0.67 ± 0.28). The overall mean of AIA in shrubs was 2.19 ± 0.25%. The mean of AIA (%) was higher in *Elaeagnus umbellata* (3.33 ± 0.23) and lowest in *Desmodium elegens* (1.50 ± 0.21) (Table 1). The overall mean of AIA in herbs was 2.39 ± 0.91%. The mean AIA (%) was highest in *Rumex nepalensis* (3.76± 0.38) and lowest in *Oxyria digyna* (0.66 ± 0.23). The overall mean of AIA in legumes and grasses was 1.71 ± 0.05%. The mean AIA (%) was highest in *Festuca arundinacea* (1.76 ± 0.24) and lowest in *Trifolium pratense* (1.66 ±0.30) (Table 1). The means of NFE (%) in the different fodder samples are presented in table 1. The overall mean NFE in tree leaves was 48.82 ± 1.13 (Table 1). The mean NFE (%) was recorded highest in *Salix alba* (54.34 ± 0.46) and lowest in *Populus deltoides* (43.30 ± 0.27). The overall mean of NFE in shrubs was 49.78 ± 1.31%. The highest mean NFE was recorded in *Elaeagnus umbellata* (53.23 ± 0.43%) and lowest in *Indigofera heterantha* (45.00 ± 0.23%). The trend in NFE (%) was as follows i.e. *Elaeagnus umbellata* (53.23 ± 0.43) >*Buddleja crispa* (52.23 ± 0.36) > *Elaeagnus angustifolia* (51.46 ± 0.34) > *Rubus saxatilis* (49.83 ± 0.37) > *Desmodium elegans* (46.93 ± 0.13) > *Indigofera heterantha* (45.00 ± 0.23) (Table 1). The overall mean NFE in the herbs was 55.02 ± 0.82%. The *Oxyria digyna* contained highest NFE i.e. 57.10± 0.32% and the minimum NFE content was recorded in *Rumex nepalensis* i.e. 52.40± 0.72%. The overall mean of NFE in legumes and grasses was 55.68± 0.53%. The mean NFE (%) was highest in *Trifolium pratense* (54.23 ± 0.48) and lowest in *Festuca arundinacea* (57.13 ± 0.40) (Table 1).

Discussion and Conclusion

The results obtained in the present study are in agreement with previous studies of (Kumar et al. 2017) who reported that the *Q. leucotrichophora* contained 57.82 to 64.36 (%) of DM. The DM content in this investigation is consistent with that reported by (Azim et al. 2001) who stated that leaves of *Elaeagnus angustifolia* contain 46.7% DM. The DM content recoded in the study are in agreement with the study of (Wangmo, 2018) who stated that *Rumex nepalensis* contains 41.25% DM and *Aconogonum spp.* contained 39.21% DM. (Tomar and Sharma, 2002) reported 15.8 and 18.5% CP in *Salix* and *Robinia*, respectively. Verma, 2020 also reported that leaves of *Quercus leucotrichophora* contained 9.70% CP. Singh et al. 2019 reported that the leaves of *Trifolium* contained 23.98% CP. Verma, 2020 reported that leaves of *Quercus semecarpifolia, Q. leucotrichophara* and *Q. glauca* contained 4.25, 4.13 and 4.23% EE, respectively. (Geng et al. 2020) reported that *Aconogonum molle* 0.97% EE which is lower than the findings of the present study. Verma, 2020 also reported that the leaves of *Quercus leucotrichophora* and *Q. glauca* contained 30.69 and 32.27 (%) CF. Chandra *et al.* 2014 recorded 19.65% CF in the leaves of *Indigofera heterantha*. Results of present study are in agreement with the findings of (Koukolova et al. 2010) reported *Trifolium pratense* contained 18.15% CF. Azim et al. (2001) reported 44.2% NDF in *Robinia pseudoacacia*, which is in agreement with the results of the current study. The findings in the present study are in accordance with results of (Geng et al. 2020) who observed that *Rubus spp.* contained 46.56% NDF. Azim et al. 2001, reported 21% ADF in *Elaeagnus* spp. which is in agreement with the findings of the present study and also reported that the TA in *Populus* spp. and *Robinia pseudoacacia* contained 8.5 and 6.9%. Pandey and Bhatt 2016, also reported that *Rubus spp.* contained 2.97% TA which is in agreement with the findings of the present study. The results in this study are in line with previous study of (Prasanth and Chandran 2017) who reported that *Rubus spp.* contained 0.66% AIA. Verma, 2020 reported that the leaves of *Quercus leucotrichophora, Q. glauca* and *Q. semecarpifolia* contained 50.45, 47.34, and 43.97% NFE, respectively. The findings of the present study are in line with the earlier study of (Koukolova et al. 2010) who recorded *Trifolium pratense* contained 42.66% NFE and (Singh et al. 2019) also reported that 44.41% NFE in *Trifolium.* Bagley et al. 1983, reported 39.50% NFE in *Festuca arundinacea.* Based on both analytical data and field observations, it can be concluded that the CP (%) was highest in shrubs (17.49 ± 1.27) and lowest in tree leaves (12.99 ± 0.72). The highest average CF (%) was found in tree leaves (31.62 ± 0.35), while legumes and grasses had the lowest (22.63 ± 1.40). Moreover, the farmer preferences correspond with the nutritional findings, highlighting the most suitable fodder species for optimal animal nutrition. These results provide valuable insights for improving feeding practices among Gaddi shepherds, ultimately enhancing livestock health and productivity in the region.

Table 1: Nutritional parameters of different fodder species utilized in sheep and goat feeding

Category			DM %	CP %	EE %	CF %	NDF %	ADF %	TA %	AIA %	NFE %
	Scientific name	Local Name	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean	Mean
Fodder tree leaves	Quercus semecarpifolia	Kharsu	61.80	9.93	3.20	37.00	53.13	47.66	3.36	1.70	46.23
	Pyrus pashia	Kainth	48.50	14.20	3.00	29.70	42.50	32.66	2.57	1.93	50.63
	Robinia pseudoacacia	Robinia	47.70	14.93	3.06	25.46	42.90	29.33	4.36	2.07	52.16
	Salix alba	Baise	38.38	13.43	3.00	25.46	31.83	23.50	3.73	4.66	54.34
	Morus serrata	Krun	44.73	13.70	1.33	31.50	41.23	34.50	3.63	2.46	49.83
	Populus deltoides	Poplar	49.43	12.56	2.30	33.76	44.10	34.46	8.06	4.03	43.30
	Quercus glauca	Banni	54.56	10.70	2.11	34.40	50.10	44.60	3.23	0.91	49.55
	Quercus leucotrichophora	Ban	57.70	10.93	3.26	35.70	49.90	43.86	3.43	0.67	46.66
	Prunus spinosa	Rihan (Paaja)	43.50	16.53	2.26	30.86	42.33	34.60	3.46	2.03	46.76
Overall Mean (Tree fodders)			49.58	12.99	2.63	31.62	44.22	36.13	3.98	2.27	48.82
Shrubs	Desmodium elegans	Priy	38.43	14.76	3.13	28.36	43.86	38.16	6.80	1.50	46.93
	Buddleja crispa	Kasleyn	32.40	18.80	2.80	22.00	40.46	25.17	4.16	1.96	52.23
	Indigofera heterantha	Kathu	34.03	22.03	3.66	26.73	38.43	27.00	2.56	2.03	45
	Rubus saxatilis	Ankhe	42.10	19.60	2.50	22.46	40.00	29.40	5.60	2	49.83
	Elaeagnus umbellata	Ghinulu	45.36	15.26	3.50	25.40	38.66	25.70	2.60	3.33	53.23
	Elaeagnus angustifolia	Pandrodu	48.00	14.46	3.43	27.30	39.43	26.23	3.33	2.33	51.46
Overall Mean (Shrubs)			40.05	17.49	3.17	25.38	40.14	28.60	4.17	2.19	49.78
Herbs	Aconogonum molle	Tarodi	35.70	15.20	3.20	23.33	38.40	28.80	2.80	2.76	55.56
	Rumex nepalensis	Albar (Jungli palak)	40.13	13.40	3.40	25.60	36.33	27.36	5.13	3.76	52.40
	Oxyria digyna	Suchali	39.16	11.86	2.76	23.16	38.10	25.66	4.93	0.66	57.10
Overall Mean (Herbs)			38.33	13.51	1.14	22.69	37.61	27.27	4.29	2.29	55.02
Legumes and grasses	Trifolium pratense	Berseen	34.10	18.70	2.40	21.23	36.13	25.16	3.53	1.66	54.23
	Festuca arundinacea	Khajar	39.16	11.60	1.90	24.03	37.33	27.70	5.43	1.76	57.13
Overall Mean (Legumes and Grasses)			36.63	15.15	2.15	22.63	36.73	26.43	4.48	1.71	55.68

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Livestock systems around the world

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Pastoral resources and quality signs: from construction to deconstruction? Some cases in the South-East of France

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Key words: food quality ; meat ; pastoralism ; livestock farming system ; current time history

Abstract

In Southeast France, pastoralism is often highlighted by quality and origin labels as links to the territoriality (or "terroir" identity) of livestock products: pastoral resources partly guarantee the quality of the product, and, in return, pastoral production contributes to the preservation of the land and its know-how. Since the 1990s, this dual relationship has been formalised, constructed and negotiated into normative specifications.

However, climate change seriously threatens the sustainability of Mediterranean rangelands and their farming systems. Livestock farmers and stakeholders are incited to re-question the link between the use of rangelands and quality or origin-linked production. At present, farming practices guaranteed by books of specifications tend to move away from pastoral resources, with potential impacts on the quality of pastoral products and the use of rangelands.

We propose a qualitative and diachronic analysis based on a methodology which intersects with environmental history and livestock farming systems. Through a series of case studies, this paper examines the trajectory of pastoral resources in quality labels in Southeast France since the 1990's, from their prominence in specifications to their reinterrogation. We built farm trajectories based on more than a dozen semi-structured interviews with farmers, supplemented by ten life narratives of other stakeholders. We also analysed current books of specifications and consulted public and private archives.

Quality labels stand out from standard products, particularly because of their seasonality, and represent a key market for pastoral production. They generate significant added value for producers by attracting committed purchases from demanding consumers. Moreover, the use of pasture and rangelands helps to reduce livestock production costs and contributes to sustainable development objectives supported by public policies. Confirming the importance of pastoral resources in quality labels is therefore essential if the sustainability of Mediterranean pastoral livestock farming systems is to be addressed in the long term.

Introduction

Pastoral farming is widespread in Southern France, particularly in Mediterranean and mountainous areas where it can claim very ancient roots and heritage status. These livestock production systems rely partly (or totally) on grazing spontaneous fodder resources (Nozières-Petit et al. 2021), mobilizing diverse environments such as natural pastures, rangelands, and biologically diverse Mediterranean forests. These resources are referred to as pastoral resources. Signs of quality and origin (e.g. geographical indications (GI)) often highlight pastoralism among their commitments (Aubron et al. 2014), especially in conservation areas such as regional or national parks. Indeed, the grazing practices, using spontaneous resources, enhance the unique quality of pastoral meats and cheeses (Martin et al. 2016). In return, GI are also considered to be beneficial for the preservation and management of the environment and natural resources (Milano and Cazella 2021).

In France, public research in agronomy and animal science has played a pivotal role in guiding the transformation of livestock farming systems since the 1960s (Cornu 2018). Pastoral production with a quality label has largely benefited from this scientific and political support (Le Gall 2021).

Since the 1990s, the dual relationship between pastoralism and quality has been formalised, constructed and negotiated into normative specifications with the support of research, and within the framework of both national and European policies. There is therefore an inherent political dimension between quality and environmental issues. However, climate change seriously threatens the sustainability of Mediterranean rangelands and their farming systems (Daliakopoulos et al. 2017). French livestock farmers need to adapt their practices to climate change, but also to others systemic disturbances, like predation. At present, farming practices guaranteed by specifications tend to move away from pastoral resources, with potential impacts on the quality of pastoral products, the use of rangelands and natural pastures, and thus on biodiversity. Through a series of case studies situated in Southeast France, this paper examines the trajectory of pastoral resources in quality labels since the 1990's, from their prominence in specifications to their current reinterrogation.

Methods

We employed a qualitative and diachronic methodology, intersecting socioenvironmental history and livestock farming systems analysis. Our research focuses on three key GI meat case studies (Table 1) for which we conducted 24 semi-structured interviews with farmers, complemented by 22 life narratives of other stakeholders. We also analysed current books of specifications and went through local public and private archives, but also through the national ones. Our methodological framework facilitated the collection of multi-scalar data, encompassing the local evolution of farming practices alongside national historical trends in pastoralism and quality-origin labelling. Our interdisciplinary entry allowed us to build farm trajectories (Moulin et al. 2008), based on five key dimensions: labor/capital allocation, infrastructure and land use, crop management, herd management (including feeding practices), and marketing strategies. These trajectories were supplemented by socio-technical and socio-ecological timelines.

Results

Recognition of the usefulness of pastoral resources by the public authorities and the scientific community

In pastoral meat production, the focus on quality linked to origin emerged quite belatedly. However, in difficult areas, farmers sought a competitive edge early on, leading to the development of the first origin-protected cheeses in pastoral areas, such as Roquefort (1925), Saint-Nectaire (1955), and Laguiole (1956). Initial specification documents were minimal, emphasizing processing practices over breeding as the primary justification for specific quality. At the time, applied agronomic research was carried out in these areas, but it was focused on increasing productivity, particularly in the case of Roquefort (artificial insemination, genetics).

Table 1. Overview of pastoral commitments in PDO and PGI case studies

Geographical indications main case studies	Commitments relating to pastoral resources
PDO Fin Gras du Mézenc (beef)	- Mandatory grazing on natural pastures from June 21st to September 21st - Fattening period with hay from local natural pastures for at least 110 days during winter
PDOs *Charcuteries de Corse* (cured pork product from free-range pigs)	- Pigs growth period (>2 months old) on rangelands (supplement authorised; max 1-2kg/days/pig) - Finishing period under oaks and chestnuts for at least 45 days between October and March
PGI Agneau de Sisteron (lamb)	- Mandatory grazing on pastoral lands for at least 180 days - At least 10ha of rangelands

To implement the link between origin-linked quality and meats, a political and scientific shift beneficial to pastoralism was needed. In the early 1970s, public authorities began acknowledging the unique characteristics of pastoral areas and their livestock systems. Public research was asked to give more attention to the risk of territorial imbalance in development schemes (Cornu, 2021). The 1972 Pastoral Law aimed to maintain pastoralism in mountain areas and recognise its specific technical and social traits, supported by new subsidies in 1973 and 1976. In 1977, a technical journal for sheep farmers devoted a landmark article to "*pastoral ecology*", which was seen as "*a new expression of an ancient tradition*". Meanwhile, French public research on pastoralism was gaining momentum. In 1978, J. Poly, director of the INRA, published a report entitled “*For a more economical and autonomous agriculture*". In 1981, a collective publication about mountains highlighted the economic interest of meat production in maximising the nutritional requirements of grazing livestock. Researchers also proved that rangelands could be managed by adjusting grazing methods and selecting appropriate supplementary feed for hardy breeds. For instance, in the 1970s-80s, the production of quality Corsican cured pork products was linked to feeding pigs chestnuts and acorns, prompting research to sustain free-range farming and develop suitable compound feed.

The shift in scientific views on pastoral resources and the rise of systemic approaches legitimized pastoral systems, offering an alternative to failed agricultural modernization. From the 1990s, livestock farmers leveraged these changes to promote pastoral products through quality and origin signs, still with a strong help of public research.

Pastoral resources: a cornerstone of quality and origin signs

Protected Geographical Indications (PGI) and Protected Designations of Origin (PDO) were recognised by the European Union in 1991-1992. In France, the *Institut National de l'Origine et de la Qualité* (National Institute of Origin and Quality), previously reserved for the wine sector, was given responsibility for GIs in the agri-food sector. This doctrinal change paved the way for the strengthening of pastoral resources as key elements to justify the typicality and territorial anchorage of animal products. Pastoral meat GIs met a strong development during this decade, particularly in the wake of the “Mad Cow crisis”.

The development of food tracers, such as terpenes, enabled a precise correlation between geographical origin and livestock dietary practices on pastures. A study commissioned in 1995 on *Fin Gras du Mézenc* showed that the richness of the flora found in natural pastures was reflected in the meat. These scientific advances met the need for legal and scientific proof of the specific nature and substantial quality of pastoral products.

This emphasis on pastoral resources in the specifications required a cognitive adaptation on the part of those involved in the sector. In the case of *Agneau de Sisteron*, pastoralism *'was a strong choice, it was a precursor to saying that pastoralism is a specific feature of our region, we have to write it down'* (former project manager). In 2001, the stakeholders met with a research centre specialised in pastoralism. After developing a specific indicator, they set a target of 10 hectares of rangelands for pasture in the book of specifications.

An ongoing decline of pastoral resources in livestock farming practices engaged in quality and origin signs
Although pastoral resources were thoroughly negotiated in the specifications, our interviews with farmers tend to assert that these are now being more and more challenged. Firstly, most farmers in the different areas point to the growing uncertainty over grazing resources, linked to climate change. In the *Fin Gras du Mézenc*, cutting dates are increasingly uncertain, and older farmers are concerned about the decline in floral diversity. Droughts and resource uncertainty in Corsica are pushing farmers toward more secure, non-pastoral fodder sources. Since the 1990s, the use of wraps by *Fin Gras du Mézenc* farmers has increased considerably. In Corsica, the use of supplementary feed is gaining pace, making farmers more dependent on price trends and geopolitical hazards (Covid-19, Ukraine…). A Corsican pig farmer explained that *"for me, droughts do not affect me... because we know that we have to feed them anyway. We work with living things, so we can't rely on natural resources"*. Although extreme, these words reveal a profound crack in the logic of quality signs and their link to the "terroir" model. In the same way, the image of the pastoral territories is being turned upside down, leading to painful cognitive divergences in highly patrimonial territories.

Livestock farmers are increasingly adapting their specifications to the current constraints by modifying feed requirements. For instance, after two temporary derogations in 2018 and 2020, the *Taureau de Camargue* PDO reduced the proportion of supplementary feed from local sources in 2022 and dropped the explicit reference to 'rangelands' and 'moorlands' for a more general "pastures". Carefully designed strategies are replaced by short-term adjustments, rational in themselves, but dangerous for the cohesion of the collectives involved.

Discussion and implications
If the decline in the use of pastoral resources within quality or origin labels persists, it could challenge the concept of terroir. Economic pressures could lead farmers to abandon pastoral practices, jeopardizing traditional landscapes and terroir-linked quality. This radical reconsideration could have a strong impact on the typicality of products, potentially undermining their organoleptic qualities and consumer perceptions.

Our observation that pastoral resources are declining in meat livestock farming practices is also evident in other productions, such as dairy products. Between 2016 and 2022, 35 French PDO cheeses requested temporary derogations, all of which concerned the feeding system: 86% requested at least once to reduce the proportion of locally sourced feed, 54% to increase compound feed, 40% to shorten the grazing period (e.g. INAO, pers. comm.). In *Picodon* (PDO cheese), farmers are adapting to climate change mainly by altering grazing areas, purchasing fodder, and housing goats indoors (Loiodice 2024). While traditional pastoral systems offer opportunities to adapt to climate change, these adaptations may come at the expense of farm economic margins and food self-sufficiency (Munoz-Ulecia et al. 2024).

However, the use of pastures and rangelands helps to reduce livestock production costs and contributes to sustainable development objectives supported by public policies (Ickowicz and Moulin 2023). Quality labels represent a significant part of pastoral livestock production in the South of France. The decline of pastoral practices under their specifications could therefore affect the maintenance of open landscapes, but also the pastoral socio-ecological systems. In this respect, although the recent Common Agricultural Policy (2013-2017) has had mixed results, especially in mountain areas (Giannoccaro et al. 2015), public policy has a role to play in reaffirming the importance of pastoral practices.

Our methodology, combining historical and zootechnical analysis, has highlighted the long-term but ever evolving relationship between quality signs and pastoral resources, the related problems that hinder their development and the evolution of socio-technical perceptions among both producers, researchers, and policy makers. As political and scientific paradigm shifts in the 1970s and 1980s advanced pastoralism and led to original and highly valued systems, continuous reassessment of approaches to pastoral practices is crucial to ensure their sustainability amid current challenges. This is true in France, but also in other agricultural systems around the world (Perley 2021). Whatever the odds, confirming the importance of pastoral resources in quality signs and helping producers through their present hardship is therefore essential if the sustainability of Mediterranean pastoral livestock farming systems is to be addressed in the long term.

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Meeting global food demand sustainably: Insights from Uruguay´s Campos Ecosystem in South America

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Key words: Grasslands; livestock systems; agri-environmental platform; feed efficiency

Abstract

The Campos ecosystem is in central-eastern Argentina, southern Brazil and Uruguay. It is described as one of the largest areas of native grasslands in temperate-subtropical environments. However, it faces challenges as a food supplier in an increased global food demand. The main threats are the reduction in the area due to competition with cash crops and forestry and climate change effects. Uruguay produces food for 30×10^6 people representing 10 times its own population. Native grasslands are the main feed source for livestock in extensive ecosystems and complement intensive pastures in crop-livestock systems. In this scenario, INIA Uruguay has been evaluating different levels of land use intensification to quantify productive, economic and environmental impacts through a series of long-term experiments (LTE). In a three-year period, four systems were tested, contrasting different levels of intensification in land use combined with different strategies for beef cattle rearing and finishing. Feeding resources included a combination of improved pastures, native grasslands and supplements. The objective of this contribution is to describe productive potential in herbage, crops and livestock production, and identify tools and key results to improve sustainable management practices in terms of achieving 400 kg LW/ha/year. Data obtained showed differences in the productivity obtained in the livestock and agriculture phases. The adjustment of management practices will provide tools to improve productivity and efficiency, minimize risks and identify mitigation and adaptation approaches to sustain future world food demands. Also, science-based information generated by LTE contributes to assisting public policy decision-makers and risk managers aligned to international commitments agreed by Uruguay in relation to the climate change agenda.

Introduction

The grasslands of Rio de la Plata region cover 76 Mha (Soriano et al. 1992), including the Campos ecosystem (approximately 65% of the area), an area that is declining over time (Carvalho et al., 2021), by agriculture and afforestation interventions. The main economic activity in this region is the extensive livestock production based on the use of native grasslands. In Uruguay, the extensive livestock production occupies 10 Mha of productive area. Cattle introduction in Uruguay dates to 1611, when the Spanish colonizer Hernandarias delivered the first herd of cattle (Barrios 2011). After 400 years of intervention, the ecosystem is still recognized for its potential as a food producer, maintaining a high biodiversity of plants, birds and mammals (Bilenca and Miñarro 2004). Because of climate change, the variability in precipitation and frequency of extreme dry and wet events is reported, as well as long-term warming in this region (Malhi et al., 2020). To attend to the increase in food demand, the redesign of systems should include practices focusing on enhancing productivity, animal welfare, system resilience and mitigation of vulnerability, soil health, including carbon sequestration, and reduction of greenhouse gas emissions through management practices (Jaurena et al. 2021).

In 2018, INIA Uruguay developed an agri-environmental platform, including seven long-term experiments (LTE) on the country's main production systems (Leoni et al. 2024). In the eastern region there are three LTE: a) "Sustainable intensification of rice rotations", located in the Paso de la Laguna Experimental Unit of INIA Treinta y Tres since 2012; b) "Extensive sheep production systems on native grasslands, since 2021, and c) "Sustainable intensification of livestock-agricultural systems" since 1995, b and c placed in the Palo a Pique Experimental Unit of INIA Treinta y Tres. The LTE are being designed to respond to problems in current and future scenarios and understand processes and cause-effect relationships. They help assess the impacts of climate variability and management practices on animals, herbage biomass, crop productivity, species diversity, availability of soil resources, quality of water, environmental footprints, and economic outcomes, among other factors. The LTE constitute an efficient research platform for researchers, producers and public policy makers (Leoni et al. 2024). The objective of this paper is to report information about herbage, crop and animal productivity from the LTE nominated as "c": Sustainable intensification of livestock-agricultural systems". This LTE compares four pasture-crop rotation systems with different degrees of land-use intensification during the 2019 – 2022 period for rearing and/or fattening processes in cattle (Pereyra et al. 2022) and identify key decisions to improve systems management.

Methods

A long-term pasture-crop experiment was installed under no-tillage in Palo a Pique experimental unit of INIA Uruguay (S33° 15´ 54´´, W54° 29´28´) in 1995 (Terra and García-Prechak 2001) and reoriented by Rovira et al. (2019). Four rotation systems with different sequences of pastures and crops are being compared (Table 1) and grazed by different beef cattle categories with the general purpose of producing 400 kg/ha/year of liveweight (LW). The experiment lacks synchronic replications, but all phases of the rotations are present each year, including an area of native grasslands in each system, in an area of 150 has. Paddocks varied from 3 to 6 has each.

Table 1. Cropping and pasture sequences of the 4 pasture–crop rotations evaluated (Pereyra et al. 2022).

Rotation	Purpose	Year of rotation					
		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
CC	Crop/hay	Oat/Sorghum	Black oat/ Soybean	Wheat/Sorghum			
	Grazing	Oat/Sorghum	Ryegrass/Setaria				
SR	Crop /hay	Idem CC	Wheat + P1	P2			
	Grazing	Idem CC	P1	P2			
LR	Crop/hay	Idem CC, SR	Wheat + P1	P2	P3	P4	
	Grazing	Idem CC, SR	P1	P2	P3	P4	
FR	Grazing	Fescue	Fescue	Fescue	Fescue	Fescue	Fescue

P: pasture, followed by pasture age (i.e., P2: second-year pasture). All pastures, including those following the grain/hay crop phase, were available for grazing. Rotation CC: Continuous cropping; SR: Short rotation; LR: Long rotation, and FR: Forage rotation.

The livestock strategy in each system is the following (Pereyra et al. 2022):

a) In the continuous cropping (CC) rotation, rearing calves (180 to 370 kg/an in 12 months), grazing based on a combination of cool and warm annual grasses (oat or ryegrass – sorghum or *Setaria itálica*) plus a native grasslands pasture (33%).

b) In the long rotation (LR), the rearing and finishing of steers (180 to 530 kg/an in 18 months), grazing strategy based on a combination of *Festuca arundinacea*, *Lotus corniculatus* and *Trifolium repens* mixture during 4 years plus a native grasslands pasture (33%).
c) In the short rotation (SR), rearing heifers (150 to 330 kg/an in 12 months) and fattening cows (450 to 520 kg/an in 5 months), grazing strategy based on *Trifolium pratense* and *Holcus lanatus* and/or *Lolium multiflorum* mixture during two years and an oversown pasture of *Festuca arundinacea*, *Lotus corniculatus* and *Trifolium repens* renewed each five years with the same mixture plus a native grasslands pasture (29%).
d) In the forage rotation (FR), finishing steers (260 to 480 kg/an in 12-15 months), grazing strategy based on a pure *Festuca arundinacea* as a permanent pasture plus a native grasslands pasture (26%).

The native grassland is composed mainly of *Paspalum notatum, Axonopus affinis, Cyperus spp., Coelorhachis selloana, Paspalum dilatatum, Stenotaphrum secundatum, Panicum milioides, Cynodon* dactylon, *Setaria geniculata* and *Axonopus argentinus* (Ayala et al. 1993).

Determinations included pasture growth and botanical composition measured once a month in quadrats of 20×50 cm each in 3 exclosure cages per paddock (adapted from Lynch 1947). Pre- and post-grazing biomass was estimated cutting 6 quadrats per paddock (20x50 cm each). Crop production was evaluated at the end of each growing season. Animal LW, stocking rate, heat stress index, water balance and forage utilization were measured once a month.

Results

Climatic conditions determined a deficit in water balance (356 mm/year, on average). Maximum temperature was 41.4°C and the minimum temperature was −5.1°C, with a marked seasonal pattern. Heat stress index was 62.1±8.3, on average, with a maximum of 81 and a minimum of 41, identifying 6.1% of days with medium heat-stress conditions.

The herbage production showed yields of 5.6±4.2 and 6.0±4.5 t DM/ha/yr for native and oversown pastures. The spring deferment applied contributed to increased biomass accumulation. Short-term pastures (2-yr) produced 8.5±6.3 t DM/ha/yr, 16% higher than the results obtained with long-term pastures (4-yr). Cool annual pastures differ in biomass accumulation being annual ryegrass superior over oat (5.0±1.2 and 2.7±2.1 t DM/ha/yr, respectively). Warm annual pasture like Sorghum and *Setaria itálica* have the potential to contribute with 13 and 7 t DM/ha/yr, respectively.

The feed options available in each system are presented in Table 2. Pasture production differs between FR and CC systems, with pasture levels in the CC system being 25% lower than those in the FR system. The LR, SR and CC include legumes in a proportion of 48, 43 and 33% of the total area of the system, respectively. Legume contribution in mixed pastures declines over time, from 39.5 to 4.9% in a four-year pasture in the LR system and from 39.7 to 21.5% in a two-year pasture in the SR system. In CC legume contribution was 8.2%.

Animals received strategic supplementation when pasture was not enough to prevent LW loss, mainly in winter or summer. The utilization of hay was maximum in LR, followed by SR; representing 15 and 12% respectively of the total biomass offered (pasture + hay). The HSGM was an important component, particularly in the LR system. The LW production differed significantly between systems, being greater in CC and SR, compared with LR and FR. The conversion efficiency did not differ significantly between systems ranging between 14.1 to 19.2 kg of feed per kg of LW produced. Rearing categories exhibit greater conversion efficiency than finishing categories.

Forage utilization varied between 50-60%, 55-62% 48-52% and 35-39% for LR, SR, CC and FR, respectively. Mean stocking rate was 614, 600, 575 and 498 kg LW/ha/yr for CC, SR, LR and FR, respectively (Pereyra et al. 2022).

Table 2: Level and type of pasture, supplements, production and efficiency in each system in 'Palo a Pique' long-term experiment in Treinta y Tres, Uruguay (three-year average), adapted from Pereyra et al. (2022).

System	Feeding options (DM, kg/ha/year)					Production	Efficiency
	Pasture	Hay[1]	PC[2]	HSMG[3]	BR[4]	LW (kg/ha/yr)	(kg feed/kg LW)
Continuos Cropping	5206 b	256	21	122	0	426 a	14.1
Short Rotation	5763 a	790	12	169	0	418 a	15.1
Long Rotation	5399 ab	940	20	616	63	369 b	16.1
Forage Rotation	6867 a	138	0	23	166	310 c	19.2
p-value	0.039	--	--	--	--	0.003	ns

[1] Hay: 6.7% crude protein (CP), metabolizable energy (ME): 5.8 MJ/kg DM; [2] Protein concentrate (PC): 46.5% CP, ME = 10.5 MJ/kg DM; [3] High moisture sorghum grain (HMSG): 8.1% CP, ME: 12.6 MJ/kg DM; [4] Balanced ration (BR): 14% CP, ME: 11.7 MJ/kg DM

The range of productivity of different crops varied between 1.20-2.43, 4.12-6.79, 2.20-3.02, and 0.76-4.02 t/ha/yr for Oat, Sorghum, Soybean and Wheat, respectively (Pereyra et al. 2022). In 2021-2022, oat, sorghum and wheat did not produce grain. In the CC system, crops produced less than those that rotate with perennial pastures (SR, LR), being 23, 9 and 16% lower in the years 2019-2020 and 2020-2021 for wheat, sorghum and soybean, respectively.

Implications and Conclusions

The effects of climate determined variations in the availability of feed resources, demanding the use of supplements to minimize animal LW losses. Native grasslands based on their resilience to stress factors played a strategic role in each system. Match feed demand and supply is a crucial process, requiring to be monitored and introduce stocking rate adjustments. From the animal perspective, the occurrence of heat stress conditions demands special solutions to minimize effects. The synergies between agriculture and livestock production provide low-cost solutions.

The objective of achieving 400 kg LW/ha/year was reached by two of the four systems evaluated (Continuous Cropping and Short Rotation). These systems included the highest proportion of rearing stock with a trend to have the best conversion efficiency rates. Systems that include a pasture phase (Short Rotation and Long Rotation) tend to show high crop production. From the results, there are opportunities to improve efficiency in the different systems tested.

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Identifying the appropriate spatial and temporal scales to address sustainable management of drylands: a US Tribal lands case study

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Keywords: Aridity Index (AI), Ecological Resilience, Native Americans, Vulnerability Assessment

Abstract

There are 234 indigenous tribes within 225,365 km^2 of tribally managed drylands within the conterminous United States of America (USA). A national report on the carbon dynamics of US Tribal drylands argued that a knowledge gap existed for these dynamics in drylands because data, publications, and research were nonexistent. However, carbon stocks of Tribal lands have been implicitly studied, and a few explicit studies have used poor experimental design to produce questionable results. We explicitly address the carbon dynamics knowledge gap by defining Tribal dryland extent using the aridity index (AI) and a time series of Moderate Resolution Imaging Spectroradiometer (MODIS) 250-m pixel resolution net primary productivity or NPPM250, g C m-2 yr-1 from 2001 to 2019 of US drylands. We compared the 19-year mean NPP of the rangeland and cropland land uses within the tribal, public, and private land ownerships within their shared ecoregions. We compared the ecological resilience of tribal and non-tribal rangeland's NPP in response to the 2002 global change-type drought. We mapped aridity thresholds associated with land degradation and used the thresholds to identify tribal lands vulnerable to increasing aridity. We conducted these analyses at multiple scales using open-source GIS software, including Google Earth Engine (GEE) and QGIS. We found that Tribal rangeland and cropland land uses had greater productivity than non-tribal drylands. We found that Tribal rangelands had greater ecological resilience in the face of a global change-type drought than non-tribal drylands. However, we also found that with increasing aridity, 86% of the Tribal land area exhibits potential vulnerabilities that include declines in food security, species richness, canopy cover, productivity, and soil fertility. These potential vulnerabilities suggest the need for complementary field and remote sensing studies to determine the integrity of these predictions.

Introduction

Drylands are defined as the 30-year mean aridity index (AI) (1970 – 2000) = mean annual precipitation (MAP) / mean annual potential evapotranspiration (MAPET, Zomer et al. 2022). Carbon dynamics in Drylands are a large source of uncertainty in global carbon budgets that have estimated US dryland carbon sinks at 0.13 Pg C yr^{-1} (Houghton et al. 1999). Drylands within the conterminous US support 234 federally recognized Tribal Nations, including 25 Tribes that are partially within and 209 that are fully within drylands. Herein, we address two propositions of carbon dynamics in Tribally controlled drylands of the United States:

- Proposition 1 (P1): a key finding of the US Global Change Research Program in the US Second State of Carbon Cycle Report stated that "... scientific data and peer-reviewed publications that pertain to carbon stocks and fluxes on Indigenous (native) lands in North America are virtually nonexistent, which makes establishing accurate baselines for carbon cycle processes problematic." (McCarthy et al. 2018).
- Proposition 2 (P2): A study by Robinson et al. (2019) addressed P1's concerns by comparing the NPP of Tribal, Private, and Public land ownerships within US drylands and concluded that privately owned land was more than twice as productive as Tribal and Public lands and thus the most sustainable type of land ownership A re-analysis of this study's ecoregion X land ownership stratification found that the productivity of Tribal lands was comparable to privately owned lands and had greater NPP than public lands (Washington-Allen and Emanuel 2020).. However, land ownership is neither a valid experimental unit nor treatment as it lacks uniform and low variance at the landscape spatial scale, and it has no agency. Public lands in US drylands are managed by multiple federal agencies and contain multiple land uses, including cropping, mining, forestry, commercial grazing, and conservation reserves, e.g., national parks. Consequently, the experimental unit should be the intersection of land ownership with individual land-uses, e.g., rangeland and cropland by ecoregions. These experimental units will have low variability and be highly homogenous.

Methods

Comparison of Land Use across Ownerships

We assembled a GIS database of publicly available datasets that included the Protected Areas Database of the U.S. that provides polygons with public, private, and tribal attributes of land ownership. The Global Aridity Index provides aridity index values as means throughout 1970 to 2000. The National Land Cover Database (NLCD) provides land use and land cover across the USA between 2001 and 2016. We addressed P1 by acquiring and intersecting with the previously mentioned GIS datasets, the 250-m pixel resolution Moderate Resolution Imaging Spectroradiometer (MODIS)-derived NPP_{M250} dataset from 2001-2019 (Robinson et al. 2018). This dataset explicitly shows annual carbon uptake from photosynthesis in g C m^{-2} yr^{-1} on Tribal lands at local to global spatial scales.

We addressed P2 by following a recommendation by (McCarthy et al. 2018) to conduct estimates of carbon cycle impacts on tribal lands by comparing **with practices on similar non-tribal lands, i.e., we stratified land ownership by ecoregions and land use.** We followed the procedures by Robinson et al. (2019), but rather than comparing land ownerships, we compared the NPP of the rangeland and cropland land uses within the three land ownerships using the Nattional Land Cover Database's (NLCD) discrete time series. We show the result for the rangelands land use that composed 40 of 55 shared ecoregions (Fig. 1). The cropland's land use was composed of 33 of 56 shared ecoregions.

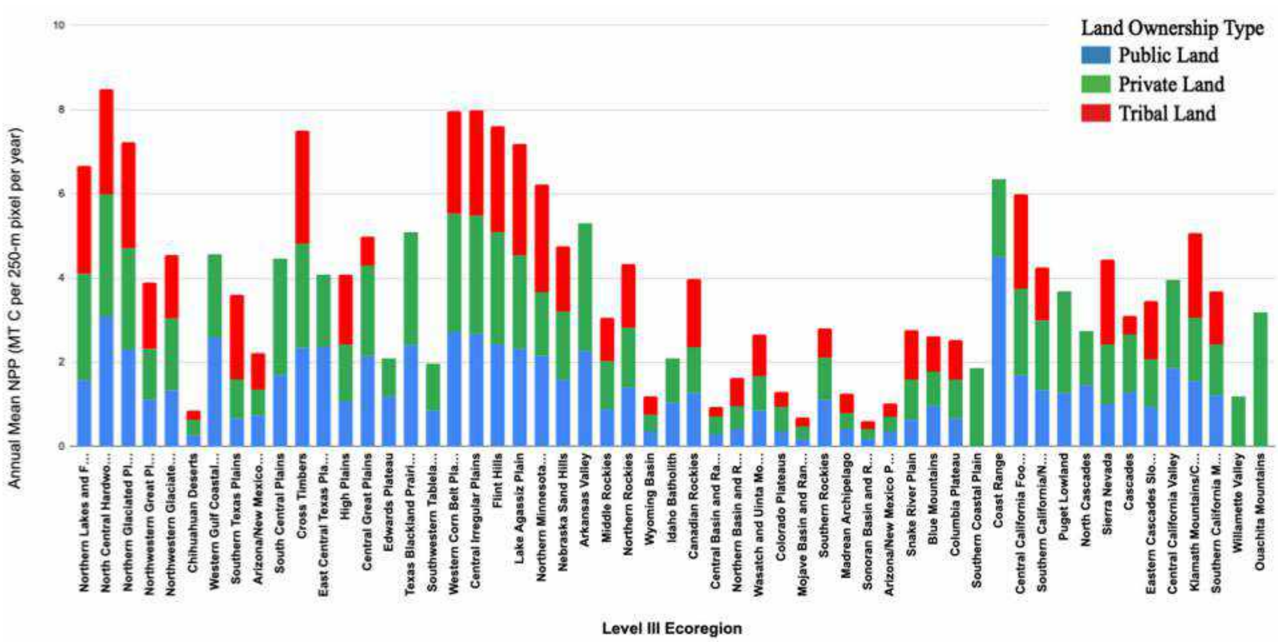

Figure 1. Comparison of NPP for three land ownerships that were stratified by EPA ecoregions and treated by the rangeland land use., i.e., grazing by commercial livestock.

Ecological Resilience

Ecological resilience is the pace, pattern, and recovery of an ecosystem in response to disturbance(s). It can be quantified in terms of amplitude, which is the threshold or magnitude of change in an ecosystem attribute, e.g., NPP over time in response to a disturbance, using a remotely sensed vegetation index change detection method. For example, in equation (1) below we calculate amplitude (the subscript A) using the 2001 MODIS $NPP_{\mathbf{M250}}$ versus the 2002 MODIS $NPP_{\mathbf{M250}}$ (the subscript D):

$$|\Delta NPP_{ijA}| = NPP_{ijR}\,(2001) - NPP_{ijD}\,(2002) + c \qquad \textbf{(1)}$$

The 2002 US drought was labeled a global change-type drought, because it led to major tree die-offs across the southwestern US (Breshears et al. 2005). The 2001 and subsequent scenes are the year before a disturbance or the reference year (the subscript R), and c is the error of uncertainty in the registration of scenes. The results of this change detection are that critical vegetation resources that “do not change” or are “increasing” in the face of drought or other disturbances are located and identified, i.e., the ecologically resilient resources are spatially identified (Washington-Allen et al. 2008).

Vulnerability to increasing Aridity

Berdugo et al. (2020) studied the response of 21 variables to increasing aridity and identified three aridity thresholds (1 – AI) that delineated four system states or phases of decline, including a state we designated “no abrupt changes” (1 – AI < 0.54), a “vegetation decline phase” (aridity threshold: 1 – AI > 0.54) that included two correlated declining variables: the NDVI and photosynthetic activity, the “soil disruption phase” (1 – AI > 0.69) that comprised 12 declining soil attributes such as soil fertility and structure, and a “systemic breakdown phase” (1 – AI > 0.83) that included declines in 7 associated variables including an increase in the variability of rainfall and a reduction in plant cover that leads to increased soil albedo and leaf stress. We assessed the mean AI’s contemporary spatial distribution for these 4 aridity states within U.S. Tribal drylands for 30 years (1970 – 2000) using the time series developed by Zomer et al. (2022),. We used the ‘landscapemetrics’ package in R to determine the patch area of the four aridity states within U.S. Tribal drylands (Hesselbarth et al. 2019, Fig. 2).

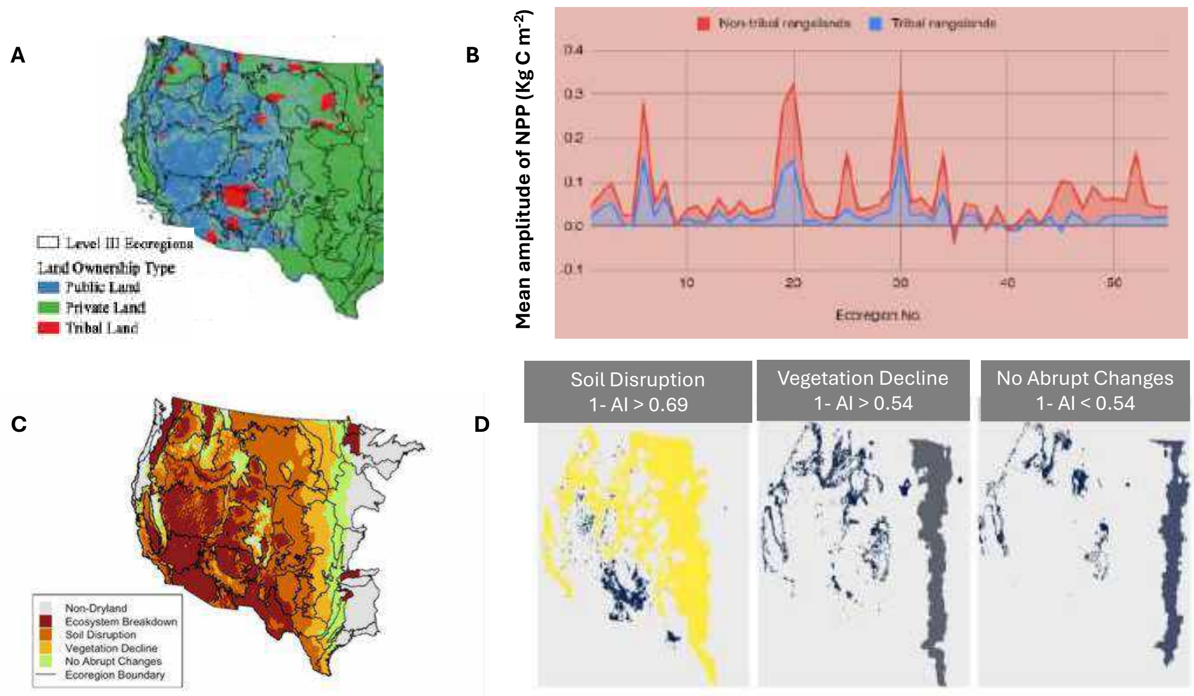

Figure 2. Comparison of the ecological resilience of tribal rangelands (in the red, A) to non-tribal rangelands (green and blue, A) where lower mean amplitude NPP values from 2001 to 2019 indicate greater resilience of tribal lands relative to the 2002 global change type drought (B). Application of the aridity thresholds to current conditions suggests the potential level of vulnerability of tribal land to increasing aridity (C). Green areas in C are stable, with the majority of tribal lands in drylands, spatially trending towards ”systemic breakdown” of 18% of the tribal lands (C).

Results

Comparison of Land Use across Ownerships

We found that the rangeland land use for the 234 Tribes in Drylands had greater productivity in 21 of the 40 shared ecoregions compared to public (4/40), and private (15/40) lands (Fig. 1). We found that the cropland land use had greater productivity in the shared ecoregions (15/33) than public (7/33) and private (11/33) lands.

Ecological Resilience

In the face of the 2002 climate-change drought, Tribal rangelands had greater ecological resilience, when quantified as amplitude, than non-tribal rangelands, i.e., public and private lands (Fig. 2B).

Vulnerability to increasing Aridity

We determined that 1,467,862 ha (14%) of Tribal lands were in the “no abrupt changes” phase (green in Fig. 2C and D) , 2,950,288 ha (29%) were in the vegetation decline state (Fig. 2D), 4,020,931 ha (39%) were in the ‘soil disruption’ state (Fig. 2D), and 1,796,894 ha of tribal lands (18%) were in the highest vulnerability category of “ecosystem breakdown” (Figure 2C).

Conclusions/Implications

We found that across the majority of the shared ecoregions, Tribal rangeland, and cropland land uses had higher productivity than Public and Private drylands and that this productivity made the rangelands more ecologically resilient in the face of a global change-type drought. However, in the face of increasing aridity, 86% of the Tribal land area potentially exhibits threats to livestock and human nutrition and food security, including sharp declines in species richness, canopy cover, productivity, soil fertility, and increases in woody encroachment, and albedo.

These potential vulnerabilities suggest the need for complementary field and remote sensing studies to determine the integrity of these predictions.

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Livestock policies in sub-Saharan Africa: trade-offs and implications for pastoralists livelihoods

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Key words: livestock; policy; trade-offs; pastoralists; rangelands

Abstract

The livestock revolution offers significant opportunities to enhance the livelihoods of smallholder farmers in Africa while improving nutrition and food security. In Sub-Saharan Africa, pastoralists play a crucial role in driving this transformation. However, current policies often fail to adequately support pastoralist livelihoods. This paper aims to analyze livestock policies in selected Anglophone and Francophone countries in Africa, examining the extent to which they integrate rangeland management and the interests of pastoralists. The study employs content analysis of livestock policies from 23 countries in Sub-Saharan Africa. Using a set of indicators from the Sustainable Assessment of Food and Agriculture (SAFA) framework of the FAO, the paper analyzes current policy objectives and strategies, and their social, environmental, and economic trade-offs, particularly with respect to pastoralists, rangelands and pastoral livelihoods. The data indicates that while pastoralists and rangeland management are recognized in livestock policies, policies may not always be conducive to pastoral livelihoods. Furthermore, policies that overlook environmental trade-offs could jeopardize pastoralist livelihoods, which heavily depend on natural resources such as water and pastures. Current policies need adjustments to accommodate the needs of pastoralists while fostering livestock growth and development.

Introduction

The livestock sector plays a crucial role in economic growth and development in sub-Saharan Africa. It serves as a source of livelihood for millions of people and fulfils multiple functions within the agricultural landscape (Banda & Tanganyika, 2021; Molina-Flores et al., 2020; Rayne & Aula, 2020). In an effort to harness the benefits of the livestock sector, many countries across the continent have introduced a range of policies. These policies aim to enhance productivity, improve food security, and support the livelihoods of communities dependent on livestock. While these policies hold promise, they often come with trade-offs or unintended consequences, particularly when key dimensions of sustainability are overlooked. Such policies risk being counterproductive if they marginalize certain groups, such as pastoralist communities, or if they exacerbate environmental degradation.

Recognizing these challenges, this study seeks to examine the coherence of livestock development policies with broader sustainability objectives. Specifically, it evaluates how these policies align with the unique needs of pastoralism and pastoralist communities, whose livelihoods depend on sustainable rangeland management and mobility. By identifying gaps and opportunities, this research aims to contribute to more inclusive and sustainable livestock development strategies that support pastoralism as a vital component of agricultural and rural systems.

Methods

The livestock policies were identified using various search engines, including Google, in November 2022. The following search strings were applied: (Country) AND livestock policy; national livestock policy AND (country name); agricultural policy AND (country) OR livestock policy. FAOLEX database, as well as the websites of the respective countries ministries, were explored for supplementary data. Only livestock and agricultural policies were considered for further analysis. Other documents, including bills, acts, and plans were excluded from the analysis. Overall, 23 policy documents were identified (Table 1). For the purpose of this study, only the most recent policies were included. Policies written in French were translated using the Deepl translator.

Table1: Summary of livestock policy documents in Africa

Livestock policy document	Country	Percentage (n=23)
Countries with stand-alone livestock policy documents	Burkina Faso, Mali, Senegal, Ghana, Mauritania, Liberia, Niger, Tanzania, Malawi, Somalia, Kenya, Zambia, South Sudan, Swaziland, Cameroon, Chad	16 (69%)
Countries with livestock policies integrated in overall agricultural policy documents	Benin, The Gambia, Namibia, Nigeria, Rwanda, Uganda, Zimbabwe,	7 (31%)
Total number of countries	23	23 (100%)

From the SAFA (Sustainability Assessment of Food and Agriculture), three main categories of indicators were selected for analysis: environmental indicators (including soil health, water pollution, and animal welfare), governance indicators (including land tenure security, conflict management, and human-livestock-wildlife interactions), and socio-economic indicators (including price stability). These indicators were chosen for their critical importance in assessing the sustainability of rangeland systems. They reflect key dimensions of ecological integrity, social equity, and economic viability, providing a comprehensive framework for evaluating the interplay between resource management, livestock production, and community well-being.

Results

The analysis of livestock policies from a governance perspective highlights key areas of focus and gaps. Land tenure emerges as a prominent priority, with 74% of the 23 policies reviewed addressing it as a critical issue. Conflict and insecurity management also receive considerable attention, featuring in 61% of the policies. However, a significant gap exists in addressing human-livestock-wildlife interactions—an essential element of sustainable rangeland management—appearing in only 9% of the documents.

From an environmental perspective, the findings reveal a stronger emphasis on soil health, with 78% of policies incorporating measures aimed at reducing soil degradation. Yet, other environmental concerns, such as water pollution management and animal welfare, are less frequently addressed. Only 26% and 35% of the policies, respectively, include these major aspects.

The economic dimension, particularly price stability, is also moderately reflected in the policies, with 56% addressing this issue. This suggests a moderate commitment to maintaining stable market conditions for livestock products, which is essential for supporting the sector's sustainability.

Despite the recognition of key sustainability issues, many policies lack clarity regarding their implementation. While 78% of the policies acknowledge soil degradation as a pressing concern, only 56% provide concrete measures to prevent or rehabilitate degraded soils. This inconsistency between policy objectives and actionable steps underscores a broader challenge in translating policy intentions into practical outcomes, especially in the environmental dimension.

Discussion

With 74% of policies prioritizing land tenure, there is a positive implication for pastoralists, as secure land rights are essential for sustaining grazing activities (Basupi et al., 2017). Land tenure security can enhance pastoralists' ability to manage resources, access credit, and invest in their livelihoods. However, without clear implementation strategies, policies may fail to translate into tangible benefits for pastoralists, particularly in areas with complex land ownership systems or competing land uses.

The fact that 61% of policies address conflict and insecurity management is crucial for pastoralist communities, who are often vulnerable to land disputes, resource conflicts, and insecurity in their grazing areas. Effective conflict resolution mechanisms can reduce disruptions to pastoral mobility, enhance community stability, and improve access to grazing lands (Chelang'a & Chesire, 2020). However, the success of these policies hinges on effective implementation and coordination at local levels, which may not always be guaranteed.

The underrepresentation of human-livestock-wildlife interactions (only 9% of policies) is a critical gap, particularly for pastoralists in areas where wildlife conservation and livestock grazing overlap. The absence of policies addressing these interactions can lead to conflicts, such as competition for water and grazing resources, and increased risks of zoonotic diseases (Vicente et al., 2021). As such, the lack of attention to this issue could undermine the sustainability of pastoral systems and negatively impact pastoralist livelihoods. These findings highlight a notable imbalance in policy priorities, suggesting that while governance frameworks largely emphasize land tenure and conflict resolution, they often overlook the complex dynamics between humans, livestock, and wildlife. This gap underscores the need for more integrative policy approaches that account for the ecological and social challenges associated with rangeland ecosystems.

The findings also reveal a disparity in the environmental priorities of livestock policies. While 78% of policies emphasize soil health and aim to reduce soil degradation, there is a mismatch between policy recognition of soil degradation as a major issue and the limited concrete measures provided (only 56% of policies include actionable steps). This discrepancy could lead to insufficient support for pastoralists who rely on healthy rangelands. Moreover, the lack of focus on water pollution management and animal welfare (addressed in only 26% and 35% of policies, respectively) poses additional risks to pastoralists, whose livelihoods depend on clean water sources and humane livestock practices. This uneven focus suggests a need for more comprehensive environmental strategies that balance soil conservation with broader sustainability goals, ensuring the long-term health of rangeland ecosystems and the welfare of livestock.

The moderate attention to price stability in 56% of policies suggests some recognition of the need for stable livestock markets, which are essential for pastoralists to secure fair prices for their products. However, the limited scope of these policies may leave pastoralists vulnerable to market fluctuations and unpredictable prices, affecting their income stability and long-term economic well-being.

Overall, the findings suggest that while livestock policies address several important issues, there is a need for greater coherence and specificity, particularly in the areas of human-livestock-wildlife interactions, environmental management, and practical implementation strategies.

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The structuring role of rangeland products in the regional livestock supply chain of west Africa

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Abstract

This study examines the impact of environmental shocks on livestock supply chains and consumption patterns in West Africa, focusing on three coastal capitals—Dakar (Senegal), Abidjan (Côte d'Ivoire), and Abuja (Nigeria). Using surveys of 4,000 households and 45 focus group discussions, we analyze how socio-demographic factors, such as income and household size, influence meat demand and the price and income elasticity of various types of meat. The findings show that beef and lamb have high price sensitivity, especially among low-income households, while fish is the most consumed protein across all income groups. Environmental shocks, including climate change and land degradation, disrupt supply chains, leading to higher meat prices and altered consumption patterns. The study highlights the importance of sustainable rangeland management practices, such as rotational grazing and agroforestry, to enhance the resilience of livestock systems and ensure food security in the face of these challenges.

Introduction

West Africa region spans arid, semi-arid, and sub-humid zones (Sahara, Sahel, Sudanian), with warm to hot temperatures year-round. It exhibits significant north-south heterogeneity, with rainfall ranging from 200mm to 1200mm annually, concentrated between July and September, influenced by the Inter-Tropical Convergence Zone. Coastal areas experience two rainy seasons: April to July and a shorter one in September-October. Frequent droughts and rising temperatures (1.7°C to 3.2°C) contribute to a 4% decline in annual rainfall, shortening crop and fodder growing periods by an average of 20%. Population growth around rural centres is increasing, but remote areas are declining. The region is home to significant livestock populations, including 25% of Africa's cattle, 33% of sheep, 40% of goats, and 20% of camels. To better understand the dynamics of livestock supply chains, it is crucial to analyze the interaction between rangeland ecosystems, livestock production, demand patterns, food security and value chain performances across the region.

Climate change and anthropogenic shocks can significantly impact livestock products' availability, quality, and safety, potentially leading to higher prices and increased price volatility (Godfray et al., 2018). Temperature fluctuations may also influence consumer preferences, though the specific effects on livestock consumption remain underexplored. Rising production costs and feed availability challenges are expected to increase prices, while supply chain inefficiencies will likely exacerbate price volatility (Muhammad et al., 2017; Mbow et al., 2019).

In addition, climate change is reshaping the socio-economic dynamics of the livestock sector, particularly for small-scale producers who are especially vulnerable (Hallegatte & Rozenberg, 2017). These changes are influencing both consumption patterns and the structure of the livestock industry, with significant implications for global and regional food security (Hasegawa et al., 2018; Amin et al., 2023) and growing awareness of climate change’s impact on livestock challenges the sector’s social license. However, the limited research on the evolution of meat demand and consumption in West Africa hinders a comprehensive understanding of how climate-related shocks could diffuse across the region’s highly concentrated and coordinated livestock supply and value chain. Therefore, complex ecological, economic, and socio-demographic factors shape the relationship between environmental shocks to rangelands and regional supply chains in West Africa. Understanding these interconnections is critical for ensuring the region's sustainable livestock systems and food security. To accomplish this, we must refine our understanding of the demand for and consumption of meat, which remains a prominent under-explored aspect in West Africa.

This paper bridges the knowledge gap by comprehensively understanding the dynamics of the demand for and consumption of meat in three West African coastal capitals: Dakar (Senegal), Abidjan (Côte d'Ivoire), and Abuja (Nigeria). It further explores how improved rangeland management, within a context of multi-dimensional shocks, could help secure the livestock supply chain and improve the livelihoods of millions across West Africa.

Method

This paper builds on the comprehensive literature review conducted by Godde et al. (2021) and the survey developed by Amin et al. (2023) on the impacts of climate change on livestock supply chains. Then, it addresses the missing link in the analysis of consumption nodes, especially for West Africa. Our approach combines quantitative and qualitative methods to analyze meat consumption and demand trends across Senegal, Nigeria, and Côte d'Ivoire. It explores perceptions of meat quality and attributes and the influence of sociodemographic factors (e.g., household size, age and gender of head, and location) on demand. The quantitative analysis uses the Almost Ideal Demand System (AIDS) model to examine family structure effects on meat consumption based on surveys of 4,000 households. Qualitative data were collected through 15 focus group discussions in each capital. Both surveys were conducted between July and September 2023.

Results

In Senegal, meat consumption varies significantly based on income, price sensitivity, and sociodemographic factors. Fish is the primary source of animal protein, followed by chicken and beef. Goat and pork consumption remains low, influenced by geographic and religious factors, particularly Islam's prohibition on pork. A baseline demand exists for beef, lamb, goat, chicken, and fish, largely unaffected by changes in income or price. Key sociodemographic factors include household size, which minimally impacts meat demand, except for eggs. Gender notably influences lamb consumption, especially during religious events like Aïd-el-Adha, when male heads of household typically purchase a ram for sacrifice. Geographic location also impacts regional consumption patterns, with certain areas displaying mimetic effects in demand for beef, lamb, goat, chicken, and fish.

The income elasticity of demand is positive for all meats. Among low-income households (average monthly income: 244,025 FCFA), demand for all meats is positively elastic, though beef and eggs exhibit inelastic demand when prices rise. Lamb, chicken, and fish show higher elasticity, responding more sensitively to price changes. For high-income households (average monthly income: 861,946 FCFA), income elasticity is generally more significant, particularly for beef (elasticity >1), indicating a higher responsiveness to income increases. Price elasticity is negative across all meats, with beef and lamb displaying significant reductions in demand with price increases. For instance, a 1% increase in beef prices leads to a 2.7% decrease in demand, and a 1% rise in lamb prices results in a 3.6% reduction in demand.

In Côte d'Ivoire, fish dominates meat consumption (98% of households), followed by beef (92%), eggs (73%), and lamb (43%). Pork (32%) and goat (7%) are less commonly consumed, with a marked decline in wild meat consumption due to diseases such as Ebola and COVID-19. Consumption patterns vary significantly with income. Beef, chicken, goat, and fish are consumed equally across income groups, while pork consumption is higher in low-income households (36%) compared to high-income households (23%). Lamb is primarily consumed by high-income households (60%), with lower consumption in intermediate (40%) and low-income (36%) groups. Egg consumption is notable across all income groups, ranging from 67% to 75%. Weekly meat consumption averages in Côte d'Ivoire are as follows: fish (1.5 kg in low-income, 2.1 kg in intermediate, 2.4 kg in high-income households), beef (1.1 kg in low-income, 1.8 kg in intermediate, 2.2 kg in high-income households), chicken (0.8 kg in low-income, 1.0 kg in intermediate, 1.5 kg in high-income households), goat (0.008 kg across all households), and lamb (0.8 kg in high-income households). Elasticity analyses show that all meats, except eggs, exhibit positive income elasticity, meaning demand increases with income. A 1% rise in income results in a 0.1% increase in beef demand and a 2.9% rise in lamb demand. Most meats show negative price elasticity, with lamb and pork being more price-sensitive than beef and fish. Cross-elasticities indicate that lamb and pork serve as substitutes for beef.

In Nigeria, fish, beef, and goat meat are the primary meats consumed. Fish is consumed by 87% of households, beef by 78%, goat meat by 67%, chicken by 64%, and eggs by 52%. Sheep and pork have relatively low consumption rates (29% and 8%, respectively), and bushmeat consumption has diminished due to bans associated with zoonotic diseases like Ebola and COVID-19. Beef is the most consumed meat, with an average weekly intake of 1.1 kg, followed by fish (0.8 kg) and chicken (0.7 kg). Pork is consumed the least, averaging just 0.2 kg. Among income groups, beef remains the dominant meat choice in low- and middle-income households, while fish and chicken are more commonly consumed in high-income households. Household size has a marginal impact on the demand for lamb, fish, and eggs but does not significantly influence the demand for beef, goat, pork, or chicken. Larger households tend to substitute lamb and eggs with more accessible fish, while beef, goat, pork, and chicken consumption remains stable. Gender influences pork demand but does not significantly affect other meats. Regarding price and income elasticity, all income elasticities are positive, except for beef. A 1% increase in income results in a 0.9% decrease in beef demand, while demand for lamb (2.3%), goat (0.4%), chicken (1.3%), pork (2.6%), fish (1.2%), and eggs (1.8%) increases. Price elasticities are negative for all meats, with pork, goat, chicken, and eggs showing higher price sensitivity than beef and fish.

Discussion

Rangelands in West Africa are vital for livestock production, forage and water, and livestock supply and value chain. However, environmental shocks degrade these ecosystems, including climate change, overgrazing, and land-use change. Climate change, marked by irregular rainfall and rising temperatures, accelerates land degradation and reduces grazing resources, directly affecting livestock productivity. Overgrazing leads to soil erosion, reduced biodiversity, and decreased land fertility, further limiting the capacity of rangelands to support livestock. Additionally, agricultural expansion and urbanization reduce available grazing areas, heightening competition for land and disrupting pastoral mobility.

Shocks to rangelands disrupt livestock supply chains by reducing herd sizes and meat production. This may lead to supply shortages and price increases across markets. Price elasticity studies indicate that a 1% rise in beef prices results in a 2.7% drop in demand, particularly impacting low-income households. Livestock trade flow across borders, especially between Sahelian and Coastal regions, is disrupted, increasing reliance on imports. If Sahelian supply sources are depleted due to multiple shocks, they may be substituted by imports from Latin America, Europe, or alternative protein sources.

Income levels, cultural preferences, and gender roles influence consumption patterns in West Africa. Price increases during supply shocks can lead wealthier consumers to reduce meat consumption or switch to cheaper proteins, while poorer households face more immediate nutritional deficits. Cultural preferences, such as the demand for specific meats during festivals, can also shift when certain types of beef become scarce.

Conclusion

The potential impacts of climate change on global livestock systems are a growing concern. Still, they are often underrepresented in major climate assessments like those by the Intergovernmental Panel on Climate Change (IPCC). This article explores how multifaceted shocks—climate change acting as both a direct and compounding factor—interact with rangelands along the land-based livestock supply chain, from production to consumption. Although quantifying the net impacts remains challenging, there is strong evidence that climate change will disrupt critical stages of the livestock supply chain, especially at consumption nodes. The study fills the knowledge gaps and underscores the importance of sustainable rangeland management practices, such as rotational grazing and agroecological practices, in enhancing livestock system resilience, supply and value chain performances, and ensuring regional food security.

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Nurturing sustainability through pastoral livelihoods in Kashmir Valley

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ABSTRACT:
The Gujjars and Bakarwals form the third largest ethnicity in the Union Territory of Jammu and Kashmir in India. Gujjars rear large ruminants such as cows and buffaloes, whereas Bakarwals are goat and sheep herdsmen. The Chopans are semi-nomads involved in traditional sheep rearing for meat and wool in the Kashmir valley. The 2030 Agenda for Sustainable Development provides the 17 Sustainable Development Goals (SDGs), that recognize the need for action on climate change to preserve the environment while sustaining the livelihood of the vulnerable, migrating, and nomadic communities. Milk is a priceless commodity for those people involved in transhumance and pastoralism. Good market linkage for meat, milk, butter, and wool through application of modern innovations is necessary. It is high time that the contribution of pastoralism to the national economy by the custodians of livestock in the unpredictable mountain ecology of Jammu & Kashmir is recognized.

Introduction
The union territory of Jammu and Kashmir is an abode inthe Himalayan mountains with widespread and abundant natural resources. Production of fruits, spices, flowers, dry fruits, wool, and cold fish is high in the region. Jammu & Kashmir in India has the world's largest transhumant population with 612,000 in number. With the Kashmiris and Dogras forming most of the population in this region of the Himalayan valley, the Gujjars and Bakarwals form the third largest ethnicity in the region. Gujjars rear large ruminants such as cows and buffaloes, whereas Bakarwals are goat and sheep herdsmen. The Chopans are semi-nomads who are involved in the traditional rearing of sheep for meat and wool in Kashmir. The 2030 Agenda for Sustainable Development provides the 17 Sustainable Development Goals (SDGs), that recognize the need for action on climate change to preserve the environment while sustaining the livelihood of the vulnerable, migrating, and nomadic communities. The pastoralists of Jammu & Kashmir who largely migrate every year need to be inclusive, safe, resilient, and have sustainable livelihoods and communities.

Milk production in Jammu & Kashmir
In the agrarian economy of the union territory, the value of the milk economy in Jammu & Kashmir is Rs 90.8 billion AUD$163 million). The annual milk production of Jammu & Kashmir is 2.5 million tonnes. Though 95% of the milk distribution in this region is still in unorganized areas, the concerned authorities and stakeholders are trying their best to push Jammu & Kashmir to be part of the 'white revolution' (making India self-sufficient in milk production) in a sustainable manner. Pastoralists have a huge contribution to make in this regard. Though they have contributed least to climate change, they are suffering the most from its deleterious effects. Despite the impacts of climate change, the average annual milk productivity per cow is planned to rise from 2,380 to 4,300 litres by the year 2027.

Challenges facing pastoralism in Kashmir Valley

The Gujjar and Bakarwal pastoralists live in the scattered valleys and alpine meadows of Jammu & Kashmir. A paucity of water resources and green pastures/fodder during winters for livestock in the Upper Himalayas compels them to move towards the Jammu province while rearing small ruminants like sheep and goats. Most of them are engaged in rearing goats, sheep, cattle and buffalo. They sell milk in the local market to earn their livelihood. With continuous movement, the unacceptance of milk in the nearest milk cooperative at the village level has led to the exploitation of herdsmen by private dairies. Lack of access to a reliable market value chain and logistics, and varying demand and supply of such milk, milk products, manure, hair and wool and woollen products prevents them from selling their products at a good price. Insufficient resources for skill development and training of these tribal pastoralists in the valley have made them choose pastoralism as a source of livelihood for generations. Finally, due to such biannual transhumance, there is reluctance by the government authorities to provide them grants in the long term.

Gujjars – the cow and buffalo keepers

Gujjar is an ethnic pastoral community of India, Pakistan, and Afghanistan. The community has a strong presence in the Union Territory of Jammu & Kashmir. Gujjars are mostly settled at the lower slopes and valleys of the Pir-Panjal and the Shivalik hills, where ecological conditions are suitable for their nomadic pastoral economy, especially during winters. The important areas of Gujjars and Bakarwal settlement concentrations in Jammu District are Jandrah, Jahri, Grota, Golad, Charwal, Samoo, Rathi and Bindi and Upper Samba hills. The Gujjars are also highly concentrated in Rajouri and Poonch districts of Jammu province. Gujjars are of three categories - settled, half settled and homeless Gujjars. The settled Gujjars stay at one place and work in agriculture. Half-settled Gujjars are those who, although they live in villages and do agriculture, for six months of summer, they leave for Pir Panjal Gujjar region and move further to Drass and Kargil with their cattle where pastures are available for grazing.

The homeless Gujjars (i.e. no permanent settlement) can be further divided into two tribes- Dodhi/Banjara Gujjars and Bakarwal Gujjars. These people keep buffaloes and lead a nomadic life. In summer, these tribal pastoralists move to the lower areas - Reasi, Udhampur and Kathua in Jammu province and Pathankot and Gurdaspur in Punjab with the buffaloe herds. The Gujjars in Jammu city are spread around Akhnoor Road and Rajpura Mandi. When the summer sets in and the snow starts melting, these people start moving to the heights of the Himalayas where green grass is available sufficiently for their cattle. Gujjars are the milk producers in Jammu region due to the sub-tropical climate. Their staple diet includes dairy products such as milk, curd, cheese, kalari, karan and lassi. They dry cheese in sunlight and then use it in winter. Dahi plays a major customary role in the Gujjar marriage rituals. They sell milk and ghee for their livelihood.

Milk – a priceless commodity for Gujjars

A Gujjar household with milk buffaloes and a son is deemed to be 'illustrious'. Gujjars consider milk a very pious resource and do not let it get wasted. Gujjars honour milk more than respect the elders. Despite the community belief, Fareed Bhai, a Gujjar from Rajpura Mandi Morh, cites the plight and the loss incurred in milk production of 60-70 Gujjar milk producers in the Jammu region. Each family usually has 50-80 buffaloes. He states that 5000 litres of milk are produced every day from 15-20 milch buffaloes owned by each family. Due to the transhumant lifestyle, Gujjar milk producers do not have access to refrigerators and in summer it becomes hard to keep milk without refrigeration for long. It gets spoilt within a few hours. Sometimes the dairy farmers keep ice cubes around the fresh milk or leave milk containers near the canals, where they are living. This leads to theft. With the increasing cost of fodder and green grass for buffaloes, it is tough to manage and rear buffaloes in the present times. With the lack of dairy plants nearby and proper marketing channels, milk processing has become a huge challenge. They are unable to sell milk in the markets at a sufficient price.

The day of a Gujjar milk producer begins with waking up at 4 am, getting milk from buffaloes, collecting all the milk, and mostly keeping the milk near the canal for a few hours for preservation. If the milk fails to reach the markets in Jammu city on time, it is spoilt. This compels the Gujjar milk producers to make kaladi/cheese out of the milk, but at times they throw the milk away in the canals when it is of no use. These dairy farmers prefer to prepare ghee, butter, and kaladi in winter than in summer. Thus, with such continuous struggle, the lives of Gujjar milk producers of Jammu have not improved by much. With a low rate of milk production and delivery and increasing expenditures, making education affordable for their children becomes difficult for the guardians. While the cost of one buffalo purchased locally ranges between Rs 40,000 (AUD$ 720) and Rs 100, 000 (AUD$1,800), the buffalo purchased from Punjab, costs around Rs 200,000 (AUD$3,600) to 300,000 ($5,400) each. These Nili Ravi buffaloes produce 18-20 litres of milk per day, while the local breeds produce only 7-10 litres milk per day. All the family members in a Gujjar family are usually involved in animal rearing and taking buffaloes out for grazing. With none or poor literacy level, Gujjar pastoralists have chosen to work this way since childhood, as they do not do any other work. Sometimes Gujjar milk producers sell their cows and buffaloes to pay to meet the rising demands of fodder. Therefore, the Gujjars are demanding for the revision of milk prices so that can receive a fair price for their milk.

Bakerwals – the sheep and goat herdsmen

Bakarwal Gujjars and homeless Gujjars rear sheep and goats as their main source of livelihood. Bakarwals migrate to high summer pastures in April during summer and return to lower winter pastures in Jammu province with the onset of winter. It takes one and a half months to reach the high pastures in Kashmir province and another one and a half months to return to low-lying pastures in Jammu province. Their stay at one seasonal pasture is around four months. Along with sheep and goats, they take horses to carry loads and Bhakarwal dogs as the guardian of the livestock. Each Bakarwal possesses around 50-150 goats and sheep. The winter season is usually the time of ceremonies, functions, rituals, and marriages resulting in a sharp rise in the demand for chevon and mutton. The Bakarwals sell their goat and sheep to the local traders. Along with this, they also sell the wool of their sheep at the local wool centres. Horses and mules are rented out at construction sites and tourist spots by them to provide fundsfor the purchase of extra feed for their cattle.

Livestock breeds

The cattle and buffalo breeds reared by the pastoralists in Jammu & Kashmir include Hariana and Sahiwal, non-descript Kashmiri cattle, Holstein Friesian, and Nili Ravi buffaloes. Buffaloes migrate from Punjab and are seen more in the Jammu region. Jammu & Kashmir has a diversity of apparel and superior carpet-type wool breeds such as Gaddi, Rampur Bushair, Bakarwal, Poonchi, Karnah, Gurez and Kashmir Merino. The endangered Bakarwal sheep breeds are found in the higher ranges of Pir Panjal mountains, Kashmir valley and low-lying hills of Jammu and Kashmir. The Punchi Bakerwali sheep are now extinct. The goat breeds reared by Bakarwals are Bhakerwal goat, Kilan, Kaghani and Lubdi. These breeds are on the verge of extinction. Adult Bhakerwal goats grow well under low-input systems. Bakarwals value the extinct Yarkandi horses who survive extreme climates, thrive on coarse feed and fodder and travel with them during the seasonal migration to difficult topographies in the Upper Himalayas. Veterinary services are inaccessible to the migratory pastoralists due to tough topography at high reaches. Foot rot is a common ailment seen during seasonal migration. Herbs such as kuth, googal, raimand, ratanjot, kodpa trees, rattibuti, jogipadshah, jatlijadi, hand, hulla, Nera, chora are used to cure the animals. With the efforts of dairy cooperatives in Jammu & Kashmir, there are more than 500 milk cooperatives to provide market access to the dairy farmers of the valley. The sale of milk and wool from browsing goats and grazing sheep through off-farm and producer companies by the Bakarwal youth is very important.

What is needed?

Alternate routes of migration after weather prediction need to be provided by the government and concerned local authorities. Mobile animal husbandry and veterinary units should be established at the village level. Need-based vocational training/ skill development programme is necessary for the youth of this community. Protection of livestock from sudden natural calamities through training in disaster management for the youth is necessary. There is a need to form producer companies for milk, milk products and wool just like Farmer Producer Organisations (FPOs) for apples, and to promote alternative livelihoods through rent, tourism, and handicrafts for the Gujjar, Bakarwal and Chopan pastoral communities in the wake of hostile changing climatic conditions. Basic education to understand instructions on health and animals' treatment and schemes relating to animal husbandry, various policies that can be introduced by the respective state and central governments for their betterment and are also necessary. The youth of the pastoralist community must work along with the guidance of veterinary, agriculture, and livestock officers for herd improvement. Record keeping on the number of herds, cost and returns from investment on improved herding and grazing, and distance covered on seasonal movements needs documentation for covering insurance of the livestock after unruly disasters and man-wildlife conflicts. Good market linkages for meat, milk, butter, and wool by application of modern financial innovations is necessary.

Conclusion

It is high time that the contribution of pastoralism to the national economy by the custodians of the livestock in the unpredictable climatic zones is recognized. Ethnographic studies of pastoralism must be carried out to get valuable insights into the national forest policies and local adaptation strategies. Concepts of transhumance and pastoralism must be incorporated into the curriculum of veterinary science and animal husbandry in India. Therefore, it is important to conserve indigenous livestock breeds, traditional knowledge, and ethno-veterinary practices (EVP) of the rarest and dwindling ethnic pastoralist tribal community of Jammu & Kashmir in India.

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Arresting grazing land condition decline in Queensland's northern gulf should be framed around improving business performance

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Key words: land condition; extension; profitability; nutrition; business principles

Abstract

Monitoring Australia's Northern Gulf region over the past two decades has shown a continuous decline in land condition, reflecting declining capacity to respond to rainfall and produce useful livestock forage. In 2004, 69% of monitored sites had their carrying capacity estimate reduced based on one or more land condition indicators, increasing to 92% in 2023. If grazing pressure and management on the ever-diminishing natural resource base continues as is, the rate of decline in land condition may further escalate.

On-property experience and research results demonstrate the importance of improved land condition, and consequently improved long-term land and animal productivity, profitability, and resilience to climatic variability. Northern beef industry financial performance data confirm business performance is maximised when per animal performance is maximised. But barriers to adoption persist and these must be overcome. Therefore, landholder engagement and extension efforts to improve land condition should focus on improving business performance through maximising per head animal performance while addressing constraints to adoption.

Introduction

The Northern Gulf area of Queensland, Australia covers 19.7 million hectares of native pasture. Rainfall is seasonal and highly variable (500-1200 mm between December to March; CV = 34 to 45%), and extreme weather events (heat waves, floods, seasonal droughts) and fire common (Rolfe et al. 2016). Rainfall variability and strong seasonality (long dry season) are the main drivers of pasture production.

Forage quality is highest during the wet season but declines during the dry season. Low protein concentrations and high stem fractions at the end of summer are normal, so low nutritional quality predominates for most of the year. Pasture growth accounts for 77% of carrying capacity variation across Queensland's soil types, land systems, pasture communities, grazing enterprises and climatic zones (Hall et al. 1998). Such poor pasture quality leads to low average annual cattle liveweight gains (~ of 100 kg $head^{-1}$ $year^{-1}$), weaning rates (~56%), and high female mortalities of between 3 to 9% (Rolfe et al. 2016), and delivers low-income returns to grazing businesses. Many graziers have been caught in a downward spiral of carrying more animals (at ever declining productivity) to maintain the same output (Holmes, 2015; Rolfe et al. 2016). Chasing greater beef production per hectare, rather than per animal unit results in significant financial and environmental cost (O'Reagain, 2011; Walsh and Cowley, 2016).

Land condition decline is relevant across the rangelands in northern Australia, as well as around the world. Shaw et al. (2007) described a significant land condition loss in the Northern Gulf region, and subsequent monitoring in 2012 and 2016 recorded further declines (Shaw pers. comm.). Further monitoring in 2023 determined land condition had worsened.

Cost of Production ($ kg^{-1} LWt^{-1}) has the largest impact on northern Australian beef business profitability (McLean et al. 2023). Operating scale and labour efficiency are important in diluting these costs. However, kg beef AE^{-1}, a function of good reproductive efficiency, low mortality rates and higher turnoff weights, is best for measuring northern Australian beef enterprise productivity. These drive income but are impossible without good animal nutrition. Good nutrition can be either purchased or provided more cheaply by productive pastures under good land management providing better quality feed for much of the year. Less than ideal land condition can be considered potentially profitable but is inherently risky (MacLeod et al. 2004), with the link between good land condition and profitability not always obvious.

Our hypothesis is that Northern Gulf graziers should focus on kg beef produced Animal $Equivalent^{-1}$ (AE = 450 kg steer) output, associated with efforts to improve land condition. However, graziers firstly need to become aware that land condition is declining, and of the profitability-driving key performance indicators (KPI's) to facilitate change. This paper seeks to encourage extension efforts to be framed around the principles of good land condition providing nutrition and seasonal resilience, greater kg beef produced AE^{-1}, as a basis for sustainable profitability.

Methodology

The study comprised two research activities:

Land condition assessment in the Northern Gulf of Queensland

The ABCD framework describes grazing land condition (Chilcott et al. 2003). Pasture composition, soil condition, weed infestation and woodland density are assessed to assign a condition ranking to a land type. 'A' condition describes a land type at 100% of original carrying capacity; 'B' condition 75%; 'C' condition 45% and 'D' condition only 20% of original carrying capacity. Approximately 260 sites around the Northern Gulf region were assessed in 2004, 2012 and 2016 using Shaw's modified rapid land condition assessment methodology (Shaw et al. 2007). Their method relied on the observer having experience in the region to understand the original condition of a particular land type. 112 of the sites were revisited in each of the three years. In 2023, 289 sites were assessed for land condition around the same region using a land condition assessment tool (LCAT) App (Hassett et al. 2021). This tool enables rapid and consistent collection of standardised land condition data, and generates a land condition score immediately, based on the input data. However, LCAT scores are calculated differently to Shaw et al. (2007). Therefore, the 2023 LCAT data for above-mentioned 112 sites were reassessed in a desktop process using the rapid land condition assessment method. Three experienced land condition assessors, who had each been involved in all, or some, of the previous three surveys undertook the reassessment as a group with vigorous discussion. Site photos (usually 4 or 5) and species composition data collected through the LCAT App were used for the reassessment. Consequently, a standardised land condition dataset for the Northern Gulf region that includes site data from 2004, 2012, 2016 and 2023 was created (Gobius and Buchanan, 2024).

Remote sensing (VegMachine (https://vegmachine.net/)) was used to estimate canopy cover change as measured by Persistent Green, that portion of vegetation estimated to not completely senesce within a year, primarily consisting of woody vegetation (trees and shrubs), although occur exceptions occur when herbaceous cover remains green (Beutel et al. 2019).

Collating published evidence of a positive relationship between good land condition, good nutrition, greater kg beef/AE and profitability

Ten studies specifically linking land condition, livestock productivity and profitability were examined (Purvis, 1986; Landsberg et al. 1998; Paton et al. 1999; Smith, 2000; MacLeod et al. 2004; MacLeod et al. 2010; Broad et al., 2011; Walsh and Cowley, 2016; Bowen et al., 2019; and Hall et al. 2020).

Results

Land condition decline in the Northern Gulf

Carrying capacity in the Northern Gulf is estimated to have declined from 74% to 60% of the original since 2004, a 0.75% loss per annum, with pasture composition and timber thickening most responsible for land condition discounts (61% and 54% of sites, respectively). In 2004, 69% of rapid assessments were discounted due to one or more land condition indicators. This increased to 76% of sites discounted in 2012, 91% in 2016, and 92% in 2023. Persistent green woody vegetation levels increased from 13% in 2003 to 22% in 2022.

Collating published evidence of a positive relationship between good land condition, good nutrition, greater kg beef produced/AE and profitability

The key management decisions identified through the literature review leading to improved land condition were:
Good record keeping to objectively measure change in management and productivity over time; reduced stock pressure, safe stocking rates, constrained variable strategies or better matching of stocking rate to carrying capacity; enabling rest and wet season spelling; using fire to manage trees, pasture quality and grazing pattern; timber thickening management; rehabilitation of degraded land and pasture improvement; cross breeding for better productivity; pregnancy testing and culling non-performers; a supplementation program.

The key benefits of improved land condition identified through the literature review were:
Improved land condition and resilience in a variable climate; improved live weight gain and turnoff weights; improved body condition scores and weaning rates; reduced mortalities; reduced steer turnoff age, earlier mating, higher turnoff percentages; no need to reduce stocking rates; less feed shortages, stable animal/herd production and sizes, lower frequency and scale of feeding costs; lower input costs and improved profitability and business resilience in variable years; more sleep and fewer worries; reductions in livestock greenhouse gas emission intensity.

Discussion

The literature evidence, in conjunction with the Australian Beef Report evidence (McLean et al. 2023) that income from profitable enterprises is derived from kg beef produced/AE, suggest that improving land condition in the northern Australian rangelands will increase profitability. The Australian Beef Report identifies that Cost of Production (COP), kg beef produced/AE and operating scale are the main KPI's for northern beef enterprises. When kg beef produced/AE is optimised, COP/AE is diluted, particularly when scale and labour efficiency are maximised. This discredits the common practise of targeting kg beef/ha by increasing stocking rates to combat declining land condition and productivity.

Species composition interacts with seasonal conditions to define animal production potential. Although relationships between liveweight gain per hectare and per animal are well understood (Jones and Sandiland,1974), they are often ignored or misunderstood by graziers. Perennial species contribute most to rangeland animal production on a long-term basis, and when seasonal conditions are near or below the mean. But in certain above average rainfall years (particularly when both rainfall amount and wet season duration are above average), short annual and biennial plant species can significantly augment animal production (Hacker and Tunbridge, 1991) and so create significant inter-annual liveweight variation. This inconsistency in the impact of perennial species can act as a barrier for graziers in clearly understanding the land condition/stocking rate/liveweight gain relationships, as graziers tend to 'anchor' on these 'good' years, making extension messages difficult. While recognizing this potential variation between years, extension effort must focus on making graziers more aware of the overarching and positive relationship between good land condition, appropriate stocking rate, good nutrition, greater kg beef produced/AE and profitability.

Group extension work with graziers serious about achieving financial and environmental sustainability should firstly be about awareness of the degree of land condition loss regionally and on their own properties; understanding the business profit drivers and having a sustained focus on them; and acquiring financial literacy. Consequently, one-on-one extension should: enable managing landscapes using evidence-based knowledge and skills; use Breedcow Herd Budgeting software to model the impact of declining land condition and identify herd management practises that can improve productivity while reducing stocking rates (Bowen et al., 2019); enable management decisions based on both financial and environmental outcomes (Walsh and Holmes, 2023). If grazing pressure and management on the ever-diminishing natural resource base continues as is, the rate of decline in land condition may further escalate. Once land condition declines to ~ 20% of original condition, it is almost impossible to reverse without costly mechanical intervention (MLA, 2024). We are under no illusions of how long land condition recovery might take; it is likely to be slower than the recorded 0.75% per annum loss of retained original carrying capacity. If land condition could be improved at 0.5% of carrying capacity per year, improving from 60% back to 75% retained original carrying capacity (B condition) will be the responsibility of the next generation of land managers. This next generation should be targeted by beef extension officers.

Conclusion

Land condition decline is relevant both across Australia's rangelands and internationally. In the absence of legislative oversight of rangeland condition, solutions are required to arrest this decline. Barriers exist to the adoption of extension messages. Extension must focus on grazier understanding of the decline in land condition, and the link between greater land condition and potential long-term profitability, highlighting management practices that will maintain or improve profitability through improved reproductive efficiency and turnoff weights, and reduced mortality and costs of production, while reducing stocking rates. Decades of warning producers of excessive stocking rates have been ignored. Stocking rates are more important than management systems in determining vegetation change (Hacker and Tunbridge, 1991) and should be closely matched to sustainable use the available pasture supply, providing homegrown feed base quality and quantity. In collaboration with industry, we need to facilitate necessary land management change before further damage to landscapes and livelihoods becomes irreversible.

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Grazing management - system perspectives

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Sustainable management to reduce grasslands grazing pressure and improve household income in northern China

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Key words: Farm optimized model; household production; lambing time; pen feeding; seasonal grazing.

Abstract

Analyses of the status of current livestock production and alternative management practices for livestock production can help farmers improve their farming systems based on their particular local resources and markets. The farm surveys and parameterization of the models were developed by scientists and farmers working together to evaluate the effects of finances, grassland management, animal management and changes in farm infrastructure. Our study aimed to utilize bioeconomic models to optimize farm and livestock production systems in the agro-pastoral area in northern China. These analyses will hopefully lead to improved incomes, provide workable options for farmers and policy makers to restore grasslands and result in sustainable utilization of China's grassland resources.

To examine possible ways to sustainably manage grassland in the agro-pastoral areas, a formal survey of sheep farmers was conducted, and data from experimental trials were obtained in Hebei Province of northern China. The model of farm management analyzed annual feed supply and demand and showed that the gap of the annual feed supply and demand could be reduced by using improved sheep breeds for meat production instead of current breeds. The model of economy analysis showed that maximal profits could be achieved by using a combination of seasonal grazing at a grazing intensity of 5.4–6 sheep ha^{-1} and pen feeding. In addition, changing lambing time to November would reduce grazing pressure during the summer, which will be beneficial for grassland restoration and enhanced ecosystem services.

By obtaining accurate on-farm information from pastoralists and using these data to parameterize two models, realistic changes in management strategies were identified to increase farm income and reduce grassland grazing pressure. This activity increased public awareness of optimized farm management tools and provided a sound basis for identifying management alternatives for the sustainable management of grassland resources.

Introduction

Traditional livestock management practices in northern China are often based on survival through the year rather than producing goods for a market and running the farm as a business. What happens on these grasslands has important implications for millions of people in this region of China, and also safeguards the northern and the southeast cropland region of China. Analyses of the status of current livestock production and alternative management practices for livestock production can help farmers improve their farming systems based on their particular local resources and markets (Takahashi et al. 2011; Komarek et al. 2012; Zheng et al. 2013). Model analysis of farm production provides a valuable tool for both government officials and farmers to optimize natural resource use for livestock production. Model solutions have been used to try and guide farmers to increase market access and develop quality standards, thereby making livestock production more profitable Parsons et al. 2011; Komarek et al. 2012; Zheng et al. 2013). The objective of our study was to utilize bioeconomic models to optimize farm and livestock production systems in the agro-pastoral area of Fengning County, Hebei Province in northern China. The farming analysis model was developed by scientists and farmers working together in the northern grassland area of China to evaluate the effects of finance, grassland and animal management and farm infrastructural changes (Kemp et al. 2011). The objective of our study was to utilize bioeconomic models to optimize farm and livestock production systems in the agro-pastoral area of Fengning County, Hebei Province in northern China. These analyses will hopefully lead to improved incomes, provide workable options for farmers and policy makers to restore grasslands and result in sustainable utilization of China's grassland resources.

Methods

Data to parameterize the models were obtained from various sources, including farm surveys, published information, expert opinions and field trials (Ma et al. 2014). Several functional relationships between various biological parameters and either grassland condition or livestock condition were derived using experimental trials in the local area (Figure 1).

Data collected from the farm surveys and field trials were used to parameterize two models: StageONE Feed-Balance Analyser Model and StageTWO Optimising Model (Takahashi et al. 2011). The model uses metabolisable energy to link feed supply, demand and utilization. Both models derive net farm livestock financial returns for the starting conditions using biophysical and financial data.

Figure 1 Study location of Fengning County, Hebei Province in northern China.

Results

Current sheep production system in Fengning County

In the southeast portion of the Mongolian Plateau, Hebei fine-wool sheep and small-tail sheep crossed with Mongolian sheep are the dominant livestock. The typical farm averages 5 to 8 ha of land for fodder (typically maize silage, oats, wheat and potatoes), and about 700 ha of grassland is communally used by the village. Lambs are born from January to March and sold at about 8 to 12 months of age, according to the herder's need and market price. Grassland is continuously grazed at a stocking rate of 4.0 sheep ha−1 throughout the year, resulting in very high grazing pressures. Though a few small household farmers feed sheep during winter, energy and nutrient deficiency are typical from late-September to May because of poor forage nutrition and animal management (Figure 2a).

Options for farm improvement using different sheep breeds

In recent years, most farmers switched their focus to meat production due to the favorable mutton market. Farmers prefer small-tail sheep to other varieties because of the high birth rate, though this variety is not good for meat production. Given the poor nutrition of animals during winter and the high cost of purchased fodder, one alternative strategy is to use sheep varieties with good meat production. Some local farmers have crossed local ewes such as small-tail sheep with German Merino rams or Dubo rams for improved meat production. These crosses can increase live-weight gain with grazing during the summer and pen feeding in winter. Data from these new sheep breeds and the pen feeding trial were used to re-run the StageONE Model. The model results showed that the energy gap between maintenance and actual feed intake was narrowed (Figure 2b).

Options for farm improvement by changing lambing time

Results from the StageONE Model showed that lambing in January through March resulted in a sub-maintenance level of energy intake for ewes during most of the year (Figure 3a). Lambing in Jan. would be predicted to result in a major feed deficit from January through April (60% of maintenance). April lambing was closer to the maintenance level during November to February, but resulted in a large feed deficit during March to June (50% of maintenance). Lambing in June enabled an improved feed equivalent during winter and spring; however, intake did not meet maintenance levels during summer grazing in June and July. Lambing in November allowed intake to reach maintenance levels for nearly the entire year. This strategy might be further improved by possibly selling lambs and cull animals earlier (3 to 4 months of age) and by providing good nutrition in feeding pens. By lambing in November, pregnant ewes would have a greater probability of accessing higher quality forage during the summer, resulting in a higher lamb birth weight.

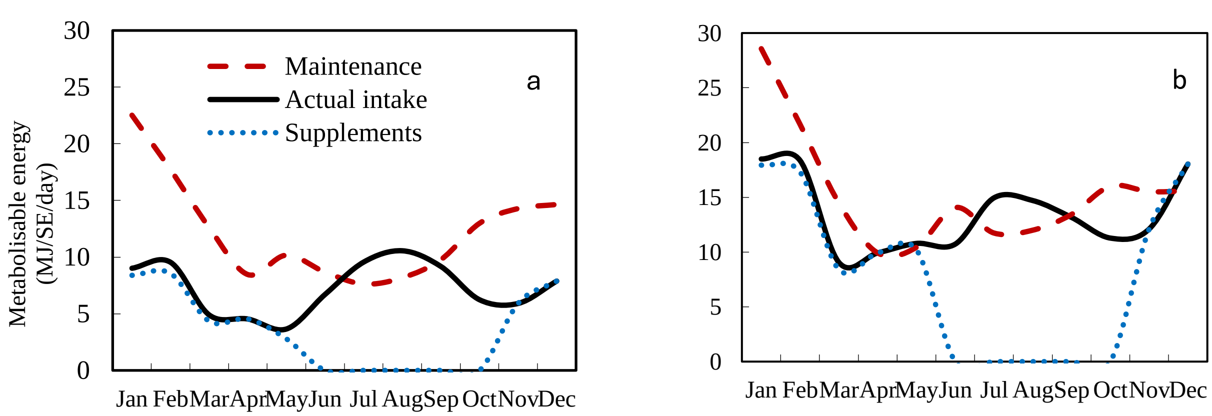

Figure 2 Metabolisable energy (ME) requirement, total ME intake and ME from supplements at the same live-weight per sheep equivalent for a typical farm in Fengning County, Hebei Province: a) current farm production and b) farm production using an improved sheep breed. (Note: Total ME intake is the intake of forage plus supplements. Ewes lambing in January).

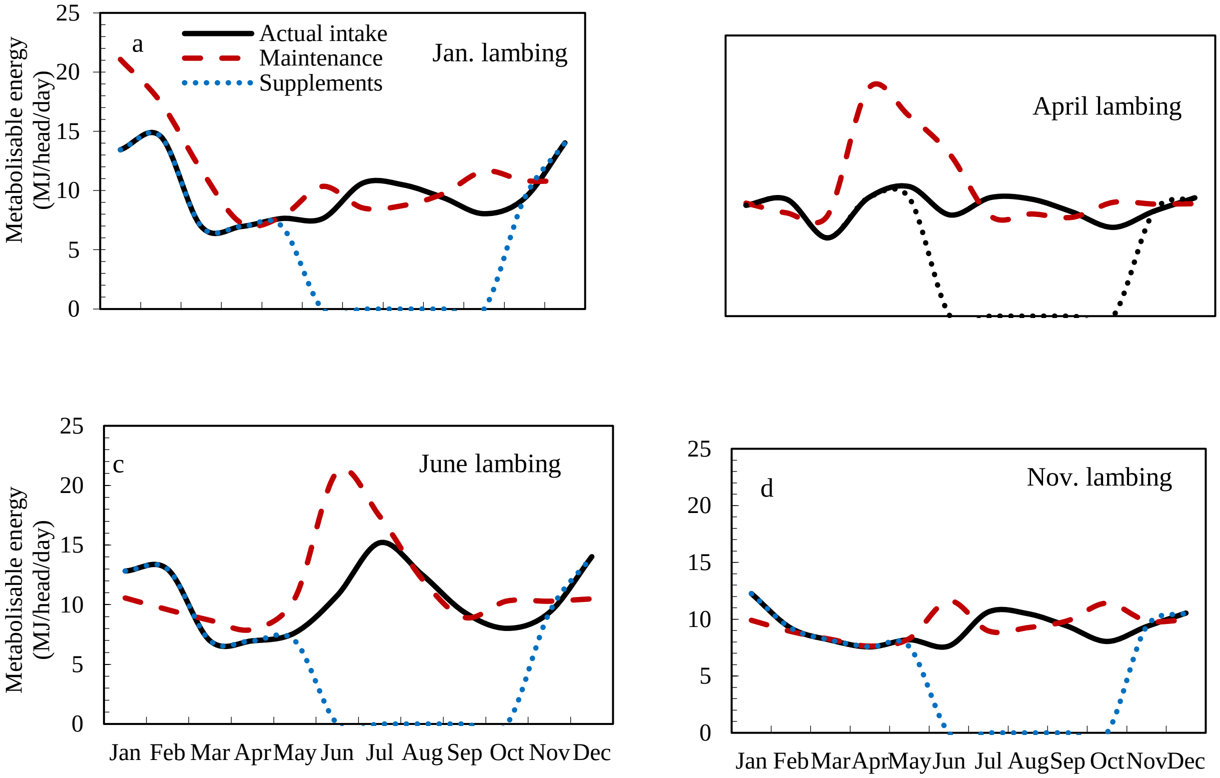

Figure 3 The effect of lambing time on feed energy balance for ewes in Fengning County, Hebei Province for: a) lambing in January (typical practice), b) lambing in April, c) lambing in June and d) lambing in November. With pen feeding from 15 Oct. to 15 June, feeding oat hay at 0.2 kg/day/head, alfalfa hay at 0.5 kg/day/head, maize grain at 0.1 kg/day/head, and other protein sources at 0.1 kg/day/head (ME = metabolisable energy).

Discussion

A key issue for managing livestock is maintaining a balance between livestock feed requirement and livestock feed availability (Darnhofer et al. 2010; Ma et al. 2014). Efforts to achieve this balance typically focus on increasing the forage and feed available to livestock and improved livestock performance through breeding (Herrero et al. 2009). Based on our local farm survey and the application of *StageONE* and *StageTWO* Models, we identified several strategies that may be beneficial for improving sheep management in northern China.

Analyses of the current livestock production status and alternative production management strategies through on-farm surveys and the application of model analysis showed the following changes should be made to the current farming system: 1) grasslands should only be grazed during the growing season, 2) pen feeding should be done during the non-growing season and 3) lambing time should be changed. These changes would better match local resources and lamb markets. The farm surveys and parameterization of the models were developed by scientists and farmers working together to evaluate the effects of finances, grassland management, animal management and changes in farm infrastructure. By obtaining accurate on-farm information from pastoralists and using these data to parameterize two models, realistic changes in management strategies were identified to increase farm income and reduce grassland grazing pressure. This activity increased public awareness of optimized farm management tools and provided a sound basis for identifying management alternatives for the sustainable management of grassland resources. Hopefully this process can be applied in other regions of China to more sustainably manage China's vital grassland ecosystems and improve the livelihood of pastoralists.

Acknowledgements

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Sustainable sheep ranching through regenerative grazing in the western United States: the case of Shaniko wool company on carbon neutrality

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Key words: soils; carbon sequestration; rangelands; sheep farmers; wool production; regenerative grazing

Abstract

Ranching has historically been one of the most economically and socially rewarding activities for many families in the Western United States. However, climatic and socioeconomic changes have brought public scrutiny to the environmental impact of ranching. Our Imperial Stock Ranch, with a 153-year legacy, has proactively addressed these challenges by adopting advanced sustainable practices to "make the land win" while producing commodities from dryland cropland and livestock grazing for local markets. In 2016, we achieved certification to the Responsible Wool Standard (RWS), becoming the first ranch globally to meet this leading standard for sheep and wool production. This milestone enabled us to partner with renowned fashion brands, providing sustainable wool that was even used in Team USA Olympic uniforms (2014, 2018, 2022 and 2024). In 2018, we founded Shaniko Wool Company (SWC) as a Farm Group to expand the supply of wool in the US that meets RWS global standards. SWC now includes ten ranches, collectively grazing over 1 million hectares across the country. To quantify the impact of our sustainable wool production, we collaborated with Oregon State University in 2019. By 2020, a program was developed to measure organic soil carbon and model greenhouse gas emissions for the entire farm group using the COMET Farm Model. This model indicates that the farm group can offset all emissions from our operations. For instance, the Imperial Stock Ranch alone has the potential to offset 2,809 tons of CO_2 annually, while the entire farm group can offset an estimated 91,444 tons annually. The future direction for our farm group involves certifying the entire group to sell carbon credits, creating a new income source alongside our existing production of food and fiber, sustaining humankind. Our commitment to sustainability not only benefits the environment but also strengthens the economic resilience of our ranching communities.

Ranch history

The family owned ranch; Imperial Stock Ranch is located in the high desert of Oregon's interior in the western United States. It was started by a young man who was born in a covered wagon as his family traveled west on the

Oregon Trail in 1852. He grew up in western Oregon where his family had settled, but in 1871, when he was 19 years old, he went east over the mountains into Oregon's dry interior to make his own start, filing on a homestead claim of 64 hectares (160 acres). He brought in cattle and sheep to graze the range lands and plowed enough land to establish grain and hay crops. He grew his operation from this modest beginning, and by 1900, he was Oregon's largest owner of land and livestock with a ranch of 13,000 hectares (32,000 acres). For 154 years, the Imperial Stock Ranch has been producing sheep, cattle, grains and hay on the same landscape. We recognize that we are temporary stewards of the land; that the land was here before us and will be here long after we're gone. We're aware of both our insignificance and our importance; and that the land provides sustenance for all life.

Stewardship

My husband's (late Mr. Carver) goal was always to "see the land win." He knew that the health of natural resources has a direct effect on your harvests, your bottom line, and your hope for the future. Working with local natural resource agency partners, by 1989, we had a written Conservation Management Plan for our whole operation that put the health of natural resources as the top focus; and we began implementing a host of changes. In our region of the high desert, we receive less than 200 mm of precipitation per year. Our plan considered both grazing management and crop management, with water conservation at the core.

Our plan included creating many off-stream water developments capturing, storing and safely releasing the water from rain and snow events, as well as natural springs. We changed the grazing strategy and were very strategic with the placement of supplements for the livestock. We created fencing to control grazing pressure and rest for plant communities. We converted thousands of acres of dry farm ground to no till, parking the plow forever, and keeping plants in all the fields every year.

Two creeks are born on our ranch, and in 1990, about when we were beginning this comprehensive mind shift on management, only two salmon returned to spawn in the local Buckhollow Creek. The first 15 miles of that stream start in our ranch, and this statistic was a huge wake-up call. Working with our agencies and other landowners in the basin, the Buckhollow Watershed Project (NRCS, 1994) was born as a collaborative, comprehensive, basin-wide approach to restoration. We hoped we would see a difference in our lifetime, but we did not know if it could happen that fast. We began to see changes after the first year. By 2010, just 20 years later, we saw thousands of salmon return to Buckhollow Creek showing a significant change.

Adaptation to changing market conditions

For 100 years, we always sold our wool harvest to the same company. However, in spring of 1999, changes in the market made the company stop buying the wool as they changed their operations to other countries. That would profoundly change our life. It was a time when tens of thousands of U.S. sheep producers were going out of the sheep business largely driven by this textile manufacturing shift. My husband said, "Find a new way to sell the wool, or sheep will be gone."

From that day forward, I took us from ranch to retail in our own branded products: wool yarns, and eventually, apparel, home fashions, and production yarn to brand partners. I built supply chain relationships to transform the raw (greasy) wool, and wholesale / retail relationships with brands and stores, eventually working with some of the most influential brands in North America and known around the world. But this did not happen overnight. This effort was made by pairing the wool with our heritage and the leading agricultural practices we had now been implementing for decades. I was busy telling our "sunlight story" of the land, grazing animals, and the gifts of creation. About how sheep transforms plant protein into the food, fiber and shelter that give us life. And how we are called to honor that. It resonated with authenticity. The provenance of the wool was critical to our effort and story, in yarn, home fashions, and apparel. We used every part of the harvest and then added value to the waste created at each step of the process. We shifted to this new model of marketing just as we had shifted our ways on the land.

After 13 years of hard work, we got a call from Ralph Lauren during the 2012 London Olympics, when there was a controversy over the Chinese-made Team USA uniforms. They were looking for an American yarn and to see if they could make the uniforms in the U.S. again. That all eventually led to an order that became the yarns for the 2014 Team USA uniforms for the Winter Olympics in Sochi, Russia. And then, Ralph Lauren told our story. This influenced others, and more brands came calling. That call too, changed our life.

I began my journey in textiles in 1999 in an effort to preserve sheep on our land. I had no idea that it would take me back to our collective history and simultaneously propel me into a future I could never have imagined. That it would become the vehicle that would connect me to the timeless traditions and skills of making textiles, take me to their roots, teach me, and deepen not only my agricultural experience, but my whole life perspective. This journey of taking our harvest direct to the market, shepherding it through every step, opened windows through which I gained clarity on things I had never even thought about before, bringing important and unforgettable people into my life. It built meaningful connections that erased the urban/rural divide for us, and bonded me to folks far across the country, and now the world, in a way I'd never been nor would have been otherwise. I began to know how important their work is. It helped me see our own work in agriculture with an even deeper purpose. I learned how much we needed each other; how we could learn from each other; and our lives became richer because of it. We began to rebuild the connections that were destroyed through globalization and the separation and isolation of individual steps in the textile supply system. With separation and isolation, the importance of place has been diminished, and with it, the motivation for stewardship. We're left with anonymity, which contributes to devaluing products, and breeds distrust in the marketplace. Perhaps the greatest consequence has been the degradation of natural resources and negative climate impacts.

Certification
Following our 2014 Olympic notoriety, we saw tremendous growth in our textile journey. Many brands were calling. One of those was Patagonia, who asked us to be third-party audited for our land and animal practices. Patagonia was part of an international working group that was developing a new global standard for sheep and wool production called the Responsible Wool Standard (RWS) (reference). When the RWS standard was launched in 2016, Imperial Stock Ranch became the first ranch in the world certified.

Expansion
In 2018, we established Shaniko Wool Company to scale the supply of American wool that met RWS certification, choosing a name that honored a story greater than our ranch alone. Shaniko Wool is a Farm Group supplying RWS certified wool. Together, we shear about 226,796 kg of wool each year and are grazing over 1 million hectares (2.6 million acres) in the western U.S. Shaniko Wool is continuing the strong relationships we had built within the U. S. textile industry in our own ranch's efforts since 1999; and my husband's legacy in resource stewardship. When Ralph Lauren called on us for wool for the 2022 Team USA Winter Olympics uniforms, they were made with Shaniko Wool.

Beyond the Standard
In 2019, we were criticized about the impacts of agriculture and in particular, livestock production. It was the motivation I needed to take the next logical step. What was our net footprint as ranchers? In early 2020, we responded to this increasing concern over the ecosystem and climate impacts of ranching, specifically sheep production. Working with a team of range and soil scientists from Oregon State University, we launched a measurement and research effort I called the Shaniko Wool Carbon Initiative. Up until now, we had our observations, and some monitoring, yield data, species counts, resource agency testimony, and certification to third-party standards in support of our work. But we had never formally "measured" or quantified our ecosystem deliverables. I did not even know if we could!

Our purpose was to determine the ecosystem and climate impacts of each ranching operation with carbon as a key performance indicator, plus collateral benefits. Science says that if soil carbon levels increase over time, additional positive benefits may include:

- Increases in soil organic matter
- Increased nutrient availability
- Improved water infiltration and water holding capacity
- Greater system biodiversity
- Improved habitats
- Resilience to extreme weather events
- Improved disease resistance
- Improved livelihoods

By 2023, we had baselined all 2.6 million acres.

Our research team is presenting our data and findings at this conference (Prado-Tarango *et al*. 2025), and I want to emphasize why this work is significant. When we began measuring, I was not sure what the sampling would reveal. However, I knew it would provide us with valuable information and a new tool to better understand our system. The primary purpose of this research is to offer actionable feedback to farmers and ranchers, enabling them to refine their management practices. What we have discovered has been overwhelmingly positive. Our operations are functioning as carbon sinks, with negative net greenhouse gas emissions. The methane produced by livestock is being fully offset by the carbon sequestration capacity of our rangeland ecosystems. These findings not only validate our observations but also provide robust evidence of our environmental impact. This data has proven instrumental in supporting the sale of our wool, instilling confidence in the companies that purchase it, and enhancing the marketability of our products. Additionally, our research has undergone auditing by ecosystem services organizations, resulting in the Shaniko Wool Farm Group being approved as a “project” capable of generating high-quality carbon credits. These credits can serve as offsets or insets, opening up a promising new revenue stream for family agriculture. The term "regenerative" is widely used today, but this research has provided concrete evidence that we are achieving regenerative outcomes. It transcends mere practices or approaches, offering quantifiable proof of success. For me, this has been the most meaningful work I have ever been involved in. It validates the vision my husband and I shared decades ago and the transformative changes we made to see the land thrive. Today, we are measuring that success and witnessing the results firsthand.

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It's time to revisit the dichotomy between researchers and producers regarding rotational grazing

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Key words: livestock, forage, defoliation, meta-analysis

Abstract
In 1998 Norton offered an explanation for why researchers and commercial producers have opposing views on rotational grazing. Most researchers agreed to a lack of evidence of an improvement to forage yield or animal production due to rotational grazing, while producers were generally happy with higher production and income. He attributed this difference to a question of scale: research studies in small paddocks carry the implicit and reasonable assumption that both forage availability and its utilization are spatially homogeneous, whereas those parameters are highly variable across a continuously grazed rangeland landscape. Rotational grazing can ameliorate the patch grazing patterns encountered on extensive rangelands. An unheralded outcome from many grazing trials is that the stocking rate on experimental pastures could be maintained at much higher rates than on commercial properties near the research station, without adverse ecological impacts for either treatment. This appears to be a small-paddock phenomenon. Since 1998, many studies have looked at rotational grazing at a landscape/property scale with mixed results: some positive, some neutral, some negative. However, the adoption of rotational grazing on 130,000 ha of communal rangeland in Central Asia is a testament to its potential benefits to land, livestock and households. Adding to the confusion, recent meta-analyses of grazing studies have generated contrasting conclusions. The key issue appears to be the degree to which the design of a rotation is reflected in the plant/herbivore interface. A disconnect between the intended treatment and its expression in grazing behaviour is evident when defoliation frequency has been measured in grazing trials. We can hypothesize, therefore, that failure of the rotation treatment to be implemented as intended could explain a lack of differentiation between continuous versus rotation treatments. This paper surveys rotational grazing studies to examine this hypothesis.

Introduction
One of the most intriguing aspects of rangeland grazing research is the persistence of opposing views about rotational grazing, one claiming benefits to both forage and livestock production while the other states that the rotation is no better than continuous grazing. Reviews of published research going back to Sampson (1951) and many others since then demonstrate a general disadvantage to rotational grazing management, while reports indicate that commercial producers enjoy higher plant and animal production; their adherence to rotation practices is confirmed by a consensus of higher income. Norton (1998) attempted to resolve this dichotomy by showing that a flaw permeated most grazing trials in the form of research designs that utilized relatively small research paddocks. In those research situations, behavioral limitations on access to the entire pasture on a daily basis did

not apply. He argued that on extensive rangelands, rotational grazing could mitigate the patch-grazing patterns that concentrate grazing impacts on focal points from which degradation spreads. There have since been a number of studies of grazing rotations at a commercial station, landscape or ranch scale, but the dichotomy remains.

Meta-analyses of rotational grazing

Among reviews of grazing research studies, the oft-cited analysis by Briske et al. (2008) concluded that continuous grazing was superior or equal to rotational grazing in terms of both plant and livestock production in the vast majority of the 47 papers they reviewed. They employed a simple ‘vote count’ method of assessment. Wolf (Wolf & Horney 2015, based on Chapter 2 in Wolf’s 2016 thesis, University of California, Davis) addressed the same 47 papers but went deeper in a meta-analysis that teased out discreet variables that may not have exhibited significant differences in Briske et al.’s coarse analysis. She used a response ratio to measure the effect size, Rotation/Continuous, and looked at plant production (kg/ha), animal production per head (kg) and animal production per ha (kg/ha). She confirmed the broad conclusions of Briske et al. but also found that rotational grazing performs better in larger rangeland areas, in more seasonally variable environments, in more arid environments, and as grazing periods become longer.

McDonald et al. (2021) conducted a systematic review of global literature (280 studies) that compared ecological and production outcomes of rotational grazing to continuous grazing. Most studies reported no difference or no consistent difference in biodiversity, land condition or production variables, similar to conclusions in reviews by O’Reagain & Turner (1992, >50 studies), Briske et al. (2008) and di Virgilio et al. (2019, 278 publications). However, where differences were observed by McDonald et al., more studies reported positive rather than negative responses under rotational grazing. The exception was livestock weight gain, where 34% reported a negative response.

In a companion report, McDonald et al. (2019, 176 studies) addressed the specific question of how the length of the rest period in rotational grazing systems affects biological outcomes. They found a significant effect: at rest:graze ratios greater than 6:1, plant biomass was greater under the rotation; as rest:graze ratios increased, there was greater weight gain and more livestock production per ha. Meanwhile, plant diversity and species richness declined as rest:graze ratios increased.

In contrast to previously cited meta-analyses, Hawkins (2017), through a meta-analysis of data sets from 1972 to 2016 comparing continuous grazing to the Holistic Planned Grazing™ method of rotational grazing, found no difference in plant basal cover, plant biomass or livestock weight gain.

Rotational grazing on commercial-scale properties

The preference among commercial producers for adopting rotational grazing in place of traditional continuous grazing is evident in the small proportion who have rejected rotations after a trial period (e.g. Bork et al. 2021). There is a relatively small number of commercial enterprise-scale studies of rotational grazing. However, let us look closely at a few cases of grazing at a landscape scale.

On semi-arid, degraded rangeland in Southwest Tajikistan, an IFAD (International Fund for Agricultural Development) project (2014–2019) recommended rotational grazing for households herding livestock on communal village land, with each grazing unit area being grazed only once per year or per season to reverse the pervasive degradation. Impact analyses in 2018 and 2022 of the 400 participating villages managing 130,000 ha of rangeland revealed that cow weights were higher, herds were bigger, milk yield had doubled, and household income substantially increased (Norton 2022). Forage was more abundant. A rest:graze ratio of at least 15 was suggested. A follow-up survey indicated that households continued to practice rotations long after the project concluded, and voluntarily reduced herd numbers.

In Patagonia, Oliva et al. (2021) found that the application of rotational grazing for 3 years (mid-2012–mid-2015) under Holistic Resource Management (HGM) on 13,600 ha divided into five paddocks versus a matching area continuously grazed, caused negative effects on ewe liveweights and lambing rates. The only significant change in vegetation saw cover of the low-palatable tussock grass increase under continuous grazing. Rainfall was below an average 239 mm and declined throughout the study period. Grazing periods ranged from 23–68 days (mean 34), with rest periods of 160–319 days (mean 246).

In the Flooding Pampa region of eastern Argentina at higher rainfall (935 mm), Jacobo et al. (2006) studied rotational grazing for 4 years (1993–1996) at four sites; at each site one cattle farm managed with rotational grazing while the adjacent farm was kept under continuous grazing. The rotations involved 10–12 paddocks occupied by 400–500 breeding cows at a mean stocking rate of 1 AU/ha, 60% above the average for the region, for the continuously grazed farms as well. Grazing periods ranged from 3–15 days, and rest periods 25–90 days, the timing adjusted according to the growth rate of dominant grasses. Rotational grazing promoted high-value forage species such as legumes while low-value species, like prostrate summer grasses, decreased. This benefit was more pronounced in drier years. More litter cover and less bare ground signaled an improving ecological condition.

Augustine et al. (2020) cooperated with a consortium of livestock producers on the short-grass prairie of north-central Colorado – the Collaborative Adaptive Rangeland Management group (CARM) – to implement a grazing experiment on 2600 ha (340 mm average rainfall), evaluating responses of vegetation and cattle performance to multipaddock adaptive rotational grazing and season-long continuous grazing. The 11-member CARM group made decisions on annual stocking rate and the sequence and timing of movements among the rotation paddocks. Ten paired 130-ha paddocks were grazed by a single herd of steers. This design matched a continuous paddock to its rotation counterpart; the continuous grazing herd was spread among the ten paddocks for the grazing season. The herd size started at 214 yearling steers in 2014, but rose steadily to 280 steers by 2018, upon the recommendations of the stakeholder group. This trajectory is consistent with Norton's (1998) perspective on the amplifying effect of moderately small paddocks on carrying capacity. The authors could not find any grazing management effects on grass production, but they observed a 12–16% decline in cattle weight gain each year under the rotation compared to continuous grazing. A following paper (Porensky et al. 2021) documented tiller defoliation frequency and intensity on the dominant western wheatgrass (*Pascopyrum smithii*) within the grazing-system experiment described by Augustine et al. (2020). Roughly two-thirds of grass tillers remained ungrazed under both grazing systems.

Another way of referring to this result is to say that the experimental design was not reflected in the plant-animal interface. This phenomenon, of failure to infer the rotational grazing plan from evidence of livestock defoliation activity when the rotation study is accompanied by data on defoliation patterns, has been reported a number of times: for example, Gammon (1978), Hart et al. (1993), and Heitschmidt et al. (1990). In these examples, the effect of the rotation *per se* on defoliation pattern is weak or absent. As Gammon (1984) observed, if the rotation design cannot be deduced from defoliation patterns alone, the rotation was not implemented as intended.

Conclusion

The lack of congruence in performance between rangelands rotationally grazed and those continuously grazed may be due simply to a failure of the rotation design being expressed in the defoliation behaviour of grazing livestock. In other words, the rotation was not really implemented at all. However, as the rest:graze ratio increases, with longer rest periods and increasingly shorter graze periods, rotations are more likely to exhibit improvements in ecological condition and increases in both forage and livestock production. The range management profession still lacks a clear understanding of how rotational grazing works, and so contradictions in the research record and conflicting recommendations persist.

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Virtual fencing aids rest-based grazing and mustering in an extensive cattle grazing system

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Key words: Virtual Fencing; Cattle; Grazing; Regenerative; Rangelands

Abstract

Virtual fencing (VF) remotely manages livestock grazing using GPS-enabled collars that communicate the location of boundaries to animals. This technology has been demonstrated in cattle, with commercial use occurring in Tasmania and Queensland. VF is of particular interest for livestock management in rangeland environments where property size and topography can reduce the economic viability of installing new fencing infrastructure.

This research aimed to assess VF as a tool to facilitate rest-based grazing and aid mustering in an extensive beef grazing system. A trial involving 100 mixed breed heifers was undertaken at Wintinna Station (via Coober Pedy) in South Australia from April – October 2023. During the trial, the cattle were trained to a commercial VF system. A range of inclusion zones were established in different areas of a 4,500ha paddock with a central dam. Cattle were successfully contained by the VF system and grazed within each new inclusion zone once activated. The VF system was also used to aid in mustering the trial paddock. A virtual laneway 1km in width was activated 24 hours prior to scheduled mustering and all 100 cattle were contained within it. The following day the laneway was deactivated, and the paddock was mustered by two motorbikes in approximately three hours with no requirement for aircraft. The GPS tracking function of the technology enabled all animals to be accounted for.

The results of this trial indicate that VF can facilitate rest-based grazing practices within extensive beef grazing systems. VF's use as a tool to aid in mustering cattle was also demonstrated. With further development and reduced regulatory constraints, VF could have a significant impact on the way that rangelands are managed into the future.

Introduction

The potential for virtual fencing as a management tool in extensive cattle grazing systems has become an area of interest for Australian pastoralists. Rotational grazing is a valuable tool for protecting soil health (Byrnes et al. 2018). and plant biodiversity in grazing enterprises (McDonald et al. 2019). However, implementing rotational grazing using physical fencing presents significant challenges for extensive grazing systems. The large area of these systems makes temporary fencing and the cost of installing permanent fences impractical (Anderson et al. 2014). Consequently, virtual fencing has emerged as a potential solution to enable rotational grazing and improve management in extensive grazing systems.

Virtual fencing is a GPS-enabled technology that delivers cues to livestock via a collar, encouraging containment or exclusion from a prescribed area. An audio cue paired with an electric pulse informs the animals of the GPS boundary, defining their grazing area.

This study investigated the suitability of virtual fencing to facilitate rest-based grazing in the South Australian rangelands. The role of virtual fencing in aiding mustering was also investigated to assess virtual fencing as a holistic tool for improved operations on cattle stations.

Methods

This experiment was undertaken in Dead Finish paddock at Wintinna Station (via Coober Pedy SA), a 45km^2 (4,500ha) area comprising of uplands and open gently sloping plains with shrubby drainage lines. The predominant pasture species in Dead Finish paddock were Mitchell Grass (*Astrebla spp*.), Bladder Saltbush (*Atriplex vesicaria*), and Flinders Grass (*Iseilema spp.*). The water source in Dead Finish was a dam located in the West/Northwest of the paddock.

In April 2024, one-hundred mixed breed *Bos indicus/Bos taurus* heifers (average liveweight 300 ± 50kg) were selected from the herd at Wintinna Station. The heifers were weighed and confirmed not pregnant via rectal palpation prior to allocation to the trial.

The Vence virtual fencing system and CattleRider virtual fencing collars were used in this experiment (Vence, MSD, San Diego, California, USA). CattleRider collars were fitted to each heifer as per Vence protocols (Purcell, pers. comment). Virtual fences were created using the Vence online computer software and communicated to collars via long range wide area network (LoRaWAN) connectivity and global positioning system (GPS). The virtual fencing was implemented via the collars through administration of audio and pulse signals underpinned by associative learning theory (Lee et al. 2009).

The heifers were trained to the virtual fencing system in a 1.5km^2 (150ha) holding paddock. A virtual fence was activated along the physical boundary fence of the holding paddock for three days. The virtual fence was then changed to exclude the cattle from approximately one third of the paddock for a further four days.

On day 0 of the experiment, the heifers were walked approximately 8km from the holding paddock to Dead Finish. A virtual fence was activated in Dead Finish to exclude the heifers from an approximately 11km^2 (1,100ha) strip along the northern boundary of the paddock. On day 28, the virtual fence was changed to create an approximately 16km^2 (1,600ha) rectangular grazing area in the southwest of Dead Finish. On day 92, a capture lane (1km wide, 5km long) was activated to concentrate the cattle prior to mustering. Twenty-four hours later the capture lane was deactivated, and the cattle were mustered on two-wheeled motorbikes and walked approximately 8km to the closest cattle yards.

GPS heat maps were generated using the Vence virtual fencing online computer program and contain information from activation to deactivation of each virtual fencing configuration.

Results

The training period was successful with effective exclusion from one third of the training paddock achieved for four days (Fig. 1). Minor breaches of the virtual fence occurred during this time, indicated by blue shading within the red exclusion zone in Fig. 1.

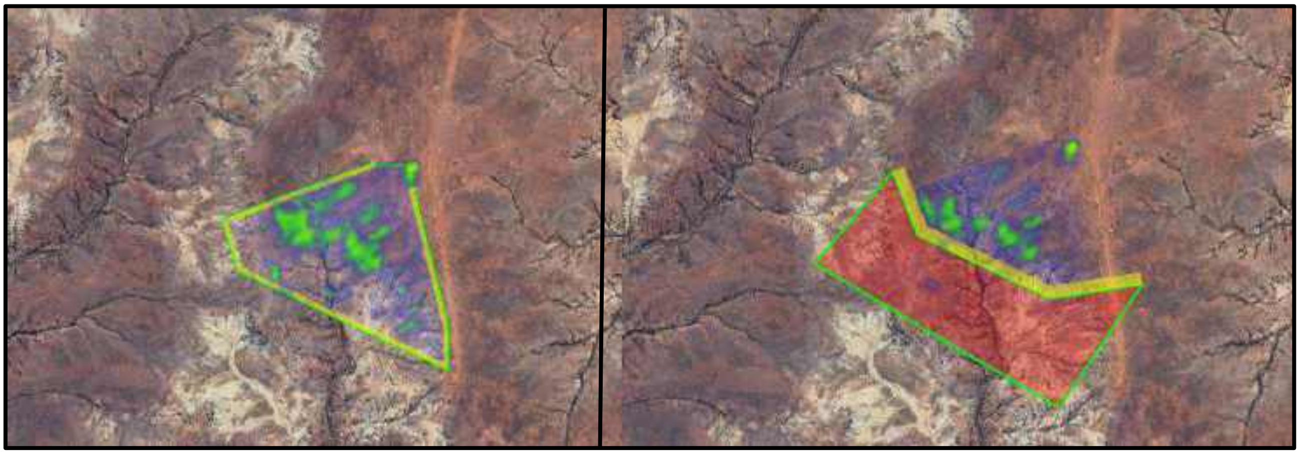

Fig. 1. Virtual fencing configurations and GPS location heat maps in the holding paddock during the training phase

A virtual fence successfully excluded the heifers from the northern boundary of Dead Finish for 27 days. Grazing distribution across the allocated area was relatively uniform with some concentration of grazing around shrubby drainage lines (Fig. 2). There were minor breaches of the virtual fence along a main drainage line through the virtual fence, indicated by blue shading along the prominent creek line in Fig. 2.

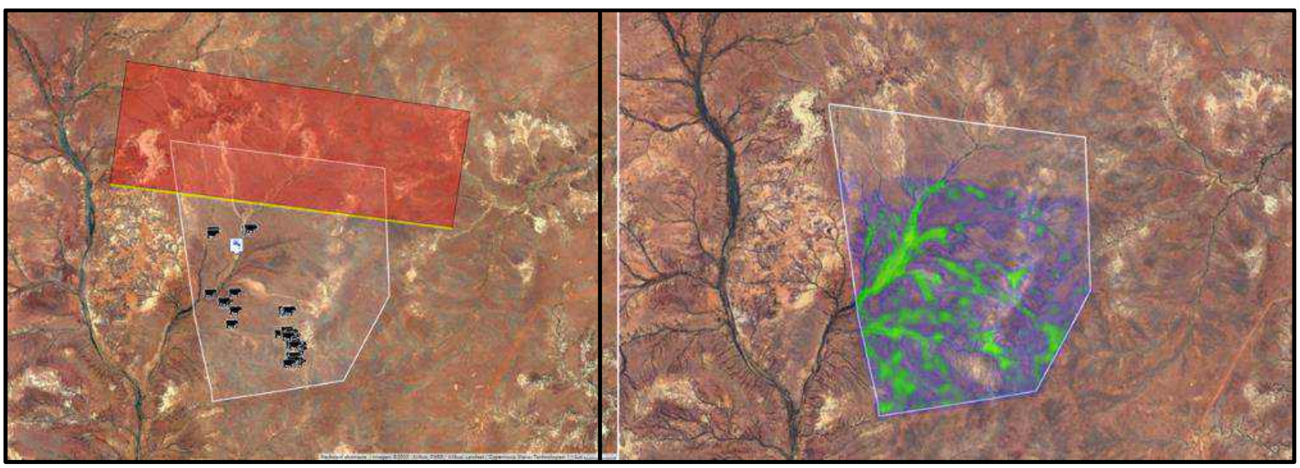

Fig. 2. The virtual fence configuration and GPS location heat map in Dead Finish from day 0 to end of day 27

The heifers were effectively contained within the Southwestern corner of Dead Finish by the virtual fencing system (Fig.3). Grazing locations were uniform across the allocated area. However, locations surrounding shrubby drainage lines were accessed more heavily, indicated by green shading in Fig. 3. There were breaches of the virtual fence along drainage lines to the west, north and east of the allocated area.

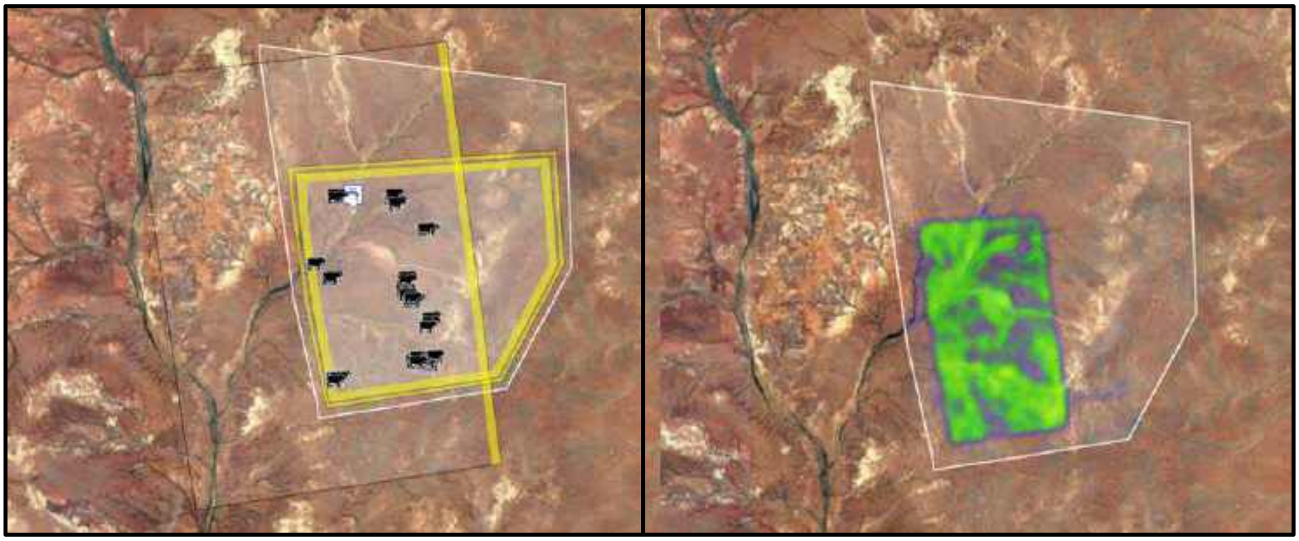

Fig. 3. The virtual fence configuration and GPS location heat map in Dead Finish from day 28 to end of day 91

The capture lane on day 92 effectively contained the heifers during the 24 hours prior to mustering. When the capture lane was deactivated immediately prior to mustering, all collars successfully received the instruction. All 100 heifers were mustered from Dead Finish within three hours by two people on two-wheeled motorbikes.

Discussion

Virtual fencing effectively contained heifers to specified areas within Dead Finish. Minor breaches of the virtual fence occurred throughout the experiment. However, overall containment of the heifers was acceptable. Breaches occurred mostly along drainage lines through the virtual fences. This was most likely due to the presence of moisture and abundant palatable pasture species in these areas. On day 61 of the experiment, a storm occurred at Wintinna Station and 35mm of rainfall was recorded. Twelve heifers breached the virtual fence during this storm, contributing to the GPS location recordings outside of the allocated grazing area. It is common for cattle to travel large distances through physical fences during a storm (Fennell, pers. Comment). The virtual fencing allowed identification of those who had breached the boundary and assurance that they had returned following the storm.

Virtual fencing improved the efficiency of mustering the heifers from Dead Finish. The use of a capture lane to condense the heifers prior to mustering saved the labour of two people for two hours each and the cost of an aircraft. Utilising virtual fencing enabled mustering of 100% of the heifers in Dead Finish, a very rare occurrence on cattle stations of this size.

Virtual fencing shows promise as a tool for improved grazing management and mustering efficacy in extensive cattle grazing systems. The use of virtual fencing at Wintinna Station increased monitoring of animals, reduced labour inputs, improved pasture management through rotational grazing and improved farm safety through reduced requirement for large musters and aircraft. The availability of virtual fencing to Australian pastoralists has the potential to contribute to sustainable rangeland management into the future.

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Improving tactical decision making in the western NSW pastoral zone

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Key words: grazing management; livestock production; decision making

Abstract
The Profitable Grazing Systems program: Improving Tactical Decision Making (ITDM) is a group-based training program designed specifically for the New South Wales rangelands. The objective of the program is to assist pastoralists with the adoption of strategic grazing management practices to improve farm business profitability. The program launched in 2021 and has since graduated three groups of pastoralists from Packsaddle, in the state's northwest corner, to Booligal, in the south-eastern rangelands.

Over a 12 to 18 month period, a small group of pastoralists participate in five training sessions. Each session covers a different aspect of rangeland grazing management, culminating in the development of a tactical grazing plan during the final session. At the program's onset, pastoralists are assigned the task of establishing a monitoring paddock, a pivotal tool enabling them to gauge progress towards their management objective. This strategic approach facilitates the self-assessment of the applied grazing strategies' efficacy within their unique landscape, providing guidance for informed decision-making at the program's completion.

Combining their own property knowledge with targeted grazing strategies, pastoralists learn to assess pastures, identify the productive species in their landscape and manipulate grazing management to increase the prevalence of valuable, perennial plants in the feedbase, thereby, improving their ability to condition paddocks to respond to rainfall and withstand dry periods. Complementary skills in livestock production are also covered to build capacity in condition scoring and optimal feed allocation to achieve production goals.

Upon program completion, pastoralists depart equipped with an enhanced ability to monitor, measure, and record pasture and livestock condition, thereby fostering improvements in whole property performance. By merging their existing property knowledge with fresh skills in grazing management, participants are better equipped to navigate the challenges of rangeland management, ultimately paving the way for sustained profitability and resilience within their operations.

Introduction
In the diverse arid and semi-arid rangelands of New South Wales (NSW), effective pasture management is critical for maintaining sustainable and productive grazing businesses. Pastoralists need to manage distinct challenges, including unreliable rainfall, total grazing pressure, variable feedbase composition and growth (Hacker et al. 2019; Hacker and McDonald 2021), leading to the need to make informed, real-time decisions about livestock management and resource allocation.

The Improving Tactical Decision Making (ITDM) program, developed by Western Local Land Services and part of Meat & Livestock Australia's Profitable Grazing Systems (PGS) initiative, is designed to support pastoralists in navigating these challenges by equipping them with practical tools and approaches for strategic grazing management. The group-based coaching model is tailored specifically to the needs of rangeland pastoralists in NSW. By focusing on increasing the capacity of pastoralist's decision making related to grazing periods, key species management, and livestock production, the program aims to enhance whole-property performance and drive greater productivity, sustainability, and profitability for grazing enterprises.

Program Structure

The ITDM program follows tactical management principles (Campbell and Hacker 2000) where participants develop their ability to set an objective, determine strategies to achieve the objective, implement their strategy and monitor accordingly. Five coaching sessions are held on property with a small group of pastoralists for up to 18 months. In preparation for each session, a pasture sample is conducted on four key pasture species at the host property monitoring site. The pasture sample informs feed budgeting activities and discussions relating to plant availability compared to animal selectivity assumptions (Graetz and Wilson 1980; Pahl 2019).

Each session covers different aspects of rangeland grazing management building on from the last, with the final session focused on creating a tactical management plan (Figure 1). The program emphasises practical skills in pasture evaluation, livestock condition scoring, and feed budgeting, all aligned with production objectives. Participants learn to identify key pasture species, recognise quality and quantity trends, and understand crucial rest and recovery phases for landscape health. Grazing management techniques are demonstrated to promote palatable, perennial plants, and participants develop the ability to assess the impact of grazing on plants at different growth stages. Seasonal trigger points (Hacker et al. 2006) are identified for each property and decision plans are created aligned with the livestock production system. Additionally, the program incorporates livestock condition scoring training and remote sensing technology, alongside on-ground measurements, to support decision-making. By the end of the program, pastoralists are equipped to monitor pasture and livestock conditions more effectively, aiming to improve overall property performance and supporting sustained profitability and resilience.

All participating pastoralists complete a baseline survey prior to entering the program and again at completion to assess the knowledge and skills gained from participating. Commencing with the 2023-2024 intakes, pastoralists were also surveyed on their intention to change their business practices as a result of participating. Smaller surveys are conducted at the end of each session to gain feedback on the delivery and inform improvements throughout an intake.

Following each intake, a review of the sessions is undertaken by staff to improve program delivery. Resulting modifications are based on staff experience and direct feedback from pastoralists, aiming to increase pastoralist engagement and knowledge comprehension throughout the program.

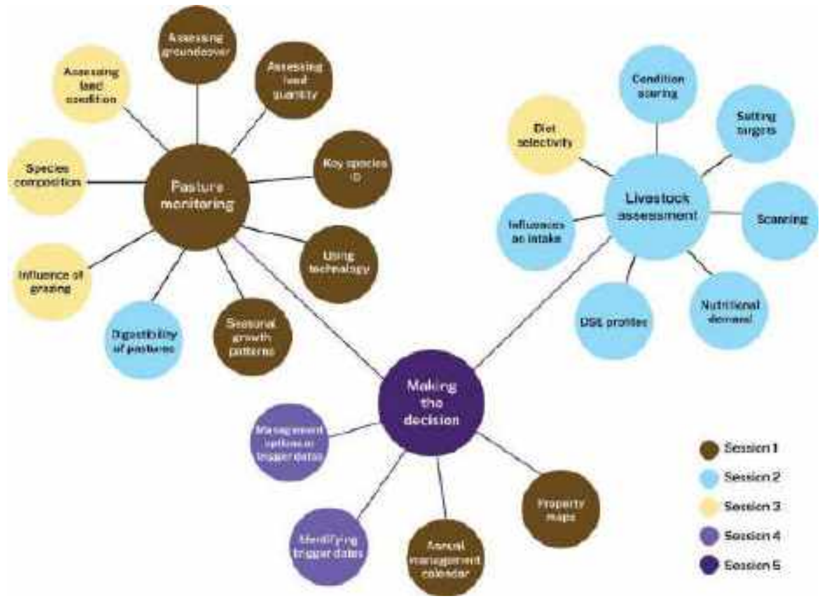

Figure 1. Session breakdown of the ITDM program.

Outcomes

At the time of writing, the ITDM program has been successfully implemented through three groups based in the Oxley (2021), Packsaddle (2023-2024), Ivanhoe and Booligal (2023-2024) areas where the total area managed by participating pastoralists equates to 482,654 ha. In each locality, pastoralists have self-assessed an increased capacity in grazing management and livestock production techniques (Tables 1 and 2).

Table 1. Averaged pre- and post-program self-assessment survey results from three groups of ITDM participants.

On a scale of 1 (low) to 10 (high), how confident are participants in their ability to:	Pre-Program	Post-Program	Change (+/-)
Assess feed digestibility	4.07	7.69	+ 3.62
Estimate feed quantity in kg DM/ha	2.57	7	+ 4.43
Use condition scoring to assess livestock condition	6.36	8.69	+ 2.33
Adjust stocking rate based on feed supply and demand	5.93	8.38	+ 2.45
Manage livestock nutrition to meet production targets	5.57	7.69	+ 2.12
Manage ewes according to their pregnancy status to reduce lamb and ewe mortality	5.64	7.77	+ 2.13
Adjust stock numbers guided by your grazing strategy and monitoring	6.14	8.62	+ 2.48

Table 2. Averaged pre- and post-program self-assessment survey results from the Oxley (pilot program) and the Packsaddle (P), Ivanhoe (I) and Booligal (B) (2023-2024 groups) participants of ITDM.

On a scale of 1 (low) to 10 (high), how confident are participants in their ability to:	Pre-Program - Oxley	Post-Program - Oxley	Change (+/-) - Oxley	Pre-Program – P, I, B	Post-Program– P, I, B	Change (+/-)– P, I, B
Assess feed digestibility	4.75	6.75	+ 2.00	3.80	8.11	+ 4.31
Estimate feed quantity in kg DM/ha	3.00	5.25	+ 2.25	2.40	7.78	+ 5.38
Use condition scoring to assess livestock condition	7.50	8.25	+ 0.75	5.90	8.89	+ 2.99
Adjust stocking rate based on feed supply and demand	7.25	8.00	+ 0.75	5.40	8.56	+ 3.16
Manage livestock nutrition to meet production targets	5.50	7.50	+ 2.00	5.60	7.78	+ 2.18
Manage ewes according to their pregnancy status to reduce lamb and ewe mortality	7.50	7.50	0.00	4.90	7.89	+ 2.99
Adjust stock numbers guided by your grazing strategy and monitoring	7.50	8.50	+ 1.00	5.60	8.67	+ 3.07

All participants (10) from the 2023-2024 intakes indicated they plan to make changes to how they manage their business as a result of participating in the program, and fifty percent (5) had already made changes before program completion. Pastoralists in the first (pilot) intake of the program were not surveyed on practice change.

Learnings

Improving Tactical Decision Making was first delivered as a pilot program in 2021. This initial intake of pastoralists had a reasonably high self-assessed confidence in livestock production related skills (7.25 - 7.50) prior to their participation in the program. When reassessed at the conclusion of ITDM, a small increase (0.00 - +1.00) in confidence was seen across these skills compared to feedbase related skills (+2.00 - +2.25). In contrast with the two 2023-2024 groups, whose livestock-based skills were rated lower overall (4.90 - 5.90) and saw a larger increase in confidence (+2.18 - +3.16), finishing the program at a similar level of confidence to the pilot participants. Interestingly, all intakes shared a low confidence in their ability to assess feed digestibility and estimate feed quantity in kg DM/ha prior to the program, with the largest increase in confidence post-program seen in the more recent intakes (+4.31 - +5.38).

Following the delivery of the pilot program, modifications were made based on experience and feedback from the initial delivery. Predominant changes included refining session plans and presentations, redesigning feed budgeting templates and the creation of supporting material. Additional interactive field activities were also developed for the final session to encourage pastoralists to utilise skills obtained earlier in the program and present findings to the group. Following the delivery of the 2023-2024 Packsaddle, Ivanhoe and Booligal groups, each session will be reviewed, and updates made before delivery to future intakes of the program. Adjustments are informed by the level of expertise in the incoming groups but also the lessons learned from the past groups.

It is difficult to discern whether the preliminary modifications of the program led to the larger increase in confidence level between the pilot and recent program intakes or pastoralists with lower initial confidence gained more from the program. The pilot program was conducted directly after an extended drought when pastoralist focus was likely directed towards more intensive livestock management due to ration feeding programs.

Additionally, service provider support is known to increase in dry periods, likely contributing to an increase in capacity before participation. In contrast, the most recent intakes were initiated during a high rainfall period. Moreover, the geographic spread of participants could lead to discrepancies in opening confidence levels due to differences in production systems, climate and landscape challenges. Furthermore, additional differences in the implementation of the content have occurred at each intake due to changes in personnel delivering the program.

The commitment to practice change demonstrated by the survey results of the ITDM program suggests that when pastoralists are coached through the tools and knowledge to tactically manage their pastures, significant capacity building improvements can be observed. Therefore, the integration of monitoring tools, such as condition scoring, feed budgeting, and remote sensing technology, with increased understanding of grazing management principles enables pastoralists to be more confident in making informed, tactical decisions that align with environmental conditions. Although the program successfully built participants' capacity to make data-driven decisions, long-term monitoring and ongoing support are essential to ensure that these new practices are maintained and refined over time. Furthermore, while the integration of remote sensing technology has been beneficial, it requires pastoralists to have adequate technological ability and appropriate training to operate independently, which may present challenges for some participants beyond the program.

Conclusion

The Improving Tactical Decision Making program has proven to be an effective tool for enhancing grazing management and resource allocation confidence in three groups of pastoralists in the NSW rangelands. As climate variability continues to impact the productivity of rangelands, adaptive management strategies like those taught in the ITDM program will be increasingly important for the long-term viability of arid and semi-arid grazing systems. The success of this program to date highlights the value of providing pastoralists with the knowledge, skills, and tools necessary to make informed decisions and adapt to changing conditions. Through continued support and innovation, the program has the potential to make a significant contribution to sustainable grazing management in the western NSW pastoral zone.

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Fenceless grazing

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Key words: Livestock; Grazing; Regenerating Agriculture

Abstract

Whilst it should be a given that livestock handling and instinctive behavior is a primary skill taught to every apprentice stock-handler, the fact remains that many animals never achieve their full production potential due to poor juvenile imprinting and mishandling by humans. This human/animal interaction and primary contact that carries throughout the lives of both can strongly influence animal impact on rangelands.

Roaming livestock that are contained by random fences, or limited by their walking distance to water, can have a significant impact on soil structure, surface water quality, perennial plant root survival and leaf regeneration. These and other degradations do little to endear livestock to ecologists and with little to no management of grazing practices in vast areas of the planet's grasslands, may see the forced disappearance of introduced livestock from our ecosystems.

Yet, what if we could accurately manage productive, carbon-sequestering grasslands through training humans to teach livestock to graze better? This remains my quest as a teacher of farmers.

Introduction

I have come to understand how easily we can 'park' or place animals in specifically suitable areas of the range through Low Stress Stock Handling training and the study of human/livestock communication. The specific movements that the handler should perform to train livestock to herd in this manner through body language are complex, and the associated skills are advanced yet, once understood, easily replicated.

Methods

Within the training of livestock to 'park', we aim to encourage the herd to move and stop responsively, then take all of the movement out of them for a given time. As the herd becomes superbly trusting and disciplined, the shepherd will need to pay intense attention to the available feed and move the animals accordingly. Individual animals that are troubled by humans will need extra work or possibly be culled from the herd.

The movements and body language conveyed to the herd or mob by the shepherd, work with the training of Low Stress Stockhandling instinctive behaviors, namely that –

1) Animals generally move in the direction they are facing
2) Herding animals mostly want to follow other animals

3) Animals strongly want to keep an eye on that which is pressuring them
4) Animals will do what they can to have pressure released

Combining these instincts with a principle of animal movement that parallel movement with the animal whilst in the forward section of one or both of its eyes will tend to slow it down or stop it, enabling communication to neutralize forward movement. This will ultimately stop the leaders of a herd or mob from grazing and wandering beyond the pasture or range upon which they are being 'parked.' To start the movement up again, the shepherd must re-form the herd or mob from its leadership to its tail animals and gently drive them away from the pressure.

Results

10 Meaningful Outcomes of Training Livestock to 'Park'

1. Significant reduction in overgrazing of edible plants
2. Elevated graziers ability to select areas for grazing and nutrient defecation
3. Increased on-Range decision making to avoid grazing-sensitive regions and areas
4. More specific control of animal traffic and camps on riparian zones
5. Improved and impactful grazing pressure on higher and steeper Range areas
6. Significantly reduced waste deposition in waterways
7. Improved animal production gains due to less herd movement
8. Targeted nutrient movement and dispersal uphill from water sources
9. Enacting time-controlled grazing plans for livestock
10. Herds that require less pressure to move or control

Implications

Evolution has determined that herding animals are a protein and energy source for their carnivorous predators. In the absence of these predators, most herds, great and small, rapidly become sedentary. This is extraordinarily detrimental to water points and riparian zones that were historically the domain of the predator and at which prey animals drank quickly and left, not lying around like a hotel poolside.

Historically, a balance of vegetative cover was maintained by not overgrazing due to the herds being moved on by the predators. There are thousands of hectares of degraded landscapes across the rangelands due to soil salinity escalation from the baring out of vegetation by herding animals.

Yet, if herding animals can learn to trust their handlers or shepherds' decision-making that there will always be continual adequate feed and water provided, their demeanor will change positively by reverting to a psychology that is controlled by instinct but without predatory pressure. Thus, they can be trained to spend their non-drinking time well away from vulnerable waterways and riparian zones. These grasslands on the range have added benefits of providing a wider diversity of edible and non-edible plant species, open visibility to provide safer loafing pastures, more relaxed and complete rumination time and thus feed conversion and less competition from other herds or mobs.

Conclusions

Ultimately, heavy-handed laws may be enacted to control and restrict grazing pressure on rangelands. These would unlikely be as effective as the motivation of the shepherd, herdsman or farmer to maintain their livestock in a positive plane of nutrition whilst simultaneously regenerating their rangelands.

If it is possible to regain the skills, knowledge and experiences of the shepherds of 1925 and earlier, grazing livestock with the capacity to remain where 'parked' would certainly become best practice for the modern grazier.

Groundcover, biodiversity, soil health and functional water cycle are all indicators of rangeland health. Whilst many of these regions are designated National Parks or Conservation areas, those that are managed by grazing livestock can also be maintained with these indicators functional.

By understanding and practicing these methods of 'parking' animals, as well as effective shepherding, it is possible to decommission infrastructure such as fences on the rangelands and at the same time, regeneratively manage vast areas of the planets grass and shrublands.

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‘Care’ of country: Grazing management and sense of place

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Key words: production; ‘spelling’; landscape; stewardship; attachment

Abstract

In the semi-arid rangelands of southern Australia livestock producers must balance livestock production with landscape function to achieve business resilience. Under highly variable climatic conditions, their approach to grazing management is a key element in achieving production and landscape targets. At the same time, the socio-economic environment is difficult as they typically live on very large, isolated properties subject to a highly variable climate and financial volatility. We conducted semi-structured interviews with six producers, three operating in a ‘well-functioning’ landscape and three in a ‘recovering’ landscape, to provide a detailed description of their approach to grazing management and explore the perceived production, biophysical and personal benefits derived from their grazing practices. Producers in a well-functioning landscape focussed on animal and plant performance, prioritising the management of productive/palatable forage species, implementing extended rest periods for regeneration while managing stock numbers conservatively. In a recovering landscape, producers primarily focussed on improving landscape function with enterprise type and animal production adjusted to support regeneration. These producers place emphasis on the seedling growth of valued species, encourage the growth and expansion of perennial species and adjusting livestock number to match carrying capacity as the country improves. A key personal benefit is a sense of accomplishment from ‘care’ of country demonstrated by producer ‘attentiveness, responsiveness, and adaptation’ in their grazing management practices. In addition, producers often expressed an emotional connection with country: *“my mental health is very attuned to the health of the land”* and *“I really want to heal the land”*. Our work reveals a positive feedback loop between environmental stewardship and personal well-being.

Introduction

Livestock producers in the semi-arid rangelands of southern Australia need to be particularly attuned to the natural environment to balance livestock production while maintaining or improving landscape function to support profitable and sustainable enterprises. Operating under highly variable climatic conditions including frequent periods of drought, producer approaches to grazing management are critical to achieving landscape and production targets. Key elements of management in these grazing enterprises include, for example, managing the carrying capacity (i.e. matching livestock numbers to available feed), implementing strategic rest from grazing to preserve/increase desirable, productive forage species and to maintain/enhance ground cover (Hacker and McDonald 2021).

The socio-economic environment in which producers operate is also complex and dynamic. They typically live on very large (>10,000 ha), isolated family run properties subject to high inter-annual financial volatility reflecting fluctuating seasonal conditions and commodity prices (Sinclair et al. 2019). Nevertheless, these properties are more than places of economic dependence, they enable a distinctive way of life in which the natural environment is often valued for its 'vastness and openness imbued with significant meanings' (Holmes and Day 1995, Masterson et al 2017). These meanings frequently lead individuals to acquire an affective attachment to the land they manage (Mullendore et al. 2011).

In this paper we describe the different approaches to grazing management used in the semi-arid rangelands of southern Australia. We provide insights into these producers' perceptions of the production, biophysical, and social co-benefits derived from their grazing practices. The paper will contribute to an improved understanding from a producer's perspective of how the different grazing systems affect productivity, resource condition and profitability in semi-arid rangeland livestock production systems.

Methods

Semi-structured interviews were conducted with six producers purposively selected based on the status of their country and were drawn from a list provided by an informant with extensive experience working across the Western Division of New South Wales (NSW), Australia. Three producers (known as Producers 1, 3 and 5) operated more in a 'well-functioning' landscape whereas the other three producers (known as Producers 2, 4 and 6) operated in a 'recovering' landscape progressing to a better state. A 'well-functioning' landscape is viewed as one in which the biophysical system is functionally sound (with soil, water and nutrients retained on-site). A 'recovering' landscape is viewed as one that has been mismanaged in the past but now the function of the biophysical system is improving over time with management (with soil, water and nutrients increasingly retained on-site) (Tongway and Hindley 2005).

An interview schedule was designed around broad questions but with prompts to ensure the relevant data was collected. Firstly, background information was collected including a description of the enterprise (e.g. livestock type, herd/flock size, markets targeted) and the property (e.g. size, soil type, vegetation). This was followed by a broad discussion around the grazing management system (e.g. stocking rate, grazing practice, stock movement, mob numbers); management objectives (e.g. production and resource targets); and factors influencing the approach taken (e.g. physical, market). Finally, a discussion centred on the benefits from the grazing management system including both biophysical (e.g. landscape changes) and personal (e.g. wealth creation, lifestyle, well-being).

The interviews were conducted by telephone between July 2022 and February 2023 and with the permission of the interviewees the interviews were recorded digitally. The interviews were transcribed 'intelligent' verbatim by a private transcription service and are the principal source of data used in this paper. The median time taken for an interview was approximately 90 minutes with a typical word count around 12,000 words. The transcription data were examined and categorised around responding to the interview topics.

Key findings

All producer interviewees practiced rotational grazing in paddocks that had been previously subdivided apart from Producer 5 who set stocked large paddocks with extended rest periods. Livestock were run as single or multiple mobs according to producer preference. Merino or Dorper ewes were the core enterprise with most properties harvesting managed or unmanaged goats. The overarching management objective for producers: *"We just want to keep our grazing numbers at an appropriate level that can balance production and the natural environment"*

(Producer 3). There were, however, differences in management focus reflecting the status of the country they manage as explained below.

Well-functioning landscape producers

The primary focus of well-functioning landscape producers was to maintain and opportunistically improve healthy and diverse country allowing them to concentrate on achieving the highest quality feed practicable and to set high animal production targets. Producer 5 summed up the approach to their business:

"… trying to regenerate some land and maintain the better country as it is which, in turn, means we can have all year-round production and be able to turn off a large number of finished lambs from a small number of breeders."

The approach is underpinned by three core grazing management principles: maintain a consistent, conservative livestock number, foster productive, palatable plant species and implement flexible rest periods as this group of producers explained:

"The nature of the seasons out here is that when it's good, it's so good. … it's important to have the breeding stock at the right numbers so you can capitalise on that from an economic perspective, but also having the number set so if the season does dry off, you're still not rushing to sell a heap of stock off."

"We watch certain species like … bladder saltbush. Once the animals start to graze them the alarm bells start to ring. … It's a fairly unforgiving species … because if you graze too hard you've got to start from scratch again."

"So, any country that needs a spell to regenerate bush we can give the country … six months or one or two years off or whatever we think it needs."

The grazing strategy employed ensures ground cover is at least maintained, if not improved, enabling the country to withstand frequent and severe droughts minimising any soil loss from erosion.

Recovering landscape producers

The focus of recovering landscape producers was primarily on progressively improving landscape function and the role of livestock was to support achieving landscape goals. Initially when these producers acquired the property, they made substantial production trade-offs but overtime as their management gradually improved the landscape, they made less production trade-offs and had more enterprise options available, for example, moving from agisting cattle to a self-replacing Merino flock. The typical business approach for these producers:

"What drives our business here is … call it a goal what we want our landscape to look like … which determines most of our actions. As in our stock [numbers] … have got to be in balance with the land" (Producer 2).

The approach is underpinned by three core management principles: foster the seedling growth of valued species, encourage the growth and expansion of perennial species and adjust stock numbers to match carrying capacity. As these producers explained:

"Where we have potential [for] a lot of new seedlings of desired species coming on … our grazing [duration] would certainly be much shorter … particularly the seedlings that are coming away [i.e. recently emerged]."

"We've got to monitor and know how much distance there is between our perennial plants. So, we do monitor … at least annually. After a year's grazing [we know] we are actually improving the volume of perennial plants."

"The recovery of the most severely grazed perennial plant is the key to when you move them [livestock] and how long before you can come back."

The grazing strategy enables renewal of country with a change to more desirable species, a re-establishing of existing plants, an improvement in soil health and a *"better"* ground cover. But as Producer 2 cautioned: "*These rangelands out here are very fragile. One good year of work can be undone and can set you back 10 years of progress by getting one year wrong"*.

Personal benefits

Producers identified a mix of economic, environmental and social benefits attached to their grazing management and property. Producers expressed a sense of accomplishment from their 'care' of country as demonstrated by their 'attentiveness, responsiveness and adaptation' (Dreyfus and Dreyfus 1986 cited in Krzywoszynska 2015) in their grazing management practice: *"how we run our business ... it's in our best interest to take care of our landscape. That's very important to us."* and from building a viable, resilient business in a "*very reliably unreliable location"*. It provides a satisfying way of life: *"a beautiful place to live. And you get to see a huge variety of seasons. And you watch the weather every day. It is a great and exciting place to live and work."*

Producers described the connection between the status of country and personal well-being. "I didn't realise it, but my mental health is very attuned to the health of the land. … So, when the country's doing well, I'm doing well." Another important factor … is actually having land, which is in the condition it's in, because that makes life a lot easier. We're so fortunate to have a … pretty healthy environment". Country is viewed as something producers can nurture and restore back to health: "I really want to heal the land … I do admire the way we're doing it".

Discussion and conclusion

A key limitation of this study is that only six rangeland producers from across the Western Division of NSW were interviewed and there is no suggestion that these findings are reflective of the industry. Rather it provides some insights into how producers manage their livestock operation under differing landscape conditions and the co-benefits they believe they receive.

The producers interviewed considered land condition, the quality of the forage base and animal requirements in developing their grazing management strategy. Irrespective of whether producers operated in a well-functioning or recovering landscape, they practised a system of rotational grazing and prioritised the management of native pasture species reflective of the 'tactical' approach recommended by Campbell and Hacker (2000) as 'best practice'. However, there were differences between producers in their management objectives, and this depended on the productive capacity of the land in setting production and landscape targets.

Despite the property size, these producers possessed an intimate knowledge and understanding of the natural environment, its complexities and frailties. This study provides insights into how they use their grazing to maintain or build ecological resilience, in so doing demonstrating their environmental stewardship (Rajala et al.).

Producers revealed a strong connection to their land as evidenced by the positive emotions they expressed about it. To an extent this connectiveness bestows these producers with a personal resilience compensating for the difficulties they may face working and living in a challenging environment on which they depend for their livelihood.

This study provides policymakers with an understanding of how some rangeland producers are balancing production and landscape function for long-term viability. Irrespective of whether they operate in a well-functioning or a recovering landscape, producers interviewed were not prepared to compromise resource condition over production.

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Cattle walk further than 3 km from water in central Australia, but only if they have to!

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Key words: carrying capacity; grazing behaviour; rangeland management; research adoption

Abstract
In arid central Australia pastoral leases are very large (2000–5000 km^2), with large paddock sizes (200–500 km^2), are often poorly developed with few waters, and some stations remain largely unfenced. Although cattle spend most of their time within 4 km of water, it is not uncommon for more than 50% of station area to be beyond 4 km from water. This has consequences for carrying capacity and utilisation of central Australian stations. If paddocks are stocked to total area rather than watered area, this can lead to high pasture utilisation within 4 km of water and low animal performance. Cattle landscape use was investigated in the Paddock Challenge project (Materne *et al.* 2025) to help inform producers about future development options and to test current carrying capacity methodology assumptions. The study used GPS collars to track the location of 280 cattle in nine paddocks on four stations. In this paper we examined the locational data to see how water location influenced cattle landscape use. The data can be used to identify future infrastructure investment and adjustment of stocking rates to optimise landscape use, and cattle performance and production. Cattle spent about 70% of their time within 3 km of water and 90% of their time within 4 km, but this depended on pasture utilisation. The higher the pasture utilisation, the further cattle walked from water. This is consistent with the current Northern Territory (NT) long-term carrying capacity (LTCC) methodology, which assumes cattle use all the area within 3 km and half the area between 3 and 5 km. Information about cattle landscape use was used by producers to inform management and development decisions. The results highlight new opportunities for improving cattle management and addressing environmental, production, and economic goals on Central Australia's commercial cattle stations. The locational data will be further analysed to look at the effect of land type, fire, rainfall and seasons on landscape use and link landscape use to animal performance.

Introduction

Arid rangelands in central Australia, with large pastoral leases and paddocks, often face significant infrastructure limitations. Water points are a large factor influencing cattle distribution and forage utilisation in northern Australian rangelands (Hodder and Low 1978; Tomkins *et al.* 2009). As a result, an estimate of watered area needs to be factored into the assessment of safe utilisation rates on extensive properties (Walsh and Cowley 2011). In central Australia, a 5-km grazing radius was recommended to capture most grazing pressure (Squires 1981), but Hodder and Low (1978) found cattle typically grazed within 3 to 4 km of water in good seasons and up to 8 km in drier years. In the Barkly region, while cattle can range up to 11 km from water during the late dry season, 80–90% of their activity occurs within 5 km, and 65% of that is within 3 km (Fisher 2001; Cowley *et al.* 2020).

Current NT LTCC methodology assumes the majority of grazing occurs within 5 km of a watering point, most of which occurs within 3 km (Cowley and Walsh 2023). This has been reduced from 8 km (Bastin and Shaw 1988) and 5 km (Chilcott 2005) previously used in the region. The assumed watered area has a large impact on a station's estimated carrying capacity. The Paddock Challenge was a federally funded project aimed at evaluating the profitability of applying recommended carrying capacity on two pastoral properties in Central Australia. As part of the Paddock Challenge project, landscape use was monitored by GPS collars to provide local data to test the watered area assumptions of the carrying capacity methodology used in central Australia (Materne *et al*. 2025).

Table 1. Summary of cattle numbers fitted with a GNSS collar. * Very large unfenced area

Station	Paddock/ Watered area	Paddock area (km^2)	Watered area (km^2)	% >5km	No. of waters	Cattle class	n	Date
MGP	Brice's	239	65	45	2	Breeder	20	04/2023–05/2024
	Mary's	303	118	44	3	Breeder	20	05/2023–05/2024
	No.1	64	44	6	1	Breeder	20	05/2023–05/2024
LDV	Night	2960	754	40	31	Breeder	20	09/2023–05/2024
MDS	8- & 18-Mile	unfenced	238	*	10	Breeder	40	04/2023–08/2023
	8- & 18-Mile	unfenced	238	*	10	Steer	40	04/2023–08/2023
OMP	4 Pdk Rotation	195	78	35	2	Breeder	20	07/2023–12/2023
	4 Pdk Rotation	195	78	35	2	Steer	20	07/2023–12/2023
	Waterhouse	91	25	49	1	Breeder	20	09/2023–03/2024
	Waterhouse	91	25	49	1	Steer	20	09/2023–03/2024
	South Stuart	26	21	1	1	Steer	20	12/2023–04/2024
	North Stuart	20	11	22	1	Steer	20	12/2023–04/2024

Methods

Cattle landscape use was tracked with Global Navigation Satellite System (GNSS) collars. Three hundred GNSS collars were deployed across four stations and nine paddocks, between July 2023 and May 2024. Each paddock contained 20 collared animals per class, providing tracking data every 10 minutes (Table 1). Each collar was swapped approximately every 4 months depending on stations' planned activities. Data within 100–150 m of a waterpoint was excluded from the analysed data to remove the records of cattle camping at waters. GNSS data was processed using QGIS and Python scripting for spatial analysis and pattern identification, with data points filtered based on distance from water. Pasture utilisation (the percent of annual pasture growth eaten by livestock) was modelled in paddocks following Cowley and Walsh (2023) assuming cattle grazed within the watered area, defined as all the area within 3 km and half the area within 3 to 5 km. Where modelled data was not available, pasture utilisation was estimated based on previous years modelled data on the Old Man Plains Research station (OMP) and knowledge of current stocking rates and percentile pasture growth.

Results

All stations experienced well above average rainfall (80th percentile class) and pasture growth prior to the deployment of the GNSS collars (2022/23). Mt Denison (MDS) and OMP recorded a further above average season in 2023/24 in the 75th percentile class while Mulga Park (MGP) and Lyndavale (LDV) only recorded average conditions in the 50th percentile class. Data duration varied between collars due to battery life and retention. Not all deployed collars were retrieved on all dates, hence the range in number of collars given in Table 2. Cattle predominantly spent time within 4 km of water, despite significant areas of the paddocks being further than 5 km from a water source.

Utilisation rate influenced time spent with distance from water. With low pasture utilisation rates (5–15%) cattle generally spent greater than or equal to 70% of their time within 3 km from water, and 90% within 4 km, while paddocks with medium to high utilisation (>15%) only spent 45–50% of their time within 3 km of water and up to 28% of their time further than 5 km from water (Table 2). The exception to this was Mary's Paddock on Mulga Park where cattle spent time in the far northern side of the paddock greater than 5 km from water, even with low utilisation rates, perhaps due to localised storm activity. Landscape use with distance from water did not vary with cattle class or coat colour.

Discussion

Producers in the Paddock Challenge used information on how cattle were using the paddocks to inform future water development. In the NT, LTCC is calculated by:

Median Pasture Growth × Utilisation Rate / Demand × Watered Area (100% within 3 km + 50% within 3–5 km).

Cattle landscape use with distance from water in these central Australian paddocks is consistent with the watered area assumptions of this methodology and is consistent with findings on the Barkly in an extensive Mitchell grass paddock, where the number of cattle per waterpoint was the most reliable indicator of grazing distance from water (Cowley *et al*. 2020). Higher utilisation rates are associated with poorer animal performance due to decreased diet quality and quantity (Ash and Stafford Smith 1996). Stocking to the LTCC by watered area will help to ensure adequate feed is available within their preferred 0–4 km grazing range and potentially improve animal performance and productivity. Here we found that cattle walked further with higher utilisation rates, which suggests cattle were walking further from water to meet their nutritional requirements. Walking further distances will incur an additional energy cost which could further reduce animal performance.

Table 2. Summary of time spent in relation to distance from water. * Estimate

Station	Paddock/ Watered area	Class	*N* range	Pasture utilisation (%)	Time (%) Distance from water <3 km	3–4 km	4–5 km	>5 km
MGP	Brice’s	Breeder	n = 8-1	5-10	73.2	11.6	6.4	8.8
	Mary’s	Breeder	n =11-1	5-10	56.6	13.9	4.4	25.1
	No. 1	Breeder	n =11-1	5-10	78.7	13.9	5.2	2.2
LDV	Night	Breeder-black coat	n = 7-3	5-10*	83.0	13.7	2.9	0.4
	Night	Breeder-white coat	n = 9-1	5-10*	85.6	11.6	2.1	0.7
MDS	8 & 18-Mile	Breeder	n =36-12	25-40	50.7	11.9	9.8	27.7
	8 & 18-Mile	Steer	n =17-14	25-40	50.3	13.4	9.2	27.1
OMP	4 Pad Rot.	Breeder	n =15-10	5-15*	70.2	8.8	9.6	11.4
	4 Pad Rot.	Steer	n =20-11	5-15*	74.8	9.3	6.9	9.0
	Waterhouse	Breeder	n =18-3	5-15*	69.5	16.7	10.9	2.9
	Waterhouse	Steer	n =20-3	5-15*	67.9	17.6	11.6	2.9
	Stuart South	Steer	n =18-3	5-15*	87.3	12.0	0.5	0.2
	Stuart North	Steer	n =16-3	15-30*	44.6	32.5	13.8	9.1

Paddock size will influence how cattle use the landscape. In the small 26-km^2 South Stuart paddock only 1% was beyond 5 km from water, which obviously limited use beyond 5 km. However, the pattern of paddock use was very similar to that observed in the massive 2960-km^2 Night paddock with 40% of the total area beyond 5 km from water. Both paddocks had low estimated pasture utilisation, and in both paddocks, time spent within 3 km from water was more than 80% and beyond 5 km less than 1%.

Although pregnant cows’ increased water needs during late gestation leads them to visit water points more frequently (Creamer and Horback 2024), steers did not travel further from water than breeders, regardless of pasture utilisation levels, or whether over the cooler (MDS) or hotter (OMP) months. Similarly light-coated cattle are more heat adapted than dark-coated cattle (Barendse 2017), which could potentially influence time spent with distance from water. However, breeder time spent with distance from water on Lyndavale did not vary between coat shades. It is possible that heat stress was not an issue when data was collected, although it did include data during spring and summer.

In this study we estimated pasture utilisation for some locations, but we intend to model pasture utilisation for these sites in the future. Additionally, factors such as land type, fire, rainfall, and seasons and using the speed animals were travelling to distinguish between cattle grazing, walking, and resting will be examined, as well as linking landscape use to animal performance. Although this study was based on relatively small numbers of cattle, they represent real commercial enterprises. It provided an invaluable demonstration to producers of how their cattle are actually using the landscape, opening up discussion on current management practices and planning future developments.

Conclusion

Data from the Paddock Challenge project provided insights into cattle movement patterns, highlighting that despite large paddock sizes, cattle class or coat colour, if stocked to the LTCC, cattle often used only a fraction of the available grazing land beyond 4 km. The influence of water and land type on grazing patterns warrants further exploration, particularly in relation to stocking rates and carrying capacity over different seasons. Investing in water infrastructure to better distribute grazing could reduce pasture utilisation and enhance animal performance and production in poorly watered areas.

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Livestock intensification

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Cushioning pastoralist against the effects of drought: The case of beef feedlotting and rangeland restoration

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Key words: Feedlotting; Rangelands; Pastoralism; beef; Bottom-Up Economic Transformation Agenda.

Abstract

The beef industry in Kenya is the largest contributor to livestock value added products as well as a major contributor to income and employment. Its contribution to societal welfare is particularly relevant in the rangelands, where beef production is the main economic activity. The four major beef production systems in Kenya are pastoralism, ranching, agro-pastoralism systems, and feedlots (FAO, 2017). Feedlotting is one of the initiatives, being promoted through the Bottom-Up Economic Transformation Agenda (BETA) to cushion the pastoralists from perennial livestock losses, avail sufficient feeds and water, and access high-end and export markets for both live animals and meat. Currently the feedlot system is under-developed and faces challenges that affect returns; lack of stratification of production, high capital investment and low technical skills in feedlot management, limited availability of suitable feed due to competition for grains and long finishing times of up to 12 months in feedlots with poor productivity. The success of the BETA agenda will contribute to increased productivity, reduced livestock losses, increased incomes, and restored rangelands. At least 450 feedlots are to be established, one in each identified ward, to support at least 10 cooperatives, create employment for livestock extensionists/advisors/service providers and entrepreneurs in the value chain using the best technologies and innovations. Pastoralists will have guaranteed market for their livestock and the reduced stocking pressure will facilitate recovery of rangelands.

Introduction

Globally, rangelands are considered to be the world's largest ecosystem biome with high biodiversity and socio-economic and cultural value (Bengtsson et al. 2019). Rangelands cover over 54% of the world's terrestrial surface (Rangelands Atlas 2024) and support over 30% of world's human population (Sala et al. 2017). Locally, the Arid and Semi-Arid Lands (ASALs) cover 80% 89% of Kenya's landmass (Birch 2018), accounting for 30-out of a total of 47 counties, with these areas mainly defined by their levels of aridity, consistently high ambient temperatures, and low rainfall that has high spatial and temporal variation of 200 to 750 mm annually (Pratt and Gwynne 1977; Heady 2019). Vegetation of the ASAL areas is made up grasslands, wooded grasslands and shrub/woodlands (Nyongesa et al 2023).

Estimates show that the ASAL areas hold approximately 16 million people, which is about 30% of national population (Njoka et al 2016). The climate and vegetation type has for centuries supported pastoralism as the main livelihood (Nyariki and Amwata 2019). While traditionally pastoralism was classified as a livelihood type where majority of the people derive more than 50% of the livelihoods from livestock (Dong 2016), we adopt a much broader definition that embraces a landscape and systems approach (Plieninger et al 2023). This is because of the many goods and services that are provided by pastoralism and its landscape that have often been overlooked, namely fish, tourism, inputs in agriculture, recreation, environmental, support and regulatory services.

Recent estimates quantified the value of the pastoral sector to have an economic worth of US$1.13 billion (Nyariki & Amwata 2019) with the livestock sector and non-livestock sector accounting for 92% (US$1.04 billion) and 8% (US$0.0903 billion) respectively. The livestock sub-sector, which is the mainstay of the ASALs contributes 10% of the GDP (KNBS 2023), and employs more than 50% of the ASAL based workforce (AECF 2020).

Despite their demonstrated and strategic importance to Kenya's economy and overall development, the ASALs face several challenges limiting their potential and contribution to national development. The ASAL areas are prone to droughts, which have become more frequent and intense in the last 15 years (Haile 2019). They are also very susceptible to the vagaries of climate change (SEI 2023); aside from droughts and low rainfall, these include floods, livestock disease outbreaks, attacks by invasive species, and even locusts.

Before the advent of the devolved government (Odhiambo 2013) ASAL areas received minimal national development investments. The ASALs have also attracted increasing human population given their vast spatial coverage on the one hand and increasing population pressure in the more mesic parts of the country. The majority of these people (One future trust 2024 settle down to practice crop production in these marginal lands but often with inappropriate technologies and mindset of the higher potential areas. Vast areas of the ASALs are also degraded (Wavinya 2023) with patches of bare soils, gulleys, hard pans and species (NRT 2023), rendering pasture production and access by livestock impossible. These challenges have negatively impacted the environment and livelihoods in these areas, including massive loss of livestock during droughts (NDMA 2023), floods and disease outbreaks (SEI 2023) e.g. Peste des Petits Ruminants (PPR), East Coast Fever (ECF), Foot and Mouth Disease (FMD), Rift Valley Fever (RVF); degradation of the range and environment, and visible low Human Development Index (HDI). Consequently, literacy levels, sanitation, social amenities are low, while poverty and malnutrition are very high (GoK 2016).

The estimated livestock population of Kenya's ASALs is 16 million beef cattle, 33 million goats, 22 million sheep and 4.4 million camels. With respect to production of beef, Kenya currently produces 244,217 MT as at 2022 (Statista 2024; NIPFN.KNBS 2024) annually, a huge drop from about 589,000 MT in 2017 (Statista 2024). Consumption is estimated at 553,200 MT (FAO 2016; Kenya Market Trust 2020, PETs- BETA 2023) with per capita consumption estimated at 16 kg (Kenya Market Trust 2019). Kenya has an estimated beef production deficit of some 308,983 MT (Kenya Market Trust 2019), a gap that needs to be closed. Currently, the gap is filled informally by livestock from neighbouring Tanzania, Uganda, Ethiopia and Somalia (ibid).

It is against this background that the government through its Bottom-up Economic Transformation Agenda (BETA) developed a Pastoralist feedlot system program to address the challenges.

Methods

Based on the above, we propose a food systems approach that targets the traditional livelihoods of the pastoralists as possible and pragmatic options that can address the challenges in the long run. The proposal is anchored on establishment of pastoralist feedlot systems integrated with measures of improvement in the primary resource base – rangelands, improvements of livestock production and provision of opportunities for diversifying sources of incomes.

The project will be implemented in 450 wards of 31 counties with Arid, Semi-Arid and marginal environments. Each feedlot will be made up of approximately 5,000 acres of land, a water reservoir (dam) of 750,000 to 800,000m^3 capacity, water sources for the surrounding communities (e.g. boreholes).

One feedlot is expected to directly benefit ten villages around each feedlot, with an average of 25 households in a community for about 112,000 Households in total. It is expected that indirect beneficiaries from the program would be five times the number of beneficiaries per feedlot, giving an estimated 562,500 indirect Households as beneficiaries. This brings the total number of all beneficiaries to 674,500 Households that can be extrapolated to an average of 3 million persons. In addition to the direct beneficiaries, the program is projected to create at least 2,700 jobs directly in the feedlots, and a factor of at least 10 (27,000) jobs indirectly linked to the feedlots.

The feedlot systems program has been designed to open up opportunities for MSMEs and further jobs. The projected employment and business opportunities will also encourage children to go to school as the families will now settle and not move from place to place (nomadic lifestyle). The design is heavily reliant on the feedlots accessing livestock from the neighbouring pastoralist communities. The expectation is that each household will be able to sell at least two heads of cattle per month (24 annually) to the feedlot. The feedlots are expected to intensively fatten and finish the livestock with natural grass over a target three-month period (more realistically six months initially). The feedlots can sell finished livestock as live animals or slaughter and sell as carcasses. Whichever option, it is expected that the feedlot will share a portion of the profits as bonus payments to the supplier communities.

Secondly, the feedlot system will strive to enhance rangeland improvement outside the feedlots, directly targeting the neighbouring pastoralist grazing areas. This will be a collaboration with the local communities in a participatory manner in order to secure the targeted area for rehabilitation. For a start, the program will target about 20,000 acres of pastoral land through the in-situ soil and water conservation method, using the Vallerani system that has already been tried and tested. The Vallerani System (VS) is a mechanized system that combines traditional water harvesting techniques and the mechanization of micro-basins, for the restoration of large-scale degraded soils, which can be applied for reforestation, pasture improvement, crops, windbreaks, etc (Vallerani System EN | Vallerani System). Other rangeland rehabilitation techniques including bush clearing, scratching and in extreme cases, reseeding will be applied to enhance rangeland pasture and forage production and productivity.

To increase feedlot production and productivity, the program will target the improvement of pastoralists livestock genetics, through a participatory breeding program and a comprehensive livestock disease surveillance and management program. Because of the prevalent droughts where water and pasture become inadequate, each feedlot will have a portion of the land dedicated to pastoralist resilience. The feedlots will produce forages and sell these to the pastoralists during periods of scarcity. A key feature underpinning the program design is ensuring investments have quantifiable and positive returns on investments. It is proposed that the feedlots be run as a profitable venture, even while involving participation of the local communities. The program will provide options and guidance for effective management of the feedlots.

Results/Progress

Three Counties already have the feedlot infrastructure in place and are at different levels of implementation with more counties committing resources to fence off the initial 5,000 acres identified with the community. It is expected that once the first three take off the rest will be motivated to fast track their implementation

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Sustainable intensification of grazing operations using targeted supplementation

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Key words: Grazing steers, Supplementation, Bermudagrass, Native Range, Finishing

Abstract

These projects were conducted in the subhumid rangelands (Klemme Research Range [KLEMME]) and on introduced forages Oklahoma (Eastern Research Station [ERS]) USA. Targeted supplementation to increase performance of growing cattle, maximise production per hectare, and replace synthetic fertiliser on pasture. Treatments at Klemme included: 1) Positive Control (PC)– 1 kg daily supplementation with distiller's grains (DDGS) cubes in late summer, or 2) High Supplement (HS) - DDGS cubes offered at 0.75% of liveweight all summer with 33% increase stocking rate. Treatments at ERS included: 1) Fertilized Control (FC) - no supplementation on N fertilized pastures; 2) Fertilized Supplement (FS) – steers fed 1.2 kg/day supplemental DDG cubes on N fertilized pastures throughout the summer; or 3) High Supplement (HS) – steers supplemented DDG cubes at 0.75% of BW/d on unfertilized pastures.. The HS treatment increased LW gain/ha by 89% compared with PC at KLEMME and increased steer performance while replacing synthetic N inputs in FC and FS treatments at ERS. At KLEMME, calculated N use efficiency, N2O emissions, methane emissions, total CO2 equivalent emissions and CO2 equivalent emission intensity (kg/kg LWG) were decreased in HS. At ERS calculated N use efficiency, N2O emissions, total methane emissions total CO2 equivalent emissions and CO2 emission intensity were intermediate for HS, but CO2 equivalent emission intensity was improved. Performance of steers followed through finishing on high-concentrate diets were not affected by previous supplementation treatment during grazing and increased gains prefinishing resulted in similar carcass weights with decreased days on feed and 15% less total feed required for finishing without impacting carcass quality. Targeted supplementation has the potential to increase performance in intensified grazing systems, increase beef production per hectare, and reduce grazed forage and harvested feeds with the potential to reduce the overall environmental impact of beef production.

Introduction

Producers are under significant economic pressures to maximize production per acre, which can prove harmful to the range condition, when desired forage species are overgrazed and decline in the stand. Feeding high levels of supplemental feed based on corn co-products of the ethanol production industry can offset forage consumption by 0.5 to 0.55 kg per kg supplemented in grazing calves (Adams et al., 2022a) and lead to higher stocking rates, without reductions in forage mass and animal performance (Wallis et al., 2023).

Research examining subsequent feedlot performance and carcass quality as affected by stocker supplementation programs continues to be limited and generally inconsistent (Reuter and Beck, 2013). A novel extruded dried distillers grains (DDG) cube (MasterHand Milling, LLC; Lexington, NE) has recently reached the market in the Great Plains states, expanding the potential utility in feeding these byproducts without feedbunks and losses to wind. Therefore this project is proposed to investigate the impacts of DDG cube supplementation and increased stocking rates on performance, sustainability, and subsequent finishing performance of growing steers grazing native range in western Oklahoma (Klemme Research Range, Besse Ok; KLEMME) with comparison to similar projects conducted at the Eastern Research Station near Haskell OK, which is composed primarily of bermudagrass based pastures (ERS).

Methods

Klemme Range Research Station

Grazing trial was conducted Marvin Klemme Range Research Station (Klemme), near Bessie, Oklahoma (35°25’00.4” N, 99°03’42.6” W). This site is characterized by rolling Red Shale uplands (2 – 15% slopes) dissected by deep drainages with shallow Cordell silty clay loam soils, which are shallow (25 to 36 cm) and contain numerous rocky outcrops of hard red siltstone. These Red Shale sites support mixed-grass prairie as the potential climax natural vegetation (Gillen et al., 2000). The steers grazed for 130 days from mid May to early October each year and were follwed through finishing in a commercial feedlot.

In each year, 140 steers (BW = 240 ± 21 kg in yr 1 and 255 ± 19 kg in yr 2) were randomly allocated to the 6 pastures. Pastures were allocated to 2 supplementation treatments (n = 3 pastures/treatment), 1) Positive Control (PC) - steers were stocked at 2.4 ha/steer and provided with 2.26 kg of supplemental DDGS cubes on alternate days (daily supplementation rate of 1.13 kg/steer) only during the late summer; and 2) High Supplement (HS) – stocking rate of steers were increased by 33% (1.6 ha/steer) with supplemental DDGS cubes provided at a rate of 0.75% BW/d for the entire grazing season.

Eastern Research Station

Grazing trial was conducted at the ERS station in eastern Oklahoma, the methods and results of the grazing experiment are reported in Adams et al. (2022b). Briefly, each year, crossbred steers (n = 140) were assigned to pastures, and pastures were assigned to one of three treatments (n = 3 pastures/treatment); 1) Fertilized Control (FC) - steers grazed N fertilised pastures (112 kg N/ha) with no supplementation; 2) Positive Control (PC) – steers were supplemented DDG cubes at 1.2 kg/d prorated for 3-d/wk feeding on N fertilized pastures; or 3) High Supplement (HS) – steers were supplemented DDG cubes at 0.75% of BW/d prorated for 5-d/wk feeding on unfertilized pastures.

Subsequent Finishing

Following summer grazing at KLEMME and ERS, steers were transported to a commercial finishing operation (Buffalo Feeders LLC in Buffalo Oklahoma) to evaluate the carryover effects of summer supplementation on finishing performance and efficiency. Because of the size and scale of the pens in the commercial feedlot used for finishing the steers, the steers were comingled across treatments and pastures within the commercial scale pens to remove and confounding effect of pen allocation. Steers were transitioned to high concentrate finishing diets by providing a starter and 2 step-up diets with progressively lower concentrations of roughage for 5 days each with 2 day rations blending between each step. Steers were fed until a targeted 1.5-cm backfat was reached at the 10th rib.

Calculations

Equations from Garrett et al. (2004), Guiroy et al. (2001), and Tedeschi et al. (2004) were used to estimate composition of BW and gain and to allocate individual DM intake (DMI) to steers within pens. This allowed for determination of feed efficiency (G:F), and days on feed required to reach 28% EBF during the finishing period for individual animals. Nutrient retention and greenhouse gas emissions were calculated as well, based on NASEM (2016) and IPCC (2007) equations. Net protein retained in LWG (NPg) and Net Nitrogen (NN, g/day) were used along with estimated N inputs to calculate N use recovery. Enteric methane and emissions were calculated using equations from the Intergovernmental Panel on Climate Change (IPCC, 2006). Methane emission conversion to CO2 equivalents were made using a conversion factor of CH4 $\times 25$ and Nitrous Oxide conversion to CO2 equivalents were made using a conversion factor of N2O $\times EF \times 298$.

Statistical Methods

Performance and calculated greenhouse gas emissions were analyzed for each location separately using the mixed procedure of SAS (SAS Inst. Inc. Cary, NC). The original pasture group was used as the experimental unit in this analysis, due to the comingling of cattle in pens for finishing. The fixed effects in the model included the supplementation treatment on pasture, the year and the year by treatment interaction. The random effect included pasture within each treatment by year. Least-squares means were separated using the predicted differences statement in SAS.

Results

Grazing Performance and Calculated Greenhouse Gas Emissions

At the KLEMME site, steers grazing native range with the HS treatment gained 0.12 kg per day more than PC (0.98 vs 0.87 kg/d, respectively), even though stocking rates of the HS was increased by 33%. This led to a 75% increase in LW gain/ha for HS (84kg/ha) compared with PC (48 kg/ha), which indicates that the increased feeding rate more than offset the reduction in forage availability and reduced grazing selectivity from the increased stocking rate. The increased performance lead to an increase in protein accretion by the steers improving N use efficiency, which reduced calculated N_2O emissions. There was no difference in calculated enteric methane production per steer, but total emissions (kg CO_2 equivalents/steer) and emission intensity (CO_2 Equivalent/kg LW gain) were less for HS than PC, which is related to the increased intensity of production in the HS treatment.

At ERS, supplementing at the high rate increased overall LW gain/d (0.87, 1.10, and 1.16 kg/d for FC, FS, and HS, respectively) and LW gain/ha (360, 458, and 487 kg/ha, respectively), indicating that supplementation rates offset the use of synthetic fertilizer for beef production. Nitrogen use efficiency was greater for FC than FS and HS, which did not differ. N_2O emissions were greater for FS than FC, while HS was intermediate. Calculated ruminal enteric methane production per steer was not different, but similar to N_2O emissions, Total emissions in CO2 equivalent per steer were greater for FS than FC with HS being intermediate. Due to the higher production in HS the emission intensity was lowest for HS compared with FS and FC which did not differ.

Finishing Performance and Calculated Greenhouse Gas Emissions

Steers from HS at the KLEMME range site were 25 kg heavier than PC at entry into the feedlot (393 kg vs 368 kg, respectively). The HS steers maintained this weight advantage by the time steers were reimplanted. Liveweight gain per day (1.5 kg/d) was not different during the finishing period, but Gain:Feed was greater for HS than PC. The lack of performance difference and reduced feed efficiency in PC are indications that there was no compensatory gain from the gain reduction on pasture for the PC steers. There was no difference between treatments in liveweight at harvest, hot carcass weight, backfat thickness or carcass quality, but PC steers took 27 more days to finish than HS (192 days vs 165 days, respectively). There was no difference in N use efficiency during finishing buy N2O emissions, enteric methane and total emissions (CO2 equivalents, kg/steer) were reduced for HS compared with PC. Emission intensity (CO_2 Equivalent/kg LW gain) tended to be less for HS than PC.

Similar to KLEMME, for steers from ERS there was no difference in liveweight at harvest or hot carcass weight, but the FC took more days on finish than FS and HS. Nitrogen use efficiency was highest for FC, but total N2O and methane emissions (and thus Total Emissions, CO_2 equivalent/steer) were greater for FC than FS and HS.

Discussion

Producers in the USA are under pressures to maximize production by increasing stocking rates which can harm range condition and animal performance. A compact and durable DDG cube produced via a novel extrusion process improves utility in pasture supplementation by reducing wind loss and soil mixing, which is common when supplementing loose DDG in pasture settings. Feeding supplemental dried distiller's grains (DDGS) has been shown to offset forage consumption (Adams et al., 2022a) by 0.55 kg for each kg of DDGS cubes fed, which may allow for increasing stocking rates without impacting range condition. This research indicates that stocking rates can effectively be increased on native range pastures in the Southern Great Plains of the USA without reducing individual animal performance, thereby increasing total production per hectare. Replacement of synthetic N fertiliser without impacting pasture carrying capacity while increasing grazing performance is also a boon to sustainable grazing systems in introduced pastures.

Many producers are wary of adding weight gain while grazing steers fearing that additional gain prior to entering the feedlot will adversely affect finishing performance. In the current experiments, there were very little if any indications of compensatory growth in the control calves. The calves fed supplemented at the high rates in both experiments retained the advantages in weight during finishing and required less days on feed to reach the targeted finishing end point.

The increased performance while grazing to offset increased stocking rates (KLEMME) or reduced synthetic fertiliser use (ERS) reduced the environmental impacts of the grazing enterprise and these benefits carried over into the finishing phase of production by reducing feed use, days on feed, and greenhouse gas emissions.

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Intensification of extensive livestock systems using irrigated forages or hay – a bioeconomic modelling approach

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Key words: Northern Australia; regional development; water resources; Victoria River catchment

Abstract
Despite its intuitive appeal, there is very little irrigated hay or forage production in the extensive rangelands of northern Australia used for beef cattle production. There are many reasons for this, including: constraints related to lease tenure conditions; difficulty and expense of obtaining regulatory approval for irrigation development; differing skills and capacity amongst the pastoral workforce; and the economic viability of growing irrigated hay or forage.

Theoretically, the use of irrigated hay or forage production would allow pastoralists (ranchers) more options for marketing cattle: meeting market liveweight specifications for cattle at a younger age; meeting the specifications required for different markets than those typically targeted by cattle enterprises; and providing cattle which meet market specification at a different time of the year. Forages and hay may also allow graziers to implement management strategies, such as early weaning or weaner feeding, which should lead to flow-on benefits throughout the herd, including increased reproductive rates.

We used a bio-economic model (CLEM, Crop Livestock Enterprise Model) to investigate the financial and production implications of growing forages for both hay production and for ‘stand and graze’ systems in the Victoria River catchment of the Northern Territory (NT). Predicated on the average annual utilisation rate of native pasture being kept constant, the use of irrigated hay or forages allowed a higher number of breeder cattle to be maintained. Total income, liveweight gain per animal, and total beef production increased with the use of irrigation. However gross margins were typically higher for the base enterprise, i.e. without irrigation. An analysis of NPV (Net Present Value) which considers the capital cost of development as well as the annual costs, suggested that irrigated forages and hay were only viable when the capital cost of development was low and the price of beef was high.

Introduction
The majority of catchments in northern Australia contain little intensive agricultural development, such as for cropping. Extensive beef cattle grazing (pastoralism) is the dominant agricultural land use and there is very little

development of surface water or groundwater resources, except for domestic use or to supply drinking water for livestock. However, there is recent interest, and research and development, aimed at investigating options to use these water resources more intensively (Moore et al., 2021).

The Victoria River catchment of the NT covers approximately 82,400 km^2 and about 62% is used for pastoralism (Petheram et al., 2024). The majority of property sizes are between 2,000 and 4,000 km^2 (Cowley 2014). Carrying capacity estimates range (depending on range condition) from a maximum of 12.5 to 23.0 AE/km2 (AE = Adult Equivalent, a 450 kg dry cow) on basalt-derived cracking clay soils to a low of 0.5 AE/km^2 on sandy and gravelly soils in poorer condition (Pettit, undated).

The predominant beef production system is a cow-calf operation with sale animals turned off at weights to suit the live export market. About 78% of all cattle across the broader region were Brahman, with about another 17% being Brahman derived (Cowley 2014). The majority of properties surveyed ran between 15,000 and 20,000 head of cattle. The majority of cattle (68%) were bred for live export with 22% bred to be transferred and grown-out elsewhere, often on properties which are part of the same aggregated agricultural business.

Feed quality of native pasture declines in the dry season, and cattle struggle to maintain weight during this period. To counter this, a commonly held view within the northern cattle industry is that the development of water resources would allow irrigated forages and hay to be integrated into existing beef cattle enterprises, thereby improving their production and potentially, their profitability. Ideally, production would increase by allowing cattle to reach minimum selling weight at a younger age and allowing for greater weight gain during the dry season when animals on native pasture alone either lose weight, or gain very little weight. There are also potential benefits to the reproductive capacity of the herd by providing better nutrition to young females. Finally, the addition of forages and hay should allow more cattle to be carried, while still maintaining a constant average utilisation rate of native pastures. However, despite this, there are very few examples across northern Australia of beef enterprises integrating irrigation into the business.

Methods

A bio-economic modelling approach was taken using CLEM (Liedloff et al., 2024). The model is a more sophisticated improvement of an earlier model but retains the core principles of a whole-property dynamic simulation which links feed availability, animal performance, management operations and business performance (Ash et al., 2015).

Simulations included: a base enterprise with no supplemented feed; a base enterprise in which weaners were supplemented with hay bought on the open market (common practice within the industry); stand and graze options for both forage sorghum and lablab and; hay produced on-farm from both forage sorghum and Rhodes grass. Forages or hay were fed to all cattle which were weaned and less than 24 months old during the period from June to October (or June to September for the shorter growing season lablab). Excess hay was sold into the open market. Selling months were May and September/October. All male cattle (not including bulls) were sold once they had reached a minimum liveweight of 280 kg. The bottom 30% of females (as a proportion of normalised weight) were sold at a minimum liveweight of 280 kg while the model dynamically balanced breeder numbers at each sale date with further sales where required. The maximum breeder numbers were set for the period of the model run so as to maintain an average annual utilisation rate of 20% (cattle offtake of native pasture equal to 20% of native pasture growth, averaged across years), as recommended by Walsh and Cowley (2014) and in the Land Condition Guide of Pettit (undated) for clay soils. A limited sensitivity analysis was performed by considering LOW, MED (Medium) and HIGH beef prices. Gross margins, profit (as EBITDA earnings before interest, taxes, depreciation and amortisation) and NPV (net present value, which captures the capital costs required for irrigation development) were considered. The number of breeders on properties in the Victoria catchment is typically higher than the number modelled here, due to large output file sizes from CLEM's individual animal modelling. The herd size (and subsequent results) could be scaled by a factor of around 10 to reflect this (notwithstanding economies of scale in such scaling) but the raw modelled results are presented here. Further detail of the enterprise set-up and modelling assumptions are provided in Webster et al., (2024).

Results

Irrigated forages and hay increased the total liveweight of cattle sold and weaning percentages (Table 1). Gross margins were higher under the two baseline enterprises, reflecting the high variable costs associated with growing irrigated forage and hay, although the decision to irrigate becomes more attractive at HIGH beef prices. At MED beef prices, EBITDA was highest for the Rhodes grass option – profitability is highly sensitive to the cost of the irrigation options and the area of irrigation required to provide sufficient feed for each cohort. The NPV analyses showed that none of the irrigated options had a positive NPV. A significant proportion of the animal production increases at the property scale were due to increased number of breeders which could be carried when irrigated forages or hay were included in the feedbase. The estimated capital cost of development was between AUD $1.3 million and $8 million, depending on scenario and cost per ha of development.

Cattle fed irrigated forages or hay increased their rates of growth compared to the two baseline options. This meant that sale weight was reached at a younger age (Table 1). At the extreme, nearly 79% of the cohort of male cattle between 8 and 12 months old were sold in October under both hay options while none of the same cohort were sold then under the two baseline options. The majority of these cattle were sold in the following May, contributing to the stocking rate over the wet season.

Discussion

Despite the intuitive attractiveness of introducing irrigation to extensive beef cattle enterprises, very little is practiced in northern Australia. While animal production benefits can be obtained, both the initial capital outlay and ongoing costs of intensified development preclude it being a viable option – unless graziers are able to operate under a lower cost structure than modelled here, or have patient capital. In addition the enterprise would need to develop, or buy in, the additional expertise and knowledge required to run a successful irrigation enterprise of that scale. This is a constraint recognised by graziers elsewhere in northern Australia (McKellar et al 2015) and almost certainly contributes to the lack of uptake of irrigation in northern Australia. Specialist hay production is another option, but largely occurs now outside of the extensively grazed rangelands.

Acknowledgements

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Table 1 Production and financial outcomes from the different irrigated forage and beef production options for a representative property in the Victoria River catchment. Cattle were sold twice per year in all options. Cattle were sold in May for all options. Cattle were sold in September for the two base-enterprises and for lablab stand and graze. Cattle were sold in October for forage sorghum stand and graze and the two hay options.

	BASE-ENTERPRISE	BASE-ENTERPRISE PLUS HAY	FORAGE SORGHUM – STAND AND GRAZE	FORAGE SORGHUM – HAY	LABLAB – STAND AND GRAZE	RHODES GRASS – HAY
Forage/hay	None	Bought hay	Forage sorghum	Forage sorghum	Lablab	Rhodes grass
Maximum number of breeders	2050	2100	2230	2380	2290	2788
Mean of herd size (AE) across calendar year	2525	2553	2943	3084	2999	3094
Average annual pasture utilisation (%)	20.1	20.1	20.1	20.1	20.0	20.1
Weaning rate (%)	59.2	60.4	62.6	64.6	63.8	64.6
Mortality rate (%)	6.8	6.8	6.6	6.3	6.2	6.2
Percentage of 'one year old castrate males' (i.e. 8 to 11 months or 8 to 12 months old) sold in September or October	0.0	0.0	8.8	78.4	62.8	78.9
Percentage of 'one and a half year old castrate males' (i.e. 15 to 19 months old) sold in May	77.5	86.8	79.4	20.3	27.6	19.9
Percentage of 'two year old castrate males' (i.e. 20 to 23 months or 20 to 24 months old) sold in September or October	9.1	6.7	11.8	1.3	9.7	1.2
Percentage of 'two and a half year old castrate males' (i.e. 27 to 31 months old) sold in May	13.4	6.6	0.0	0.0	0.0	0.0
Liveweight sold per year (kg)	343,106	351,446	415,624	468,346	443,607	471,258
Gross margin ($/AE) (LOW BEEF PRICE)	133	120	-6	103	30	115
Profit (EBITDA) ($) (LOW BEEF PRICE)	72,596	40,766	-282,084	52,172	-173,157	91,099
Gross margin ($/AE) (MED BEEF PRICE)	219	206	79	171	119	183
Profit (EBITDA) ($) (MED BEEF PRICE)	288,753	262,178	-32,710	262,928	93,007	303,166
Gross margin ($/AE) (HIGH BEEF PRICE)	305	294	164	239	208	252
Profit (EBITDA) ($) (HIGH BEEF PRICE)	504,910	487,103	216,664	473,683	359,172	515,232

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Performance of improved range grasses and tropical legumes in the Southern Rangelands of Kenya

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Key words: legume/grass mixtures; semi-arid; Cenchrus; Megathrsus

ABSTRACT:
Sixty per cent of the IGAD landmass is arid and semi-arid. In Kenya the semi-arid and arid (ASAL) make-up 80% of the land mass. Over 60% of the livestock in the region are found in the ASAL areas and contribute between 10-50% of the GDP of individual countries in the region. The ASAL areas are faced with a myriad of challenges including climate change, livestock forage availability and environmental degradation. During the last drought Kenya lost 2.1 million animals valued at USD 406,153 (KES 52.8 Million). The frequent droughts and reduced productivity of rangelands threaten the sustainability of the livestock sector in the region. The lack of year-round adequate quantity and quality feed supply results in low weight gain and milk production and high greenhouse gas emission per unit of livestock product. To address the challenge of feed quality and quantity, the performance of improved range grass varieties (*Megathrysus maximus* variety Siambasa and *Cenchrus ciliaris*) were evaluated as sole crops or intercropped with *Clitoria ternatea* or *Macroptilium atropurpureum*) at the KALRO centre in Kiboko Eastern Kenya. The experiment was an RCBD with treatments in a 2x3 factorial arrangement. Dry matter yield, proportion of grass/ legume, chemical composition, digestibility and in-vitro fermentation were determined. The DM yield ranged from 3.3 to 5.8 tonnes/ha with the highest in *M. maximus* mixtures and the lowest in *C. ciliaris* plots. The proportion of legume in the mixtures ranged from 84-20% with the highest levels in the *C. ciliaris* mixtures. The improved range grass varieties have the potential to increase forage availability.

Introduction

Approximately 62.9 million people in the IGAD region of East Africa are currently experiencing acute food insecurity (IGAD 2024). This is approximately 25% of the entire population of the region. About 60% of the region is classified as arid and semi-arid rangelands and livestock play a key role in food security. In the semi-arid areas of IGAD, livestock provides food, income and employment for millions of livestock farmers and pastoralist's communities in the region. Export of livestock and livestock products are a significant export from the region earning foreign exchange that is seriously required in the region. The livestock sub-sector contributes between 10-50% of the GDP of individual countries in the region. In Kenya, the semi-arid lands (SAL) make-up 80% of the land mass and are home to approximately 25% of the human population. These areas face persistent for insecurity a situation that is made worse by climate change. The semi-arid areas of Kenya are home to over 60% of the livestock (cattle, sheep, goats and camels) and over 70% of the wildlife (Odero-Waitituh 2017). Livestock production is the major economic activity in these areas and is key to food security, income and employment.

However, livestock production is constrained by a number of factors including; inadequate feed quantity and quality, low yielding breeds, poor animal health services, poor market infrastructure and environmental degradation among others. This has been made worse by climate change where we have more frequent severe climatic events including droughts and floods. During the last drought Kenya lost 2.1 million animals valued at USD 406,153 (KES 52.8 Million). The frequent droughts and reduced productivity of rangelands threaten the sustainability of the livestock sector in the region. Beef cattle grazing is a key enterprise in the Semi-arid areas, however poor quality and inadequate feeds especially during the dry season. Incorporating legumes into pastures improve the cattle diet and this study aims to evaluate the productivity of mixed range grasses and tropical legumes in the semi-arid areas of Kenya.

Methods

The study was carried out at the Kenya Agricultural and Livestock Research Centre in Kiboko, Eastern Kenya. Land was prepared and divided into 5 blocks with 8 plots of 5 x5 m. The treatments included two range grasses; *Megathrysus maximus* variety Siambasa and *Cenchrus ciliaris* and two tropical legumes *Clitoria ternatea* and *Macroptilium atropurpureum.* The experiment was established during the OND 2022 rain season. The grass and legumes were grown as sole crops or as mixed crops. The experiment was an RCBD with treatments in a 2x2 factorial arrangement. Four harvests were taking starting in April to November 2023. Proximate analysis was performed using standard AOAC methods (2006)> Fibre fractions were determined using the detergent fraction method (Van Soest, 1967). Dry matter yield, proportion of grass/ legume, chemical composition, digestibility and in-vitro fermentation were determined.

Results

Forage Yield

The DM yield ranged from 3.3 to 5.8 tonnes/ha with the highest in *M. maximus* mixtures and the lowest in *C. ciliaris* plots. The proportion of legume in the mixtures ranged from 84-20% with the highest levels in the *C. ciliaris* mixtures. The improved range grass varieties have the potential to increase forage availability.

M. maximus var Siambasa as a sole crop had a signifactly higher yield *($P<0.001$)* than *C. ciliaris* (Figure 1). *C. ternatea* had a significantly higher *($P<0.03$)* dry matter yield than M. atropurpureum (Figure 1). The M. maximus intercropped with *C. ternatea* and *M. atropurpureum* had lower dry matter yield than *M. maximus* sole crop.

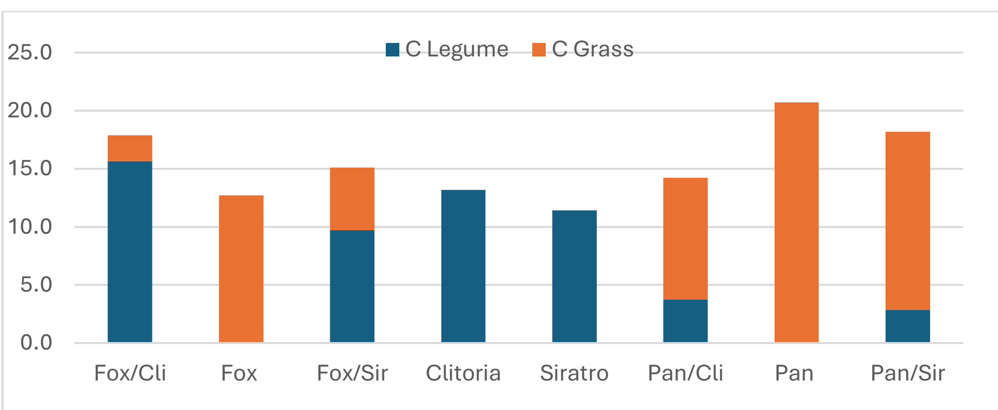

Figure 1: Forage Dry Matter Yield of Range Grasses and Tropical Legumes (t/ha)

The crude protein yield for the grass/ legume mixture ranged from 1.2 to 2.6 tons/ha/year (Table 1). The inclusion of legume increased the total crude protein yield especially when grown with *C. ciliaris*. However, the total crude protein yield was lower in both the *M. maximus* legume mixtures (Table 1).

Table 1: Crude Protein Yield for Range Grass and Legume Mixtures in Kiboko, Kenya (kg/h)

	C. ciliaris/Clitoria	*C. ciliaris*	*C. ciliaris/ siratro*	*Clitoria*	*Siratro*	*M. maximus/Clitoria*	*M. maximus*	*M. maximus/Siratro*
Grass	2176.0	1232.9	523.8	0	0	1143.6	2259.3	1671.9
Legume	30.8	0	1553.6	2597.4	1825.6	737.7	0	45.6
Total	2206.8	1232.9	2077.4	2597.4	1825.6	1881.5	2259.3	1717.5

Digestibility

Dry matter digestibility was lowest in the C. ciliaris and *M. atropurpureum*. The other mixture ha similar dry matter digestibility which ranged from 52.5 – 54% (Table 2). Organic matter digestibility was higher in the mixtures with *M. maximus* and much lower in the mixtures with *C. ciliaris* (Table 2).

Table 2: Digestibility Coefficients of Mixed Grass and Legume diets

Feed Mixer Type	DMD%	*OMD%*	*DoMD (g/Kg DM)*
C. ciliaris/Clitoria	54.0	57.1	503.0
C. ciliaris/Siratro	43.0	48.1	541.4
M. Maximus/Clitoria	52.5	54.5	466.9
M. maximus/Siratro	53.7	64.1	456.4

Discussion

Legume and grass mixtures have the potential to improve soil health and livestock production. In the ASAL areas of Kenya feed quality and especially the low digestibility and crude protein content of the local grasses limits livestock production. Legumes have a higher crude protein, energy and mineral content than tropical grasses and can be used to address the N deficit in tropical grasses. However, the selection of grasses and legumes to grow in a mixture will determine the success integrating legumes into grass pastures. Recently a number of grass varieties have been introduced in the semi-arid areas of Kenya and this experiment evaluated the compatibility of the tropical legumes and two of the grass varieties. The two legumes used reduced the *C. ciliaris* yield from 12 to only about 5 tons/ha per year. This reduction was highest in the early stages of establishment and although the proportion improved in later harvests the total yield was still very low. However, the two legumes seem to compensate for the low grass yield and there was no difference in the yield per year between the legume/grass mixtures and the grass sole crop. However, the crude protein yield was higher than that of the sole *C. ciliaris* crop. Sole *M. maximus* produced much higher yield than the grass legume mixture which could have been an indication of competition for water and minerals between the legumes and this tall tufted grass. The sole M. maximus crop had a higher crude protein content than the legume grass mixtures implying no major advantage of growing the grass in a legume mixture. As the legume proportion seems to increase with time, the trail will be keep for a number of seasons to determine if this finding will change.

Implications of the results

Although intercropping C. ciliaris reduces grass yield significantly the mixtures produce more forage of higher nutritive quality and therefore can be recommended to farmers growing *C. ciliaris*. However, different planting arrangements should be tried to determine whether the competition between the legume and grass can be reduced. More work is required before a decision on which legumes can be intercropped with *M. maximus.*

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Beef cattle grazing rangeland pastures augmented with naturalised Stylo had higher liveweight gains in the Victoria River District of the Northern Territory

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Key words: Legumes; cattle production; improved pastures, Northern Australia

Abstract

The Victoria River District (VRD) in the Northern Territory supports extensive cattle grazing on native pastures. The pasture quality and quantity of this tropical savanna is subject to significant seasonal variability with most of the rain falling between December and March. During the dry months, pasture quality rapidly declines, and protein becomes the most limiting nutrient, which is commonly replaced with urea to supplement nitrogen (Silva et al. 2022).

To address the seasonal protein deficits, the benefits of augmenting exotic legumes into the native pastures is being demonstrated at Victoria River Research Station (VRRS) situated 400km south-west of Darwin. The high protein content in legumes make them an ideal cattle feed to fill the protein gap that occurs naturally in rangelands when pasture dries off in the late dry season (August-December).

The project includes a live weight gain trial for young heifers between 6 to 12 months old grazing an existing legume augmented pasture compared to a control paddock with <5% legume yield. Near Infra-Red Spectroscopy (NIRS) data was collected in October 2023, December 2023 and May 2024 to compare crude protein content and metabolisable energy in the legume paddock versus the control. Early results from the first year suggest the weight gain of weaner heifers was significantly higher with naturalised Stylosanthes legumes.

Introduction

In the Northern Territory (NT), almost all beef cattle production occurs in extensive rangelands where cattle graze native pastures. Native rangelands are a low input and low-cost method of growing cattle on large areas of land where it is not feasible to have intensive cattle production practises such as feedlots.

In the tropical savannas of the Northern NT, annual cattle weight gain coincides with wet season rainfall, falling between December and March (Burns et al. 2010). During the wet season, consistent rainfall enables the pastures to remain green and nutrient rich, providing adequate energy and protein to cattle. After the wet season, a prolonged dry season (April–October) leads to pastures drying out and maturing, causing a decline in nutritional quality. This is characterised by a reduction in protein and energy content and an increase in indigestible components such as lignin and cellulose, making the forage less suitable for supporting consistent weight gain in cattle (Norman 1963). Often at this time cattle will be offered a urea supplement as a replacement protein source.

The ’protein gap’ that occurs from the middle of the dry season until after rain when pasture growth occurs, presents an opportunity to investigate augmenting native pastures with high protein legumes in the Victoria River District (VRD) region of the Northern Territory.

If young cattle can continue to put weight on during this time of year, it would bring heifers to joining weight sooner and provide earlier turn-off of steers. Generally, in Northern Australia, cows calve around October-December (Bortolussi, 2005). A cows energy requirements is higher in their last months of gestation and when they start lactating (McCosker et al. 2023). Legumes may provide higher energy and protein during this time, which could be extremely valuable management tool for cattle producers.

Methods

Improved paddock (1.9km^2) at Victoria River Research Station (VRRS) is predominately loamy red earths with a tall, open woodland and has a substantial amount of Stylo spp. present (*S. hamata*, *S. scarbra* and *S. viscosa*). The Stylo spp. were planted as part of a previous research trial in the 1970’s and has since become naturalised. Native grasses present in Improved paddock include *Heteropogon contortus* (Black spear grass), *Setaria surgens* (Pigeon grass), *Aristida holathera* (Kerosene grass), *Enneapogon purpurascens* (Limestone grass) and *Mnesithea formosa* (Silkytop grass). There are small areas of improved pastures including *Cenchrus setiger* (Birdwood grass) and *Urochloa mosambicensis* (Sabi grass). This paddock was referred to as (+ legume) or legume paddock.

Little Rosewood paddock (7km^2) at VRRS is a mix of alluvial cracking clays and shallow limestone country and has little to no introduced legumes (<5% total legume composition). Pastures are dominated by *Chrysopogon fallax* (ribbon grass), *Aristida latifolia* (feathertop wiregrass), *Ophiuros exaltatus* (cane grass) and *Panicum decompositum* (native millet). Native legumes include *Sesbania sp.* (pea bush), *Neptunia sp.* (Neptunia) and *Phyllanthus maderaspatensis* (spurge). This paddock was referred to as (- legume) or the control paddock.

Heifers between the age of 6-12 months were inducted into the paddocks in July 2023. 33 heifers in Improved paddock and 45 heifers in Little Rosewood paddock were measured over the trial period. Little Rosewood was stocked with a further 59 heifers and steers to ensure stocking rates matched long-term carrying capacity and paddocks had similar utilisation rates.

The animals were weighed in July 2023 when inducted to their allocated treatments and then again in September 2023, December 2023, and May 2024. Faecal NIRS samples were collected from both paddocks in October 2023, December 2023, and May 2024.

Each paddock has a series of permanent pasture photo monitoring sites that were used to record any changes throughout the trial.

Results

From July 2023 to May 2024, heifers grazing the legume augmented pasture were on average 31.3kg heavier ($p<0.001$) and grew faster (0.45kg/day v 0.35 kg/day, $p<0.001$) (Table 1).

Table 1: Average liveweight gain in the control and legume augmented paddocks from July 2023 to May 2024

Treatment	Proportion of total yield of introduced and native legumes (%)	Number of animals	Average weight gain (kg) (± 95% Confidence Interval)	Average daily weight gain (kg/day) (± 95% Confidence Intervals)
– Legume	7	45	109.9 (105-115)	0.35 (0.337 – 0.370)
+ Legume	31	31	141.2 (135-148)	0.45 (0.432 – 0.476)

Faecal NIRS was used to analyse protein and energy levels of the feed consumed by cattle in both paddocks. The improved paddock heifers' diet had a lower dry matter digestibility (DMD) to crude protein (CP) ratio and higher metabolisable energy compared to Little Rosewood paddock heifers.

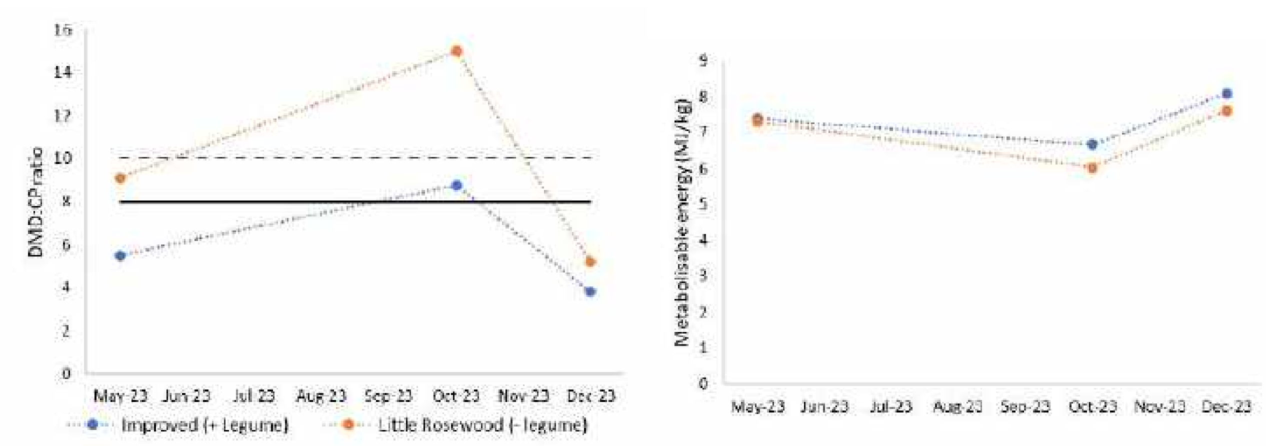

Figure 1: Faecal NIRS derived DMD%:CP% ratio and metabolizable energy in the legume and control paddocks, from October 2023 to May 2024. DMD:CP > 10 response to urea highly likely. DMD:CP>8 probable response to urea

Discussion

Heifers in the + legume paddock gained on average 100 grams more per day compared to heifers in the - legume paddock (Table 1). The increase in weight gain aligned with faecal NIRS data indicating a consistently higher crude protein (CP%) to dry matter digestibility (DMD%) ratio in the + legume paddock (Figure 1). In the late dry season, there was more metabolisable energy available in the pastures in the + legume paddock (Figure 2). This finding is consistent with previous research by Gardener (1980) which demonstrated that steers grazing a *Stylosanthes hamata*-native grass pasture exhibited improved diet selection and liveweight performance due to the higher quality forage provided by legumes. Notably, during the late dry season, metabolizable energy was also more available in the legume paddock (Figure 2), a critical period when protein and energy are often the primary constraints on cattle growth (Silva et al. 2022; Charmley et al. 2023).

The nutritional advantage of the legume paddock reduced after the wet season rains (December 2023–March 2024), as metabolizable energy levels equalized between the two paddocks. This suggests that the benefits of legumes are greatest during resource-limited periods, such as the late dry season. The late dry season nutritional benefits observed in the legume paddock are particularly significant for this environment, where limited protein and energy often constrain cattle growth. The continuation of this study through the 2024–25 wet season will provide valuable additional data to assess the long-term impact of legume augmented native pastures on cattle weight gain and overall performance.

However, the study faced challenges in selecting a true control paddock with comparable soil fertility and pasture composition. The variations in soil quality and pasture composition may have influenced the results, highlighting the complexity of isolating treatment effects in extensive grazing environments.

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Integrated livestock management with crops and trees

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Effects of moderate drought on forage quality and quantity lasted for 3 years post drought and were exacerbated by heavy grazing

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Key words: climate change; digestibility; drought; rain-out shelters; ungulate

Abstract

Growing season droughts can have major impacts on grassland vegetation and are predicted to become increasingly frequent in temperate rangelands due to climate change. To sustain livestock production systems, we need to understand what grazing management strategies will best support long-term ecosystem and livelihood sustainability in the face of increasing drought. Little is known about how droughts interact with grazing management to affect forage quality and quantity. In two North American grasslands where grazing by domestic livestock is the primary land-use, we assessed the separate and combined effects of experimental rainfall reductions and grazing management strategies on forage quality and quantity over five years. During a 2-yr experimental rainfall reduction period, rainfall reductions decreased both forage quality and quantity at one site. At a second site, heavy grazing during the first year of experimental drought reduced forage biomass and digestibility during the second year. In the first year after experimental rainfall reduction treatments ended, plots that formerly received large rainfall reductions displayed strong legacy effects. These plots had 26% to 57% less digestible forage biomass but greater forage quality than controls. Experimental treatments did not induce long-term changes in forage quantity at either site, but reductions in forage quality persisted up to three years after droughts ended. Our results highlight the resilience of North American Great Plains grasslands to both drought and grazing, but also suggest that these disturbances can have additive and long-term effects on forage nutritive value. Legacy effects of droughts on forage quality and quantity may impact ruminant nutrition for 1-3 years following a drought, and heavy grazing during drought may strengthen the effects of drought on livestock nutrition.

Introduction

The ecosystem services provided by natural grasslands can be disrupted by drought (Smith et al. 2024), and growing season droughts are predicted to become more frequent due to climate change (Knapp et al. 2023). Global change experiments routinely measure effects of simulated droughts on the biomass and community composition of natural grasslands (Smith et al. 2024). Drought-induced changes to grassland vegetation can affect wild and domesticated ungulate ruminants via shifts in both the quantity and quality of forage. For example, drought-induced reductions in forage biomass can negatively impact ruminant performance, and that effect can be exacerbated by concurrent reductions in forage quality (White et al. 2014). Conversely, droughts could maintain or increase forage quality despite drought-induced reductions in forage biomass, leading to weaker bottom-up effects on animal performance (Grant et al. 2014).

Bottom-up drought effects may be further influenced by interactions between drought and land management (e.g. grazing regimes) (White et al. 2014, Deléglise et al. 2015). Due to logistical hurdles, drought manipulation experiments rarely include manipulations of large ruminant grazers. More research is therefore needed to understand when, where and how grazing and drought interact to shape ruminant nutrition. For example, heavy grazing during drought could lead to reductions in aboveground production potential or shifts in plant species composition (e.g., Deléglise et al. 2015), both of which may result in altered forage quantity and quality. Most studies of forage quality and drought do not track recovery for multiple years after the disturbance event, so the legacy effects of drought on forage quality are also poorly understood (White et al. 2014, Deléglise et al. 2015). Legacies of prior year conditions are known to be strong drivers of grassland productivity (Sala et al. 2012), but less work has explored the role of legacy effects on forage quality. To fill these knowledge gaps, we tested the separate and combined effects of rainfall reduction and grazing treatments on forage (grass and forb) availability and nutritive value in grasslands of the northern Great Plains of North America.

Methods

The study was conducted at two field sites in the west-central semi-arid prairies of North America (EPA Level II ecoregion 9.3; Omernik 1987). One site was in eastern Montana (MT) at the Fort Keogh Livestock and Range Research Laboratory (46°20'N, 105°59'W). The other site was at a private cattle ranch (43°18'N, 105°03'W) in the Thunder Basin region of northeastern Wyoming (WY). Mean annual precipitation and temperature are 320 mm and 7.8°C at the MT site and 320 mm and 6°C at the WY site. Most precipitation falls during the growing season (April – October). Floristically, both sites are in a broad ecotone between shrublands of the North American Deserts, and grasslands of the Great Plains. Plant communities commonly include a sparse overstory of *Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle and Young (Wyoming big sagebrush) and an understory characteristic of northern mixed-grass prairie (Frost et al. 2023).

We manipulated grazing and rainfall reduction in a full factorial (3×5) with a split plot. Main plots (paddocks) were arranged in a randomized complete block design with three blocks per site. Grazing treatments were randomly assigned to three paddocks per block, and the fourth paddock was used to supply water. Grazing treatments were designed around multi-year, regionally relevant drought management strategies. Paddocks assigned to the "heavy" treatment experienced heavy grazing (70% biomass removal) during the drought period (2019-2020) and moderate grazing (50% biomass removal) during the post-drought period (2021-2023). The "stable" treatment received a consistent, moderate grazing intensity (50% biomass removal) across all years. A third "destock" treatment was also included but results are not presented here. Grazing treatments were implemented in early July in WY and early August in MT. Fort Keogh Livestock and Range Research Lab's Institutional Animal Care and Use Committee determined our use of animals was consistent with standard livestock management. Within each paddock, we established six plots (2 × 2 m). Four plots were randomly assigned to rainfall reduction treatments and two were randomly designated as control plots. Rainfall reduction treatments (-25%, -50%, -75%, and -99%) were applied with rain-out shelters (3 × 4 m) positioned over plots from April – October in 2019-2020. Rain-out shelters were removed during grazing treatments. Ambient precipitation in MT was near average in 2019 and 2020, below average in 2021, and slightly below average in 2022 and 2023. In WY, precipitation was above average in 2019, below average in 2020 and 2022, and near average in 2021 and 2023.

To sample forage, we clipped one or two 10 x 50 cm quadrats within each 2 x 2 m plot in May, June, and July for 5-yr (2019-2023). Sampling areas were excluded from grazing during the current sampling year. Forage samples were a composite of living and dead herbaceous material and excluded cactus, woody vegetation, and litter. Forage material was oven dried (60°C, 48 hr), weighed to obtain forage biomass estimates (g × m^{-2}), and ground to pass through a 2-mm screen. From the composite sample, 0.25g subsamples were added to filterbags (F57, Ankom Technology Corp., Fairport, NY, USA) and used for in-vitro organic matter (OM) digestibility analysis via an ANKOM DaisyII incubator (Daisy Incubator; Ankom Technology Corp., Fairport, NY, USA; ANKOM 2017a). Separate subsamples were used for neutral detergent fiber analysis (ANKOM 2017b). In addition, we calculated digestible forage biomass (g × m^{-2}). Species composition data are presented in Frost et al. (2023) and Bloodworth et al. (in review).

For each response variable we ran separate linear mixed models by year and site, since treatment applications and associated hypotheses differed among years, and sites experienced different weather patterns over the course of the experiment. In each model, fixed effects included percent rainfall reduction (continuous), grazing treatment (categorical), month (categorical), and all possible interactions. To account for spatial and temporal non-independence, we included random intercepts for block, paddock nested within block, and plot nested within paddock and block, and we utilized a compound symmetry covariance structure. For each model, we also included May 2019 data from each plot as a fixed effect covariate to account for baseline differences among plots. Whenever two- or three-way interactions with month were significant, we ran separate models by month. We ran models in R 4.2.1 using the nlme package (Pinheiro and Bates 2000).

Results

In Montana, experimental rainfall reduction treatments were associated with lower forage quality and quantity during the first two years. Plots experiencing the most rainfall reduction had 4.1% more fiber content than control plots (Fig. 1; main effect of rainfall reduction 2019 $P = 0.002$; 2020 $P = 0.07$). The quantity of digestible forage declined by up to 27.0% with rainfall reduction in 2019 (Fig. 1; $P = 0.001$). In 2020, digestible forage biomass declined by 46.0-53.5% with rainfall reduction in June and July, but not May (Fig. 1; rainfall reduction*month $P = 0.003$). In 2021, a natural drought year in Montana when we did not impose experimental rainfall reduction treatments, forage quality tended to be higher and forage quantity was lower in plots that had formerly been subject to experimental rainfall reductions, compared to control plots. Forage fiber content was 4.9% lower in plots with the most former rainfall reduction, compared to control plots (Fig. 1; $P < 0.0001$). In May 2021, forage digestibility was 7.4% higher in plots with the most former rainfall reduction, compared to control plots (Fig. 1; rainfall reduction*month $P = 0.008$). Even in the presence of a strong natural drought in 2021, former rainfall reduction treatments were associated with up to 57.2% lower biomass of digestible forage (Fig. 1; $P < 0.0001$). Grazing treatments did not influence forage results in Montana.

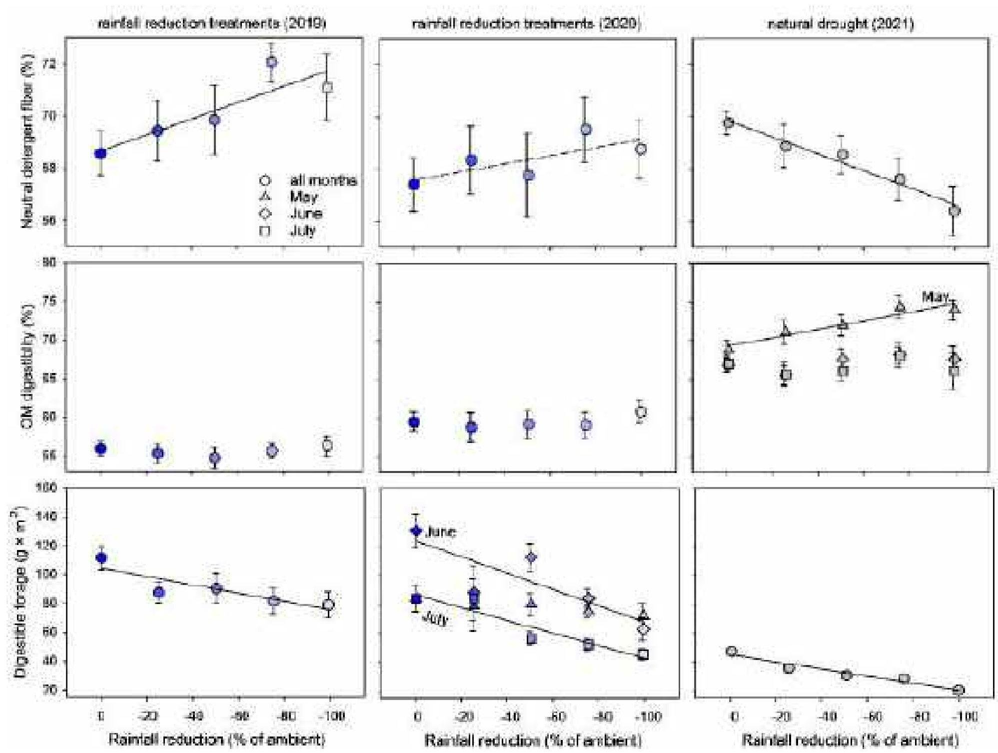

Fig. 1. Effect of rainfall reduction treatments (2019-2020) and a natural drought (2021) on average (±1 SE) forage nutritive value and biomass in Montana. Solid lines indicate significant effects of rainfall reduction ($P \leq 0.05$), and dashed lines indicate marginal significance ($0.05 < P \leq 0.10$)

In Wyoming, our treatments were mostly unrelated to forage quality or quantity during 2019-2020. In 2020, however, digestibility declined with rainfall reduction, but only in the heavy grazing treatment (P = 0.02). In 2020, forage biomass was also 27.7% lower in the heavy grazing treatment than stable grazing treatment ($P = 0.04$). During the first post-drought year (2021), forage fiber content was greater with former rainfall reduction in May, but decreased with former rainfall reduction by July (rainfall reduction*month P = 0.007). Plots that had formerly received the most rainfall reduction also had 26.2% less digestible forage (P = 0.0001).

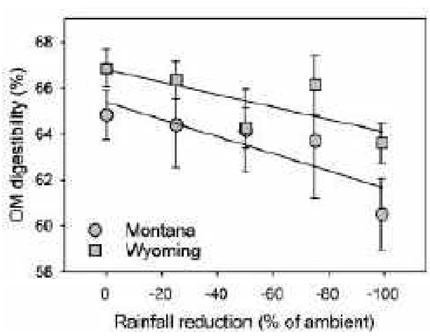

Fig. 2. Legacy effects of 2019-2020 rainfall reduction treatments on 2023 average (±1 SE) organic matter digestibility. Solid lines indicate significant main effects of rainfall reduction (P≤ 0.05)

Several effects of experimental rainfall reduction treatments persisted into 2022 and 2023. In Montana, forage fiber content patterns in 2022 matched those of 2021. Fiber content declined with former rainfall reduction ($P = 0.007$), such that plots which received the most rainfall reduction in 2019-2020 had 3.1% lower fiber content in 2022. At both sites, experimental rainfall reductions in 2019-2020 were associated with lower forage digestibility in 2023 (Fig. 2; MT $P = 0.009$; WY $P = 0.01$). Plots receiving the most rainfall reduction had 4.1-6.7% lower digestibility.

Discussion

Over a 5-yr timespan, we observed strong effects of experimental rainfall reductions and grazing management on both forage quality and quantity in two North American rangelands. Despite major differences in plant communities and weather patterns, responses were surprisingly consistent across our two sites. During experimental droughts, we observed neutral to negative effects of rainfall reductions on forage quality and quantity, as well as some evidence that heavy grazing further reduced forage quality and quantity. After experimental droughts ended, we observed short-term, strongly negative legacy effects on forage quantity. The magnitude of these effects matched or exceeded those observed in other systems (e.g., Oesterheld et al. 2001). We also observed some short-term positive legacy effects on forage quality, which were likely driven by shifts in soil nutrient availability (i.e. higher nutrient concentrations in formerly droughted plots), phenology, and species composition (Frost et al. 2023). From a ruminant nutrition perspective, the strong negative short-term legacy effects we observed on forage quantity may override any short-term positive effects on forage quality.

Grazing and drought shifted plant species composition towards less nutritious species in our study (Frost et al. 2023, Bloodworth et al. in review), leading to the potential for longer-term legacies after extreme disturbance events. Moreover, in perennial dominated systems, multi-year plant resource allocation patterns may lead to complex long-term legacies (Vermeire et al. 2024). We indeed saw evidence that experimental rainfall reductions led to reductions in forage quality at both sites in 2023, a full three years after experimental droughts ceased. Given the already low quality of forage in extensive rangelands, additional reductions could be detrimental to livestock weight gains or necessitate additional supplementation. Our findings emphasize that although northern Great Plains grasslands are resilient to both grazing and drought, these disturbances can have additive and lasting effects on a critical forage resource.

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Factors influencing pasture utilisation in northern Australian rangelands

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Key words: pasture growth; pasture utilisation; stocking rate

Abstract

Annual pasture growth and utilisation were retrospectively modelled using the biophysical GRASP model for 20 pre-existing breeder herd datasets from across northern Australia as part of a broader study to quantify the effect of pasture utilisation rates on the reproductive performance of extensive beef breeding females. Annual pasture utilisation was more influenced by variation in stocking rate in the central and northern Northern Territory (NT) regions, while variation in pasture growth explained more of the variability in pasture utilisation in the Southern NT and north eastern (NE) Queensland regions. In the Alice Springs region, median pasture utilisation was 1.8 x higher than recommended levels on commercial stations compared to the utilisation rate on the research station where it was 0.7 x recommended levels, despite higher relative rainfall for the commercial herd studies. In contrast, in the Barkly the median utilisation on commercial stations was lower than recommended levels (0.7 x recommended) possibly reflecting the high relative rainfall during those studies. On commercial stations in northern NT and NE Queensland regions, median utilisation was 1.2 and 1.3 respectively x recommended levels, but this was for years with rainfall 1.6 and 1.7 times the long-term median respectively.

Introduction

Safe pasture utilisation is commonly used in a pasture sustainability context as the proportion of pasture consumed by livestock that will maintain the underlying resource base over the long term (Hunt 2008). Northern Australian cattle production systems are typically extensive breeding enterprises with herds free-ranging in large to very large paddocks (five to 500 km²), grazing mostly on rain-fed native pastures. The summer-rainfall dominated climate supports mesic to semi-arid tropical and subtropical savannas, through to arid shrublands and grasslands. Recommended safe levels of pasture utilisation to sustain vegetation and soils are typically in the order of 5 to 25% of annual pasture growth. However, these rangelands are often utilised at rates that exceed safe levels. This work was part of the larger Sweet Spot project that examined the impact of pasture utilisation on breeder herd performance. Here we examine the factors influencing pasture utilisation in the dataset and implications for rangeland management.

Methods

Pasture growth and utilisation (for the growth year between October 1 and September 30) were modelled using the pasture growth GRASP model (Rickert *et al*. 2000) for existing breeder herd datasets at 60 paddocks (sites) across northern Australia as part of the Sweet Spot project. The herd datasets included 77,000 cattle records from 60 paddocks between 1991 and 2022 for a total of 350 site-years. Climate files for each site from SILO were combined with local/site rainfall where available. Pasture utilisation is a result of both pasture growth and animal intake. Intake and growth were calculated within the watered area (defined as all the area within 3 km and half the area between 3 and 5 km from water). Paddock pasture growth was calibrated using total standing dry matter estimated in the paddock and satellite derived green ground cover. Intake was assumed to be 8 kg/adult equivalent/day (McLennan et al. 2020) with an adult equivalent (AE) defined as a 450 kg *Bos taurus* steer walking 7 kilometres each day (McLean and Blakeley 2014). The number of AE was calculated using measured herd performance for each class and time period using the AE calculator (McLean and Blakeley 2014, version 14.63). As safe utilisation rates vary between land types, we used a simple index of utilisation; relative utilisation = modelled annual pasture utilisation/safe (long term average) utilisation for that site. Long term safe utilisation rates for each land type were determined from the literature (e.g. Ash et al. 1997, Hunt 2007). Relative rainfall = actual annual rainfall / median long-term annual rainfall.

Statistical analyses (R Core Team 2024) were performed to determine whether stocking rate or pasture growth was the greater influence on pasture utilisation in the different regions. Data from properties in each region were used for a linear model to assess the relationship between annual percent pasture utilisation and the explanatory variables of log (annual pasture growth) and stocking rate. Partial correlation coefficients for each explanatory variable were generated using the ppcor package (Kim 2015a, Kim 2015b). The dataset was analysed by broad geographical location.

Results

The dataset was skewed towards wetter years, with above median rainfall in 65% of the 350 site-years (Fig. 1a). Median relative utilisation was one in the Southern and Northern NT regions (indicating safe utilisation levels, Fig. 1b), but was less than one in the Barkly Central NT (0.7) and higher than one in NE Queensland (1.2), reflecting stocking rate trials deliberately testing high stocking rates there. The Alice region in southern NT had some very high relative utilisations which were all found on commercial stations (where the median relative utilisation was 1.8 x higher than recommended level) and which were considerably higher than for a local research station (0.7 recommended level), despite higher relative rainfall for the commercial sites (1.6 vs. 1.1 respectively). In contrast the Barkly median utilisation on commercial stations was lower than the recommended level (0.7 x recommended) possibly reflecting the high relative rainfall during those studies (1.4 x median). On commercial stations in Northern NT and NE Queensland regions, median utilisation was 1.2 and 1.3 x recommended levels, but this was for years with rainfall 1.6 and 1.7 times the long-term median.

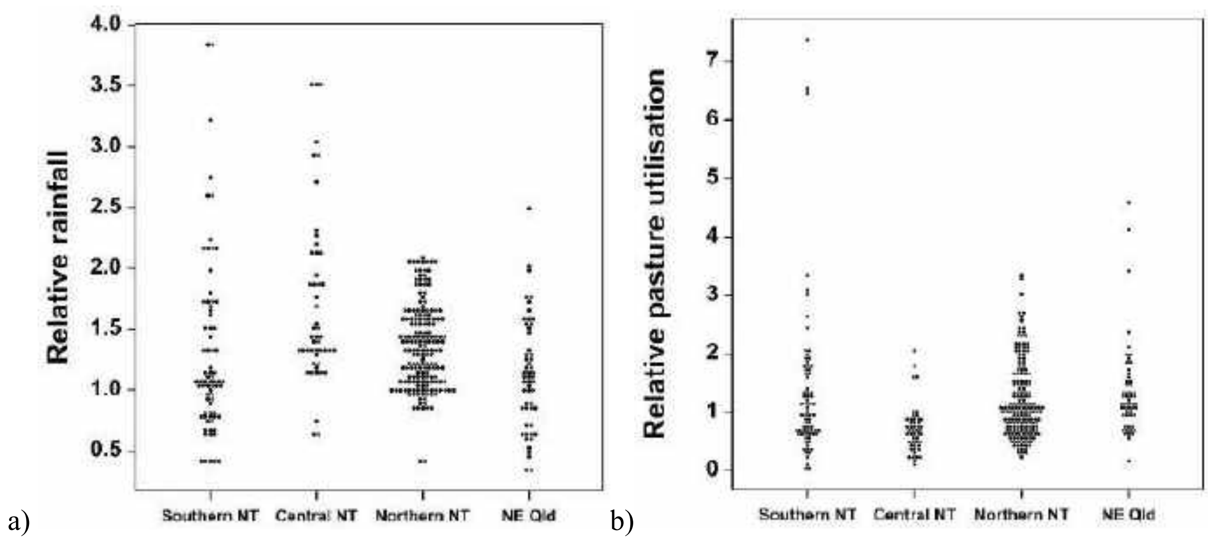

Figure 1: Variation in a) relative rainfall, 1 = median rainfall and b) relative simulated pasture utilisation, 1=safe utilisation, across regions of northern Australia on the Sweet Spot sites

Pasture growth explained more of the variation in pasture utilisation in the Southern NT and NE Queensland regions (Table 1, Fig. 2) and stocking rate explained more of the variation in annual pasture utilisation in the Northern NT and Barkly regions (Table 2, Fig. 2).

Table 1: Coefficient of regression between annual pasture utilisation and log annual pasture growth for Sweet Spot broad regions * P<0.05** P<0.01*** P<0.00001

Region – Sub-regions	df	Intercept	Slope	r^2	P
Southern NT - Alice	72	153	-45.6	0.72	***
Central NT - Barkly	47	82.7	-20.5	0.15	**
Northern NT - Katherine / Sturt Plateau / VRD	171	217	-58.9	0.26	***
North East Queensland – Central, North and Far North Qld	52	282	-75.2	0.62	***

Table 2: Coefficient of regression between annual pasture utilisation and annual stocking rate for Sweet Spot broad regions * P<0.05** P<0.01*** P<0.00001

Region – Sub-regions	**df**	**Intercept**	**Slope**	**r^2**	**P**
Southern NT - Alice	72	9.5	2.05	0.03	ns
Central NT - Barkly	47	3.2	1.18	0.48	***
Northern NT - Katherine / Sturt Plateau / VRD	171	1.3	1.46	0.70	***
North East Queensland – Central, North and Far North Qld	52	24.2	0.46	0.03	ns

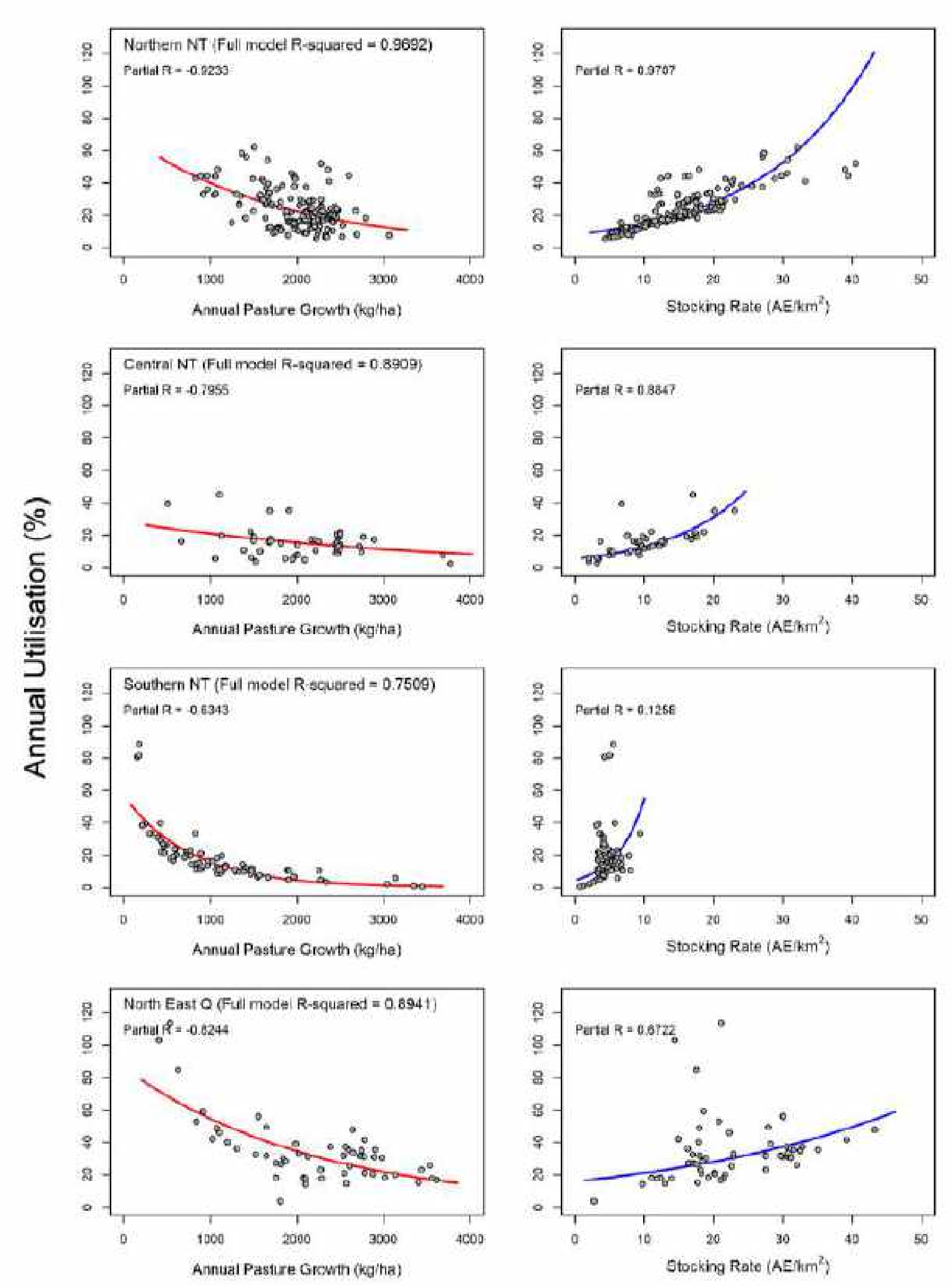

Figure 2: Relationships between pasture utilisation and pasture growth and stocking rate by region

Discussion

This dataset includes data from research herds used in cattle production studies, grazing trials for testing different stocking rates and grazing systems, and studies on collaborating commercial cattle stations. This work involves a meta-analysis of pre-existing datasets where the individual datasets are inherently idiosyncratic in nature, and the regional breakdowns were not balanced for commercial vs. research station, level of infrastructure development, land types represented, or the proportion of dry vs. wet years. Whilst the dataset was not necessarily representative of pasture utilisation rates across the broader industry it was suited to the broader Sweet Spot study where a range of pasture utilisations was needed to compare with breeder performance. Regional comparisons of the pasture utilisation results in isolation can only be made in light of the characteristics of the varying datasets within each region. For example, the Northern NT and NE Queensland regions were heavily represented by stocking rate trials deliberately examining moderate to high utilisation. This compares to the Alice Southern NT region where the research station was deliberately stocked to achieve safe utilisation in most years. Rather we examine the factors influencing the variation in pasture utilisation in the dataset and implications for rangeland management.

The modelling of pasture growth and utilisation for this study was at the paddock or watered area scale. Rather than try to model different land types separately, we used paddock scale satellite derived green ground cover and TSDM observations to calibrate average growth across all land types in the paddock. This will inevitably average across different land types that will potentially respond differently to rainfall, depending on soil water holding capacity and fertility and pasture species composition. Similarly, land type preference and use in relation to distance from water means that the actual spatial distribution of pasture utilisation within paddocks would have varied considerably. This has been partly accounted for by assuming cattle grazed only within approximately 4km from water, when pastures are not limiting within that part of the paddock which is consistent with research findings (e.g. Hodder and Low 1978). However, in very high utilisation years when utilisation was calculated to be more than 80% of growth, as was found on several occasions in the Alice and Queensland sites, it is likely that cattle walked further from water and / or supplemented their diet with browse. These highest utilisation years were due to very low pasture growth in low rainfall years, (<250kg/ha for Alice and <650kg/ha for North Queensland) combined with moderate to high stocking rates.

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The potential of feeding young cattle with irrigated crops to manage supply chain challenges in north Australian beef enterprises

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Key words: Northern Western Australia; beef enterprise; irrigated forage; finishing

Abstract

The northern Western Australian (WA) beef industry is characterised by a reduction in dry-season forage quality leading to weight loss in livestock and reduced market readiness. A potential solution is the use of irrigated forage to provide a reliable source of energy and protein to finish cattle before sale. The feasibility of this feeding strategy was simulated using the Crop Livestock Enterprise Model (CLEM) and compared with the baseline of the usual practice of grazing on dry native pasture. Calving occurs during the wet season and weaning and mustering during the dry season, with a finishing scenario for castrated males (steers) based on feeding irrigated forage during the dry season. The CLEM results showed an improvement in livestock productivity under this scenario, with higher live weight (LW) at sale due to faster weight gain while fed the irrigated forage. Furthermore, selling a higher proportion of animals at an earlier age, could potentially reduce methane emissions (and thereby create a more sustainable system) or there is the possibility of diversifying the market to include animals with higher LW but at an older age. Overall, integrating cattle production with irrigated pasture/forage, presents a significant opportunity to enhance the efficiency of beef production.

Introduction

Despite its economic importance, the beef industry of northern Western Australia (WA) experiences some challenges such as limited market opportunities and relies heavily on live exports (Chilcott et al. 2018). The climate is one of distinct wet-dry (tropical) conditions with a reduction in forage quality during the dry season resulting in weight loss in cattle. This results in animals failing to reach the target sale weight for market, such as the live weight (LW) of approximately 350 kg for two-year-old steers intended for live export for some markets like Indonesia (MacLeod et al. 2018), and as a result they might be sold at a lower price. One potential solution is to put cattle onto high-quality pastures as an improved source of energy and protein to enhance weight gain (Webster et al. 2024). Feeding products from irrigated crops and forages, such as sorghum silage and cotton seed and direct grazing of irrigated pasture, can be a valuable source of energy and protein offering opportunities to target broader markets, implement effective herd management strategies, provide a reliable feed source during dry seasons when pasture availability is limited, and diversify the business through fodder sales (Moore et al. 2021).

The economic benefit of integrating irrigated crops and forages into the beef cattle enterprises through increasing total carrying capacity and increasing the weight at sale has been reported (MacLeod et al. 2020). This study aimed to evaluate the effective utilization of irrigated forages in a beef finishing system to increase the proportion of animals that meet market specifications, and thereby to maximize productivity. The inclusion of irrigated pasture in the feedbase was assessed against a standard native pasture base scenario, focusing specifically on castrated male animals.

Methods

Scenarios

In this study, two scenarios were considered: 1) The baseline scenario where the herd grazed only native pastures, and 2) An irrigated feed scenario in which weaned calves were moved to irrigated pasture during May in the dry season. For both scenarios calving occurred during the wet season (November to April), weaning at 5 months (twice a year, May, September), with phosphorus supplement during the wet season. In the baseline scenario, animals received a urea supplement during the dry season, and hay was provided during the first two months after the May weaning (June and July).

CLEM modelling

The case study farm with each feeding scenario was simulated with the Crop Livestock Enterprise Model (CLEM, Version 2023.3.7172.0, Liedloff et al. 2024); integrated with the APSIM Next Generation (APSIMNG; Holzworth et al. 2018) framework. The simulation was set up to represent a small property, on clay soils, with approximately 2,250 breeders and with bulls included at 4% of breeding herd numbers. Feed resources were described in separate input files for native pasture (modelled with GRASP; McKeon et al. 2000) and irrigated pasture/forage (modelled with APSIM; Holzworth et al. 2014). The productivity of individual animals was simulated in CLEM in response to feed quantity and quality. Herd management activities were implemented to represent the farm for each scenario. Mating was enabled from January to May with conception based on breeder condition. Breeders of 10 years were culled each May, and bulls purchased as needed in April. Individuals who meet the LW criteria for sale were sold in either May or September. All simulations were run over a period of 12 years (from June 2010 to June 2022).

Descriptive analysis

The biophysical outputs of each scenario were reported by CLEM and summarised using the R environment. For each resource (e.g. weight gain or average quantity of beef sold), descriptive statistics were then calculated, and metrics such as growth rate of individuals were plotted using the “ggplot2” package.

Results

Based on our CLEM simulation results, livestock productivity was higher in the irrigated pasture scenario compared to the baseline (Table 1). In addition to the increased quantity of beef sold (kg LW), a higher percentage of castrated animals reached the sale weight at an earlier age (before 12 months) under the irrigated pasture scenario compared to the baseline (94.6% vs. 83.7%) (Table 1).

Table 1. The difference in steer sales and weight gain between CLEM simulations using only native pasture and feeding with irrigated forages for a representative northern Australia property.

Biophysical parameters	Simulation	
	Native pasture	Irrigated forage
Average annual castrated beef sold (kg LW)[1]	136,229	156,950
Average weight (kg LW) of castrated males, age 7-11 mo., September sale	242.0 ± 27.2 (n=5045)	278.0 ± 34.8 (n=5749)
Percentage of castrated males, age 7-11 mo. sold, September sale	83.7	94.6
Average weight (kg LW) of castrated males, age 15-20 mo., September sale	263.0 ± 11.7 (n=212)	318.0 ± 14.0 (n=101)
Average monthly weight gain of castrated males, age 5-10 mo. (kg LW)[2]	14.03	22.02
Average monthly weight gain of castrated males, age 15-20 mo. (kg LW)[2]	1.7	14.7

1. LW= Live weight.
2. These calculations were based on a weighted average due to the unequal number of animals per month. The calculation did not consider the weight gain during the final month, which was the time of sale.

As expected, the average monthly weight gain (Table 1) and average weight (Figure 1) increased when feeding growing males with high-quality pasture forage, with better performance for castrated animals at older ages (Figure 1B). This resulted in achieving the LW target for live export to a much greater extent under the irrigated pasture scenario compared to the baseline.

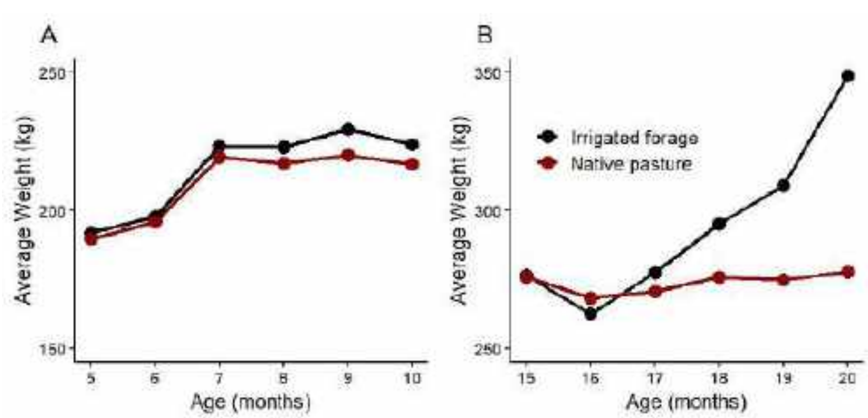

Figure 1. Difference in average liveweights (kg) for castrated animals between the native pasture and irrigated pasture/forage scenarios, A) immediately after weaning (ages 5–10 months) and B) the following year (ages 15–20 months). Note: A maximum gain of 0.83 kg/day (A) was observed at the start of the dry season (May-June) when native pasture quality remained good, and urea (throughout the dry season) and hay supplementation (June-July) were provided. This growth rate was expected, as the weaned castrate calves were in their active growth phase and had been weaned at a heavy weight. A similar trend of liveweight gain (with seasonal effects) for heifers (e.g., Fordyce and Chandra 2019) and weaners (Tyler et al. 2012) has been reported in northern Australia.

Conclusion

The use of irrigated forage was shown to increase the productivity of northern cattle herds through an increase in the average weight of animals at sale, consistent with previous studies (MacLeod et al. 2018; Monjardino et al. 2015; Webster et al. 2024). Our results also indicated that there is a potential opportunity to finish steers with alternate quality feed sources and sell a portion of them at an early age or hold them to achieve heavier weights at sale. Additionally, due to the differing rates of weight gain in 1-year-old and 2-year-old steers (Figure 1), the time of introducing animals to irrigated pastures is crucial for optimizing the use of this feed resource. For instance, selling stock at an earlier age could lead to a reduction in the enteric methane emissions of the herd, contributing to a more sustainable livestock system. On the other hand, achieving heavier weights provides opportunities for market diversification and helps meet the target LW for live export (MacLeod et al. 2018). However, a comprehensive assessment of the whole beef cattle enterprise is necessary that will consider factors such as market demand and the logistics of transporting animals for live export, including associated costs for trucking (i.e. larger animals will require more space for transport).

Overall, recommendations should be made with caution, as these results need to be economically evaluated to determine the net profit of using irrigated forage, especially considering the high capital costs associated with irrigation developments. Additionally, this study focused on castrated males (steers) over a short period, but the findings could be extended to other categories of livestock or different age groups and timeframes. Other factors, such as the size of irrigated land exploited and incorporating the animals into a feedlot system as well as considering other selling rules such as out of season to support the supply chain when there is a shortage, could also be evaluated using the CLEM framework. The next phase of this project will economically evaluate the findings of this study, as well as explore additional production scenarios that could contribute to the profitability and sustainability of the beef cattle industry in northern WA.

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Use of integrated crop-livestock systems to reduce economic risk to rangeland grazing systems

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Key words: cover crop grazing; integrated crop-livestock systems; rangeland grazing; grazing economics

Abstract

The economic sustainability of rangeland livestock operations requires that the land resource be properly managed while also optimizing the supply of forage produced and grazed. Keeping this balance of range health and adequate grazing supply, and therefore animal production, is dependent on a producer's ability to adapt to stochastic shocks, such as drought or delayed growing seasons; one such adaptive mechanism is to use alternative forages, such as cover crops, as a supplementary grazing source.

Using a simulation modelling approach on 20-years of rangeland production data from the Sandhills ecoregion of Nebraska, USA, a mixed-grass prairie in the central plains of North America, we analysed the variation in annual production risk to a grazing operation associated with having a set, non-flexible grazing plan. We then analysed how that production risk changes when a spring-grazed cover crop of cereal rye is added as an early-season grazing alternative. Within the model, forage resources of rangeland, cover crop, and hay were available to be used, with hay only being utilized once the other forages were no longer available. The model determined when to graze the cover crop and rangeland in order to maximize the total grazing days, based on the forages' within-season growth rates.

Our results indicate that there are compounding benefits to rangeland forage production by delaying grazing even by a short time, with a one day of grazing delay resulting in multiple days of additional forage later in the season. However, we also find that a spring-grazed cover crop is not an appropriate alternative forage to consistently reduce production risk in the Sandhills. This highlights the importance of having a diverse portfolio of forage types available to reduce different drivers of risk. Production risk to Sandhills graziers should be re-evaluated using a late season cover crop.

Introduction

The integration of livestock grazing into cropland is not a new concept; it was, however, historically more popular in the United States' Midwest than it is today, with major decreases noted in the 1925-1945 period (Smart *et al.*, 2021). More recently, as a response to multiple factors, including cover crop use on winter croplands and as potential mitigation to climate variation affecting livestock forage supply, integrating livestock into cropping systems has seen a resurgence in popularity (Bowman *et al.*, 2024). This increase in popularity has been complemented by an increase in studies focusing on integrated crop-livestock systems, including studies on soil health, animal production, and agronomic benefits, but a systems-level evaluation investigating how grazing cover crops may affect other aspects of a year-round grazing system was lacking. Several studies based in annual grassland systems of Australia (Thomas *et al.*, 2015; Thomas *et al.*, 2012; Dove, 2018) did evaluate the system-level impacts of grazing a dual-use crop, or a cash crop that is resistant to grazing during a portion of its growth, and found production benefits as well as the risk management benefits associated with diversified systems.

Economically, modelling livestock production within cropping systems is relatively straight-forward. The agronomic modelling of a monocrop can be algebraically determined, and livestock weights are easily tracked; Coufal (2019) modelled the farm-level benefits of grazing a cereal rye cover crop in Nebraska using this methodology. Production-level economic studies for rangeland systems are more challenging and uncommon in the literature, one reason for this is the challenges with modelling production for heterogeneous landscapes without distinct spatial boundaries. Rangeland production is, instead, typically tracked using early- and late- season biomass measurements and then correlated with climatic and grazing variables (Smart *et al.*, 2007; Stephenson *et al*., 2019) and economic studies are largely derived from animal weight data (Windh *et al.*, 2020).

In this study, we modelled production of a cereal rye cover crop using an algebraic set of equations, and we modelled a mixed-grass rangeland pasture using a sigmoid growth function for the individual cool- and warm-season grass components. We then evaluated the production-level impacts of delaying grazing to the rangeland system in the Sandhills of Nebraska, USA, by grazing the spring cover crop.

Methods

Modelling the growth of cereal rye model followed the mathematical system of equations laid out in Coufal (2019) and can be seen in detail in Windh (2023). The model was adapted to our study area at the University of Nebraska-Lincoln Barta Brothers Research Ranch near Rose, Nebraska, USA using climatic data from an on-site weather station. The model was most limited by the availability of soil moisture data. The equations follow the growth of rye on a daily time step from germination through maturity, with temperature and water stress limiting growth by an adjustment factor. The daily time-step model was important for our ability to model re-growth while grazing was occurring in our final simulation model.

Rangeland grass biomass data from the Barta Brothers Ranch was used to inform the rangeland production model. Current year herbaceous biomass was clipped from within grazing exclosures twice annually, once in mid-June to correspond with peak cool-season production and once in mid-August to correspond with peak warm-season production. Data was collected annually from 2000 to 2020, separated by functional group, and the exclosures were moved annually after the final biomass collection.

Voisin (1954) modelled the "kinetics" of grass growth and showed how marginal growth rates can be used to determine the optimal length of rest, post-grazing, before a pasture can be grazed again. Later, Cacho (1993) readdressed this topic and showed that a sigmoid curve has a better fit than other mathematical models to sets of both grazed and non-grazed grass biomass data. Following from these, we fit our data to a Gompertz growth curve; the Gompertz curve (Equation 1) is an asymmetrical, four-parameter, sigmoid equation:

$$x = Ae^{(-b)e^{-kt}}$$

The output, x, is grass biomass in lbs/acre. A is the maximum potential growth during the growing season; this defines the asymptote of the curve and is set based on measured end-of-year biomass data. b is the displacement of the curve on the x-axis. The displacement is necessary because grass growth does not begin when t, which in this case is cumulative growing degree days (GDD) with a base temperature of 40˚F, equals zero. An accumulation of several days with GDD greater than zero are required to stimulate grass to begin growing. In this equation t is growing degree days, rather than time, in order to compare multiple years of growth directly. Finally, the k parameter is the growth rate of the grass. We fit the data to the curves using known data to inform A, b, and t, and used the *easynls* package in R to determine the best fit for k, resulting in 21 annual growth curves. The derivatives of the curves gave us the daily growth rates for the simulation model.

Using the cereal rye and rangeland production values, we created a simulation model to show how the cereal rye could complement the rangeland grazing. We wanted to model how to best use our available forage portfolios on a daily time-step to 1) maximize rye use, 2) minimize hay needs, and 3) maintain rangeland health (i.e., prevent overgrazing). We modelled the simulation under three scenarios, 1) terminating rye on May 20 to plant a cash crop, 2) allowing rye grazing until it fully matures and it's quality as forage is low, and 3) a no-rye scenario to evaluate the other two rye contributions.

We developed a simulation model that follows the behavior of a cost minimization model; however, the output of interest is how each forage is selected for daily use, rather than the "minimized cost".

$$min\, C_t = \sum_{t=0}^{T} p_F x_F$$

where F is the three available forages: rye, rangeland, and hay, t is the daily timestep parameter, x is the daily (t) use of the selected forage (F), and p is the "price" set on each forage for the purpose of creating the desired behavior. p_{rye} is set as the lowest value to induce the model to use up the entire supply of rye biomass available. p_{hay} is set as the highest value to ensure the model only selects it as a last resort. $p_{rangeland}$ is set to some intermediate value, such that it is used after the rye but before the hay. Three constraints are used to emulate the properties that make the model realistic to an operation in the Sandhills of Nebraska: 1) the forage growth constraint, which used the cereal rye and rangeland production models to simulate regrowth post daily grazing events; 2) the daily use constraint, which constrains daily use of any combination of feed to 1 animal unit day worth of forage; and 3) the rangeland health constraint, which prevents the rangeland from being grazed below 650 lbs per acre. Further mathematical configuration of the model can be referenced in Windh (2023).

Results

Production models

The first surprising result was that cereal rye yields were very low in the location of our study; annual yields were 450 to 600 lbs/acre, whereas yields if 1700 lbs/acre are more common elsewhere in Nebraska. Yields of this magnitude are unlikely to provide any benefit to livestock producers as a grazing cover crop, unless there is sufficient land area to allow for stocking rates of 3 or more acres per animal unit (AU). Due to this unexpected result, we set the stocking rate of our simulation to 3 acres per AU.

The rangeland production curves, on the other hand, yielded quite varied results based on the year modelled (Figure 1). The Gompertz curve was successful in fitting curves to total annual production as well as annual warm-season production, however it was unsuccessful in fitting a curve for cool-season production due to the first data point

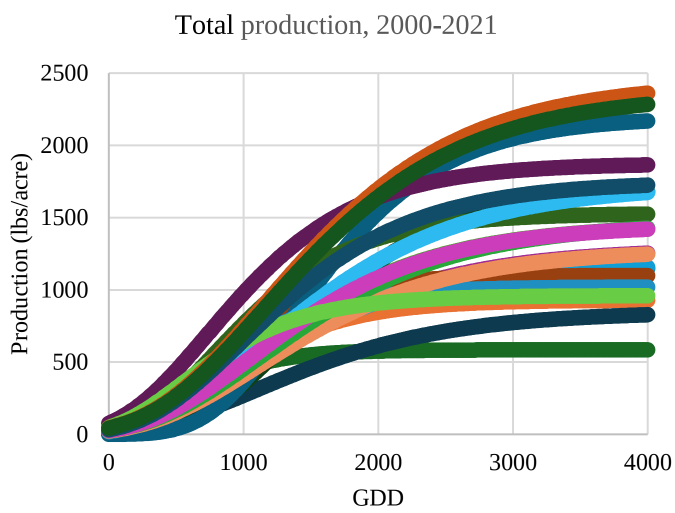

Figure 1. Total production curves derived through estimation with the Gompertz curve. Each line represents total production within one year between 2000 and 2021.

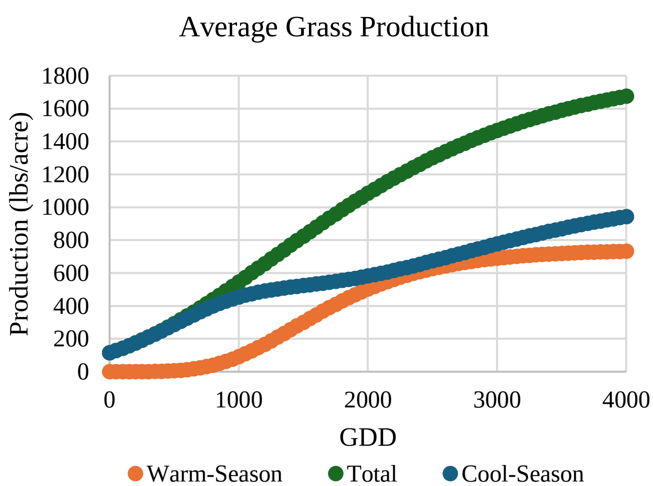

Figure 2. Average total, cool season, and warm season production curves across years 2000-2021

being from the peak cool-season production time. We were, however, able to take the difference in the total and warm-season curves to derive a cool-season curve with two-growth periods, which is consistent with the literature on cool-season grass production (Figure 2).

As mentioned, the soil moisture data was the limiting factor for modelling rye growth; due to this we ended up with 9 years for which we could simulate the full grazing system. Of those nine years, four of the years did not require any hay in addition to the cereal rye and the rangeland. The rye grazing was able to provide between 19 and 27 days of grazing in the cash crop model, and between 22 and 38 days in the no-crop model. We used the four years that did not require hay feeding to evaluate any benefits provided by the rye.

In the cash crop model, the rye is terminated on May 20 and rangeland grazing cannot occur before May 15; therefore, in this simulation the rye can only delay rangeland grazing by a maximum of 5 days. We wanted to evaluate the impact to the rangeland of delaying grazing, and while 5 days did not seem like much, it had substantial results. Between 77 and 205 lbs/acre of rangeland forage were available in excess of the 650 lb/acre threshold at the season's end; at a stocking rate of 6.66 acres/AUM that corresponds to between 19 and 52 additional grazing days as a result of a 5-day delay. More complete results can be found in Windh (2023, page 56).

Discussion

The Sandhills of Nebraska are one of the largest intact swathes of rangeland in the world, our cereal rye production results suggest that poor farming potential may have contributed to this preservation. Regardless, we can see small changes in production practices, such as delaying turnout, can yield large results. Dove (2018) found a 40% increase over the number of crop-grazing days delaying the livestock grazing. Our returns are substantially higher (400% to 1000% increase), but our stocking rates are quite conservative, especially with the 3 acres of rye per animal.

Within the production models, it would be interesting to know what caused the low cereal rye production values. The authors hypothesize that a late spring warm-up may be the cause, or possibly the soil water holding capacity of the regions' namesake sandy soils contributed to increased water stress. The cause would be interesting to investigate before producers, with more at stake, tried for a failed crop in a similarly unsuitable area. Within the rangeland production curves, further research is necessary to correlate the four parameters of the Gompertz equation with climatic drivers. Having some predictive context to the curves could clue producers into high production yields earlier in the season, or give forewarnings of climate-related forage shortages.

Despite our model not working as smoothly as one would hope, the benefits of integrating livestock into cropping systems have been shown in nearly every aspect of the system. Manure and urine add nutrients to the soil while hoof action contributes negligible soil compaction (Blanco-Canqui, 2020), cash crop yields are unaffected or increased (Bowman *et al.*, 2024), and the grazing creates another enterprise with which crop producers can diversify their operations. Further research is required to understand the full mechanics of these grazing systems, and how they work across ecoregions, but preliminary research shows it's a promising option.

Acknowledgements
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The economics of safe stocking rates in Central Australia

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Key words: economic, herd, modelling, safe stocking rate, infrastructure

Abstract

In the semi-arid rangelands of Central Australia, research undertaken at the Old Man Plain Research Station (OMP) has shown that managing stocking rate at a safe utilisation level allows land condition improvement given two La Niña years in a row. The first year provides a high rate of vegetation growth and consequent seed and the second-year results in a recruitment event from the first year's seed bank. The aim of this paper is to contrast the economics of OMP grazing strategies to an industry business-as-usual scenario. A bioeconomic model has been developed which encompasses a pasture growth model; the GRASs Production (GRASP) model linked to herd structure modelling using Breedcow and Dynama. The herd performance and other baseline data was derived from industry consultation, whereas the OMP data was derived from published data from the research station.

The analysis shows that there are economic incentives to run safe stocking rates. Besides the unequivocal environmental (land condition) benefits of running a safe stocking rate, the economic benefits are dependent on the initial status of the station and how it transitions to a safe stocking rate. The analysis concludes that there are economic benefits of running safe stocking rates, however implementation should be carefully managed by pastoralists to maintain a positive cash flow.

Introduction

Researchers have described key strategies for maintaining productivity in Northern Territory's rangelands (Walsh et al., 2014; Walsh and Cowley, 2016). One of the main principles is rigorous control over total grazing pressure by controlling animals' access to water supplies through self-mustering yards (SMY) and other infrastructure. This principle permits stocking rate adjustments in response to seasonal conditions, and most significantly, implementation of safe stocking rates (SSR). A safe stocking rate (SSR) is described as the stocking rate that allows for land condition maintenance or improvement over time. Usually, the SSR is calculated as the safe utilisation of median long term pasture growth / intake (Johnston *et al.* 1996).

The Northern Territory Department of Agriculture and Forestry (NT DAF) have been testing the application of SSR on Old Man Plains Research Station (OMP), near Alice Springs, Australia, over the last 15 years. Applying safe stocking rates has facilitated land condition improvement at OMP (Materne and Cowley 2023), increasing the cover of forage across the landscape (Bastin et al. 2024). The application of a SSR on OMP has resulted in livestock performance that is consistently higher than other properties in the region (Materne et al 2021). Properties in the Alice Springs region are typically large (average 3799km^2) and poorly developed with an average 28 watering points per station (Conradie 2014). The result of this underdevelopment leads to only 50% of the average station being within a 4km radius from water (watered area) where cattle usually graze (Hodder and Low 1978). This leads to uneven grazing pressure across the landscape and high grazing pressure surrounding waters, thus investment is infrastructure is key to further spread and control the grazing pressure

The economics of applying SSR on a commercial station has not been yet investigated. The present study aims to evaluate the economic and environmental benefits of implementing self-mustering yards (which provide control over total grazing pressure via controlling animals access to water), while running a SSR. These interventions are expected to permit pastoralists to manage stocking rates more efficiently, reduce overgrazing, and help ensure sustainable beef production in Central Australia.

Methods

In this study we applied a two-step modelling approach given the complexity of integrating the models. Firstly, pasture growth and Total Standing Dry Matter (TSDM) when grazed by cattle was modelled using the GRASP model (GRASs Production; McKeon et al. 2000; Rickert et al. 2000) which has been calibrated by NT DAF to OMP land types and land condition (Materne and Cowley 2023). The pasture growth modelling results of the land conditions and stocking rates on OMP encompassed 100-year data sets using Alice Springs Airport rainfall (LongPaddock, 2024). The modelling considered 2 land conditions (B and C – see Walsh et al. 2014) with three different management scenarios (Table 1) and 7 different constant stocking rates from 0.5 to 12 adult equivalents (AE - McLennan et al. 2020) per km^2. This provides 42 x 100-years results.

Secondly, a herd bioeconomic model has been developed which uses the relevant modelled pasture availability from the different scenarios noted above. Given the herd modelling results, the model selects the pasture growth jumping from one of the 100-year results to the most appropriate one, given the modelled land condition and stocking rate. The herd structure modelling is based on Breedcow and Dynama (Holmes et al. 2017) which were modified to allow for herd variations and un-mustered cattle (i.e. phantom herd) (d'Abbadie et al. 2024).

An initial herd and station condition was developed after discussions with both NT DAF experts and pastoralists. From the initial condition, three scenarios have been run: (a) BAU: This scenario performs as the contrafactual in which the station's business as usual (BAU) has developed across time with almost no adoption of practice change. The objective of this scenario is to reflect current poor-performing practices. This scenario was contrasted with two improved management practices, T and TS. (b) T: This scenario builds on the BAU scenario and includes the development of a network of SMY which enables a higher mustering efficiency and better herd management. (c) TS: This scenario builds on the T scenario and runs with a SSR in the watered area. The lower stocking rates will reduce pasture utilisation, improve land condition and increase animal performance.

Table 5: Main variables considered in the modelling for the initial condition and the three scenarios considered: business-as-usual (BAU), self-mustering yard development (T) and self-mustering yard development and safe stocking rate (TS)

Variables	Initial Condition	Expected status after 20-years		
		BAU	T	TS
Herd numbers mustered (AE)	5000	5000	5000	2213 - 3218
Target Stocking Rate (AE/km^2)	5	5 with destocking	5 with destocking	2.2 + 1
Weaning Rate (%)	50%	60%	70%	83.50%
Mortality rate (%)	10%	5%	5%	0.50%
Annual LWG steers (kg)	110	110	130	150
% turnoff females	15%	15%	37%	50%
% turnoff males	85%	85%	63%	50%
Land Condition	C	Maintained	Maintained	Improved to B
% water points with self-mustering yard	20%	50%	100%	100%
Mustering Efficiency	50%	80%	95%	95%
Phantom herd	50%	20%	5%	5%

The simulated station is located in Alice Springs region and was assumed to be in poor condition (land condition C- see Walsh et al. 2014) and has 1006 km^2 of watered area. It was assumed that the land condition improvement will occur when there is both a double La Niña event as the station is carrying a safe stocking rate within the watered area, so that the stocking rate increases by 1 AE per km^2 (Bastin et al. 2024). The model encompassed 20 consecutive rainfall years for each scenario, with the initial year varied from 1987 to 2004 to assess sensitivity. The model used the last 20-year average South Australian cattle prices (MLA 2024), and variable costs were discussed with pastoralists. Droughts were assumed to have no effect on prices. Fixed costs were based on current benchmarks for the region (McLean et al. 2024) and remained constant throughout the modelling. Infrastructure costs were set at $30,000 per SMY. Each scenario included an infrastructure development plan implemented in year one to understand the economic merits of infrastructure development. Scenarios were compared using net margin and net present values (NPV) with a 10% discount rate.

Results

Figure 1 shows the carried cattle for the 17 runs for each scenario. Both the BAU and T scenarios maintain a stable stocking rate over time. In the T scenario, the stocking rate stabilizes after five years due to the improved mustering efficiency from the SMY network, which helps to both control the herd and reduce numbers to desired levels. Additionally, the T scenario exhibits lower variability compared to the BAU scenario. In the TS scenario significant destocking occurs during the first five years, followed by an increase in carried cattle as land condition improves, typically after ten years on average. This improvement can occur between five to thirteen years, depending on the occurrence of a double La Niña event.

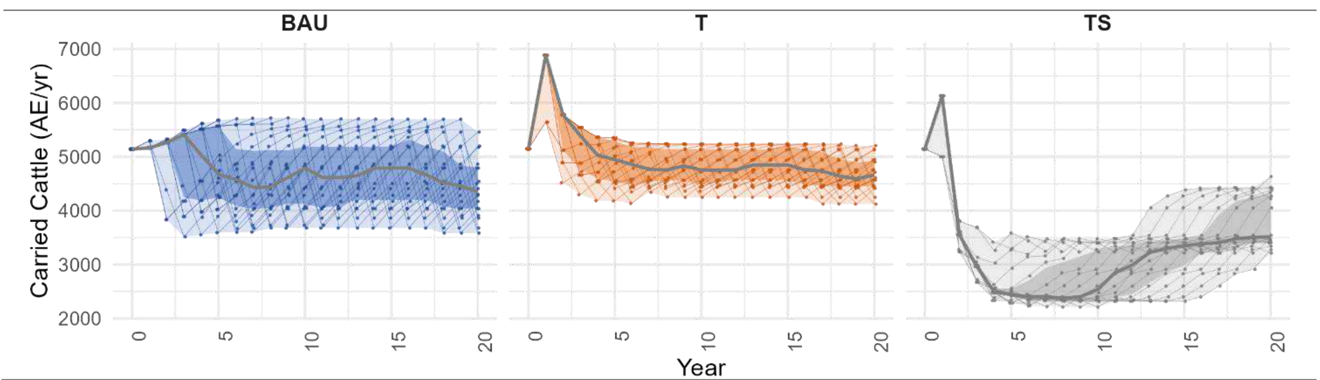

Figure 1: Yearly herd size (without considering phantom herd) for the business-as-usual (BAU), self-mustering yard development (T) and self-mustering yard development and safe stocking rate (TS) scenarios considering the

median in black and the 50% confidence interval in dark shaded colour. All 17 simulations with different starting years shown for each scenario.

The BAU scenario shows the largest variability in net margins over time (Figure 2), from the need to destock during prolonged droughts. Despite occasional highs from destocking during droughts, the overall net margin remains negative. A limitation of all scenarios is the fixed costs, which remain constant and do not adjust seasonally or in response to cash flow constraints.

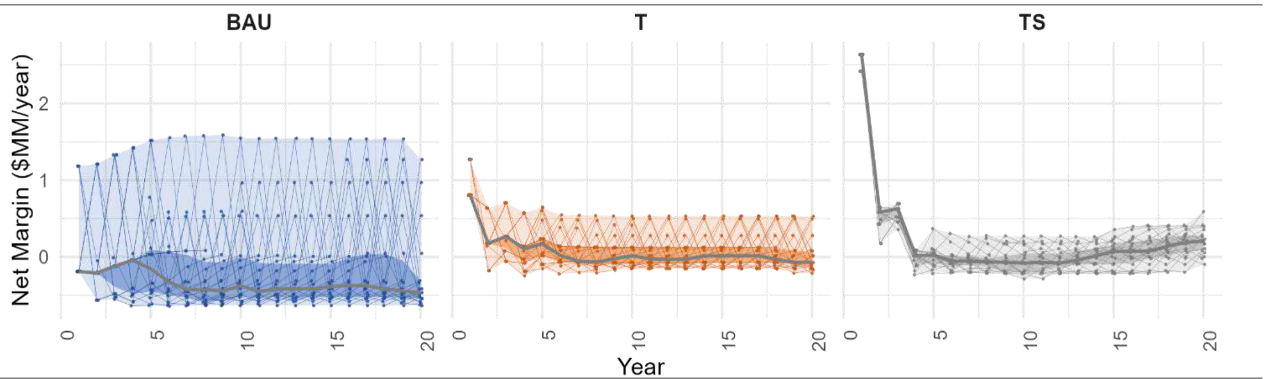

Figure 2: Yearly net margin for the business-as-usual (BAU), self-mustering yard development (T) and self-mustering yard development and safe stocking rate (TS) scenarios considering the median in black and the 50% confidence interval in dark shaded colour. All 17 simulations with different starting years shown for each scenario.

The T scenario is profitable in the first five years, with destocking of the phantom herd funding the trapyard developments. This scenario also requires destocking during droughts. After year five, cash flow averages around zero. Compared to the BAU scenario, the T scenario generates approximately $2.27 million extra in NPV (at 10% discount rate) over 20 years, with a return on the investment required to install the self-mustering yards of around 474%. In the TS scenario, peak cash flow occurs in the initial years due to destocking, which funds the self-mustering yards. From years five to thirteen, cash flow remains around zero. When the double recruitment event occurs, net margin increases as more cattle can be carried. Implementing safe stocking rates alone adds approximately $1.44 million in value, assuming the SMY are already in place.

Discussion

The results indicate that implementing SSR offers long-term economic benefits by reducing pasture utilization and eventually improving land condition, pasture growth, and animal performance. However, adopting SSR can lead to poor cash flow from the 5 to 10 years following the income gained from destocking and gaining control over total grazing pressure (TGP). This "valley of death" may deter pastoralists from adopting this strategy. To navigate this period, financing options could include the cash income from destocking, which could be deposited in banks to earn interest or used as needed. Additional income sources might include carbon credits, biodiversity credits, or investments from public donors interested in supporting enterprises that enhance and maintain land condition and biodiversity. Future research should explore additional infrastructure developments, such as more water points, and analyse the sensitivity of these interventions to varying initial conditions in this environment.

The results also highlight the benefits of investing in infrastructure such as SMY in that it improves TGP management, allowing for greater control over animal performance and significantly increases mustering efficiency. This presents an opportunity for pastoralists to leverage infrastructure development to better manage grazing pressure and potentially spread cattle with new or redeveloped water points. Consequently, the more cattle on the property, the greater the opportunity to capitalize on those above-SSR numbers. It is important to note that the BAU scenario's economics are poor, with net margins consistently below zero. A limitation of this modelling is the lack of tactical adjustments to fixed costs in response to extended dry periods. As a result, costs remain unchanged regardless of income levels, leading to negative cash flows, and as such alternative sources of income are likely to be required in order to implement the proposed changes.

Acknowledgements
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Enhancing zebu production in Madagascar through optimal nutrition and sustainable exploitation of grassy ecosystems surrounding biodiverse forests

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Key words: Zebu; Rangeland; Madagascar; Livestock; fire.

Abstract
Madagascar's poverty is partly linked to inadequate livestock nutrition and inefficient use of grassland, which covers more than half of the country's surface. Prioritising zebu nutrition and efficient use of native forage species can lead to substantial improvements.

This project involves 90 households and is working to improve zebu breeding around three protected forests in Madagascar: Ankafobe, Ibity and Itremo. The initiative focuses on pasture productivity, forage grass management and livestock nutrition. It includes demonstration farms, experimental pastures and forest plots with a fire management plan. Monitoring focuses on cow performance, forage production, grazing capacity and biomass productivity.

Across the project sites, nitrogen deficiency and low phosphorus and potassium levels are common. The successful silage production (1881 kg/ha) resulted from combining Supergraze 1000 forage sorghum with legumes in Ibity. Households fed zebus with silage and hay for the first time. In Ibity, milk production tripled, while in Itremo and Ankafobe, beneficiaries focused on calf production, achieving annual calving rates of 63.4% and 58.0%, respectively. Initially, 123 grass species were inventoried around experimental pastures. After fire and grazing, grazing capacity decreased from 1.4 ha to 0.7 ha/zebu/year, and biomass production varies between 300 and 800 kg/ha.

Madagascar remains famous for subsistence farming with long-term decline in livestock, but there are significant opportunities for integrated crop-livestock production and the sustainable use of grassland while preserving biodiversity.

Introduction

In Madagascar, grasslands are vital to the rural economy, especially for livestock farmers who rely on native forage grasses to feed their animals (Bosser 1969; Randrianarimanana et al. 2024). However, these pastures face significant challenges. Annual bush fires, often set to renew pastures, disrupt local ecosystems, threaten biodiversity, and degrade soils (Kull 2002). Additionally, population growth increases pressure on the remaining land and forage quality, heightening the demand for natural resources (WorldData.info February 2025). It is increasingly important to balance the interests of local communities with biodiversity conservation by adopting sustainable natural resource practices. Innovative solutions for managing native forage grasses and improving animal husbandry practices, particularly in feeding, could help balance animal production with the preservation of protected areas (Kew 2021). This study aims to propose solutions to enhance zebu nutrition by leveraging botanical knowledge, agricultural science, and fire management expertise.

Methods

The project collaborates with local communities living around three protected areas in Madagascar's central highlands: Ankafobe, Ibity, and Itremo. These communities have built trusting relationships with international researchers for over two decades. The project operates on the principle that farmers learn best by applying techniques observed at demonstration sites, ensuring the effective transmission of methods tailored to local conditions.

- The project is collaborating with 30 Malagasy zebu-owning households to initiate pilot activities in their villages.
- A demonstration farm per site has been established with 4 female zebus to monitor milk production, body condition, calving rates, grazing effects in the experimental pasture, and other farm activities.
- A demo barn was constructed at each site using a simple, replicable model with locally available materials.
- The project includes 2 hectares of fenced experimental pasture: 1 hectare protected from fire and 1 hectare burned, to compare grass species diversity, frequency, biomass production, and grazing management using the project zebus.
- Additionally, a one-hectare field has been set up for planting other forage crops, such as Sorghum sp., for silage production, combined with leguminous crops.
- The project also utilizes available crop residues for storage and use during the dry period.

Results

As the project aimed to enhance zebu nutrition through new techniques, the following metrics were recorded: fodder production, animal production from zebu breeding on the demonstration farm and among beneficiary farmers, including milk production, zebu body condition scores, and annual calving rates.

Forage production

The project and beneficiary households produced 770 kg/ha of Supergraze 1000 (SS1000) sorghum silage and 2704 kg of native grass hay during the last year of the project. The main crop residues used are peanut, bean and corn stalks, urea-treated rice straw to feed zebu, and sweet potato stalks to improve silage quality.

The following photos show the research activities carried out in each experimental pasture, including inventories and monitoring of the frequency and diversity of native grass species, and the rotational grazing method

Figure 1: Inventory of grass species in the experimental pasture

Figure 2: Rotational grazing with project zebus on experimental grazing land

For the pasture biodiversity, 133 species from 31 families and 95 genera including grass and forb dominated by *Poaceae, Asteraceae, Cyperaceae, Fabaceae, Orchidaceae, Rubiaceae*. Pasture quality annual biomass production is about 2,700-8,356 kg/ha depending on the fire regimes. The average biomass productivity for the 3 sites during the project is as follows:

- For unburned pasture: 2850 kg/ha in year 1 (2022), 4418 kg/ha in year 2 (2023) and 9765 kg/ha in year 3 (2024).
- For burnt pasture: 3851 kg in year 1, 2981 kg/ha in year 2 and 4985 kg/ha in year 3.

The average species per plot region is about 9 -13 for Ankafobe, 8 - 13 for Ibity and 3 - 6 for Itremo in 2024. In terms of soil quality, across all sites, the soil analysis exhibit very low levels of nitrogen, phosphorus, potassium, and calcium. Additionally, all sites show high iron toxicity, with Ankafobe being particularly affected.

Zebu production

Figure 3 illustrates the changes in calving rates for both beneficiary and project zebus over the three years of project implementation, compared to the baseline.

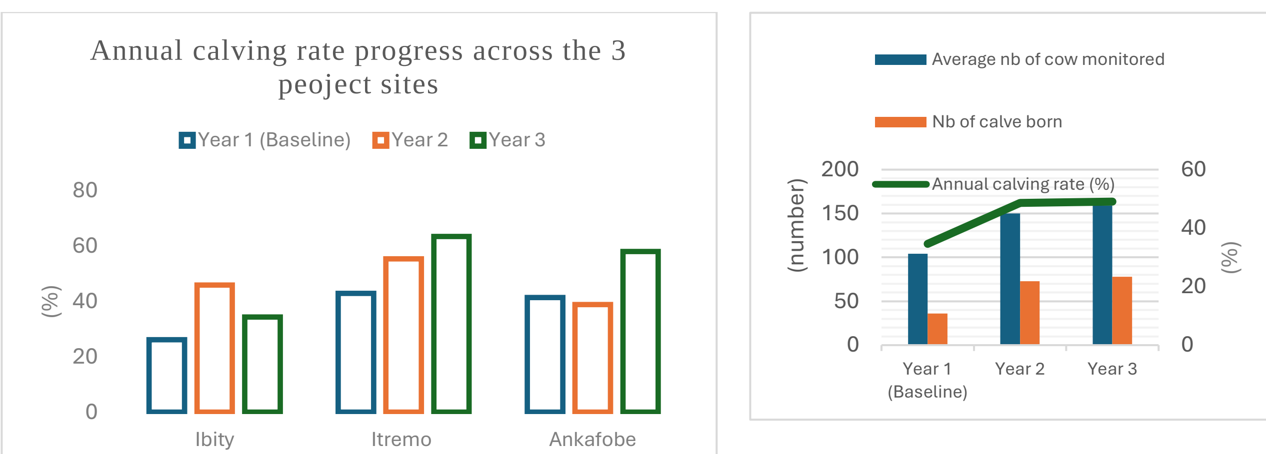
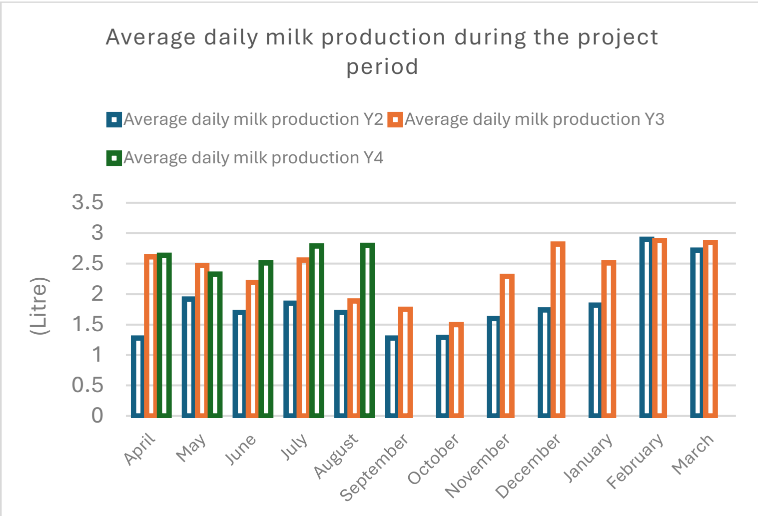


Figure 3: Change in percentage zebu calving rate over 3 project years compared with the pre-project baseline level, number of cows monitored, and number of calves born.

Beneficiaries in Ankafobe and Itremo had higher calving rates than those in Ibity, indicating a preference for more calves over milk production (Figure 4). This suggests that weaning around two months after calving encourages zebus to prepare for the next reproductive cycle.



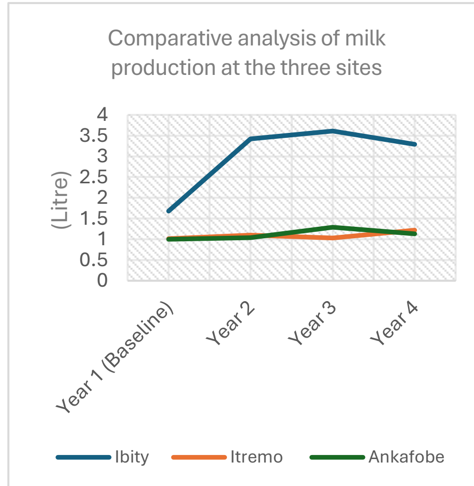


Figure 4: Average daily milk production over the 3 years of the project compared with the pre-project baseline level.

Farmers are gaining experience each year (Figure 4). Despite only having data for the first four months of year 4 (end of the project), it is evident that farmers have mastered feed stock management, ensuring sufficient feed for the dry period.

Discussion

Reducing rural poverty in Madagascar through the development of cattle farming, particularly in terms of feed, is entirely achievable. Effective pasture management using native grasses, through conservation techniques like haymaking and controlled grazing fire management, are among the best strategies, despite their challenges. In Madagascar, the focus should be on improving extensive grazing land, which is still in a legal vacuum: it is neither officially untitled property, nor land with a defined legal status (Ranjatson P et al 2021). Additionally, utilizing available resources such as crop residues to ensure consistent feeding during dry periods is beneficial. Incorporating high-nutrient, climate-tolerant, soil-covering forage species like sorghum is also highly recommended to quickly address feed deficits in native grasses. To improve soil quality, it is crucial to educate farmers on using zebu manure to create compost for their crops, as well as employing crop rotation and association techniques to alleviate land requirements, cover the soil, and increase yields for both food and feed on the same field. Decreasing the frequency of fires will reduce soil sensitivity to heavy rainfall, thereby minimizing the risks of erosion and soil degradation (Masse et al 1997, Louppe D 2004). The degraded soil quality negatively impacts the floristic and nutritional composition of the pastures, likely leading to soil erosion. The forage grasses that grow in these conditions are also expected to have low nutritional value (Rasambainarivo 1997).

Integrating zebu breeding into farming practices will further facilitate this approach. These new practices for the community will also contribute to the protection of biodiversity around protected areas.

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Poster presentations – Theme 6

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Multinational Ground Beef: Global integration of beef production systems and implications for the sustainability of rangelands

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Key words: Grazing; beef cattle; global trade; rangeland management

Abstract

In many parts of the world, including the USA, the beef supply chain engages many small-scale producers raising cows and calves on rangelands. This part of the beef supply chain is a social-ecological system where raising cattle is tied to livelihoods, land, natural resource and agricultural uses, and ecosystem processes. To produce and market beef products this system relies on transportation and markets to bring cattle to fewer and larger operations for finishing, and to a handful of beef processors for slaughter and wholesale marketing. With the inclusion of imported lean beef from South America and Oceania, US beef production is a globally connected system that impacts the sustainability of rangelands and their ecosystem services across continents. Using livestock identification inspection data and survey, this research describes California's beef production system. Managing rangeland resources for multiple ecosystem services, California's beef cattle producers seasonally move calves from rangelands often to intensive feeding operations. Fat-trim, a by-product of intensive feeding creates a demand for lean beef from grazing land cattle (including imports).

The demand for beef, dairy and mutton is projected to nearly double with the world population reaching 9 to 11 billion by 2050. Whereas increases in beef production have been primarily achieved through intensive livestock production systems, extensive systems exist in parallel and can be integrated with intensive production systems to increase production. Integration can contribute to sustaining rangelands and their ecosystem services. Data and communication technologies that support livestock records, markets, and price discovery afford more opportunity to integrate production systems at local, national, and even international levels and influence sustainability.

Introduction

The global beef industry faces unprecedented challenges as demand is projected to double by 2050, driven by population growth to 9-11 billion people (FAO 2023, OECD/FAO 2021). While intensive livestock systems have historically led production increases, extensive rangeland systems continue to play a vital role, particularly in supporting ecosystem services and rural livelihoods (Herrero et al. 2020). These systems are increasingly connected through sophisticated market mechanisms and international trade networks.

Rangelands, which cover approximately 60% of global agricultural land, represent a critical resource for food production while providing essential ecosystem services (FAO 2018). In the United States (US), small-scale producers managing these landscapes form the foundation of the beef supply chain, with most operations maintaining fewer than 50 head of cattle (USDA 2017). These producers rely on marketing infrastructure, including saleyards, to connect their operations with larger finishing facilities and processing plants. The US ground beef market exemplifies the global nature of modern beef production. Lean ground beef from grass-fed cattle in South America and Oceania is blended with fat trim from grain-fed animals finished in feedlots in the US to meet the US demand for lean ground beef (Ernst et al. 2020; Cheung and McMahon 2017).

Methods
This study analyzed California's brand inspection data collected from 2017-2021 following Barry's (2021) methodology. Brand inspections, required by law to verify ownership and prevent theft, occur during key cattle movements including sales, interstate transfers, slaughter, or entry into feeding operations. The brand inspection data included: type of transaction (e.g., sale, transfer, slaughter), cattle characteristics (e.g., breed, age, and sex class), geographic information (e.g., origin and destination of livestock), ownership changes, and number of head per transaction. Inspections occur at various points in the production chain, including saleyards, feedyards, meat processing facilities, and ranch locations.

Additional data on multinational ground beef production was gathered from industry reports and trade statistics. The analysis focused on the seasonal patterns of cattle movement, integration between production systems, market infrastructure supporting movement, and international trade flows in beef products.

Results
California Cattle Movements Analysis of California brand inspection data reveals significant seasonal movement patterns that support integrated production.

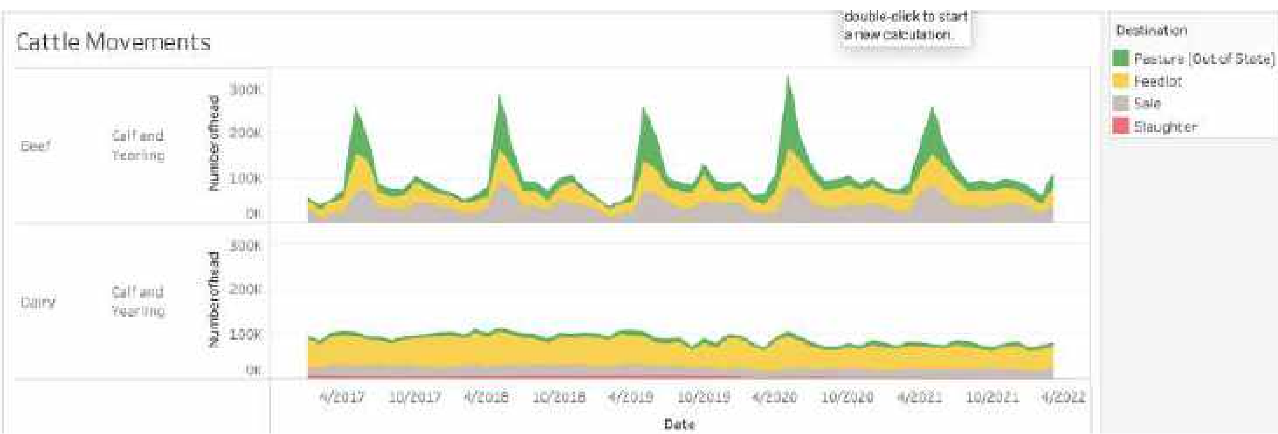

Fig. 1. Calves and yearlings (number of head) moving from California grazing lands (beef) and dairies or feed yards (dairy) from January 2017 to April 2022.

Over 560,000 head (43%) of beef calves and yearlings are moved off California's rangelands during a 12-week period each year in late spring to summer. This seasonal movement is in sharp contrast to the 1.2 million head of dairy calves, which are also moved through production systems to contribute to beef production, but with little indication of any cyclical or seasonal pattern (Fig. 1). A smaller movement occurs in fall with 15 percent (199,000 head) of beef cattle calves moved. Cattle movement data from California provides evidence that grazing cattle move from rangelands based on forage resources.

Market Integration The data shows most ranchers in California, from small-scale producers (1 to 50 head) to larger producers (more than 5,000), participate in the integrated beef production system:

- Fewer than 1% of steers and heifers go directly from rangeland to meat processing.

- Small and medium-sized producers marketed over 85 percent of their cattle through saleyards.

- Steers and heifers sold at saleyards were purchased by large-volume buyers and moved into intensive production systems for finishing.

The production of multinational ground beef demonstrates market integration. The U.S. beef production system does not produce enough lean beef to meet demand for lean ground beef. Growing efficiencies in beef production in the US have resulted in fewer beef cows in the U.S. so there are fewer cull cows and bulls. Additionally, grinding up fed cattle for ground beef no longer makes economic sense, because of the high value of beef cuts. The blending of product from different systems and countries (Table 1) not only optimizes resource use and is facilitated by trade, linking rangelands in developing nations to consumer markets in industrialized countries (Table 1).

Table 1. Production systems contributing to multinational ground beef sold in the United States

Production System	Class of Cattle	Location	Contribution to Multinational Ground Beef
Extensive grazing rangeland	Beef cull cows and bulls	US, Canada	Lean meat
Intensive grain feeding	Dairy cull cows	US	Lean meat
Extensive grazing rangeland and improved pasture	Beef stockers and cull cows	Australia Uruguay Nicaragua	Lean meat
Intensive grazing improved pasture	Dairy cows and bull calves	New Zealand	Lean meat
Feedlot raised and finished	Fed cattle (dairy)	United States	Fat trim
Extensive grazing rangeland raised; Feedlot finished	Fed cattle (beef)	United States	Fat trim

Discussion

The movement patterns revealed in California's cattle production system exemplify how local rangelands connect to global beef supply chains through complex market integration. Small-scale producers managing rangelands play a vital, yet often overlooked role in this system (Huntsinger & Oviedo 2014). The seasonal movement of cattle off California's rangelands aligns with traditional ecological knowledge about forage quality and quantity (Becchetti et al. 2016). Producers time their marketing decisions to match both environmental conditions and market opportunities. This flexibility, supported by market infrastructure like saleyards and transportation networks, enables producers to optimize both production and conservation objectives (Barry 2021). Climate change may alter the timing and reliability of forage production (World Bank 2020). As Nori and Davies (2007) argue, access to diverse marketing channels helps producers manage risk from environmental variation. The seasonal movement patterns observed in California suggest producers use market integration to adapt to both ecological and economic conditions.

In Australia, extensive grazing systems dominate beef production, with large tracts of land supporting cattle in arid and semi-arid regions. Producers rely on rotational grazing and seasonal adjustments to balance livestock needs with forage availability, similar to California ranchers. Australian producers participate in global beef trade, with a significant portion of their beef exported to markets in Asia and North America. This integration and a National Livestock Information System facilitates economic sustainability and encourages adherence to environmental standards, including the preservation of biodiversity in grazing landscapes (McIvor et al. 2011; Howden et al. 2008).

In Uruguay, beef production is deeply integrated with global markets, particularly in Europe and Asia. Uruguay's producers manage grazing lands with a focus on sustainable intensification, employing rotational grazing and native grassland conservation techniques. The Uruguayan government has actively supported sustainability through policies that incentivize ecological grazing practices, carbon footprint reduction, and traceability systems. The "National Livestock Information System" ensures that beef exported from Uruguay meets stringent environmental and food safety standards. These efforts have positioned Uruguay as a model for balancing production efficiency with ecosystem health (Modernel et al. 2016; Ernst et al.,2020).

The role of saleyards in facilitating market integration deserves special attention. These facilities serve as crucial nodes connecting small-scale producers to larger markets (Sayre et al. 2013). Buyers sort, price, and match cattle to feed resources and markets; they consolidate cattle allowing a producer with even only one head to participate in a global market.

The sustainability implications extend beyond individual operations. Research by Huntsinger and Oviedo (2014) shows how grazing on California's rangelands provides ecosystem services including biodiversity conservation, fire fuel management, and watershed protection. The economic viability supported by market integration helps maintain these extensive grazing systems rather than converting lands to more intensive uses (Cameron et al. 2014).

Looking forward, new technologies like blockchain could improve supply chain transparency and help communicate conservation values to consumers (MacLeod & McIvor 2006). Blockchain technology provides a decentralized, secure way to trace the origin, movement, and management of livestock through integrated production systems. For example, blockchain can document every step of a beef product's lifecycle, from rangeland grazing to feedlot finishing and eventual processing. This level of traceability ensures transparency, allowing consumers to make informed decisions and enabling producers to differentiate their products based on sustainability criteria (Tian 2016, Ernst et al. 2020). In Uruguay, government-mandated traceability systems already demonstrate how this technology can support premium market positioning by verifying grass-fed origins and sustainable practices (Modernel et al. 2016). Expanding blockchain globally could facilitate fair pricing for ranchers managing their grazing lands sustainably, incentivizing practices such as rotational grazing and biodiversity conservation.

Conclusions

Global market integration, particularly through ground beef production, creates demand that helps sustain these extensive grazing operations. As Capper (2012) notes, different production systems complement each other - intensive feeding creates fat trim that requires lean meat from grazing operations for optimal ground beef production. This market integration extends beyond domestic boundaries, with lean beef imports from countries like Australia and Uruguay complementing US production (USDA 2021).

The global integration of beef production systems connects diverse production systems; it provides economic opportunities that enable producers to maintain extensive grazing operations while supporting ecosystem services. As Reid et al. (2008) argue, maintaining working landscapes requires understanding and supporting the mechanisms that make them economically viable.

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Effective tools for optimal pasture management

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Key words: Pasture Management, Meal Plate Index, Species composition**.**

Measuring Pasture Availability

Effective pasture management is fundamental for livestock farmers to ensure the sustainability and productivity of their operations. The initial step is to quantify the available biomass at various times throughout the year. This can be achieved by using a calibrated ruler to measure pasture height.

Calculation of the Meal Plate Index

Once the average pasture height is determined, farmers can calculate the Meal Plate Index. This index correlates the pasture available with the pasture required for the current livestock load, effectively indicating the adequacy of the “plate” to meet daily forage demand.

Case study: Las Tres Marías Ranch

At this ranch, pasture measurements were taken seasonally over four years to calculate Plate Index. For instance, in winter 2021, the initial measurement was 2 cm, the Meal Plate Index confirmed the necessity of reducing the livestock load, opposite to the farmer´s visual estimation that the pasture was enough for the season.

Observation on Species Composition

In paddocks with appropriate rest periods and limited grazing days, an increase in frequency and vigor of C4 species, such as *Paspalum dilatatum* and *Coellorachis selloana,* was noted, especially during summer. In damp fields, the last three springs monitoring sessions revealed a high frequency of *Poa lanigera*, a winter species preferred by livestock but highly sensitive to management practices.

Key Management Practices

Livestock farmers should focus on average pasture height, height at animal entry and exit, occupation and rest periods, and livestock load. This knowledge helps in making informed decisions to enhance pasture resilience and livestock productivity.

Introduction
This case study examines three years of data collected at Las Tres Marías Ranch, focusing on the Meal Plate Index (IsPC), pasture height, and species composition. The objectives were to analyze how ranchers manage uncertainty, adapt to variability and base their decisions on balancing stocking rates, pasture availability, weather conditions, and daily management practices, all of which contribute to meat production and profitability.

Methods
Pasture height was measured using a calibrated ruler designed by researchers (Santiago Lombardo et. al, 2021). This method leverages the strong correlation between pasture height (in centimeters) and dry matter availability (kg/ha), enabling precise estimation of forage availability for livestock.

Given the heterogeneity of the native grasslands, a systematic sampling approach was developed to account for variability in species composition, soil types, and topography (meadows vs. hills). Prior to measurements, a detailed survey identified distinct plant communities, ensuring accurate sampling routes.

Measurements were taken at 20-step intervals along predetermined paths. The sampling intensity was adjusted based on paddock size:

- 80 measurements for paddocks >100 hectares
- 40 measurements for paddocks <100 hectares
- 20 measurements for cultivated pastures

Data were collected seasonally, with four measurement rounds per year. In parallel, livestock requirements were determined based on the research from the leading agronomist Martin Do Carmo (2019) of forage consumption for various livestock categories. By comparing forage availability with livestock demands, the Meal Plate Index (IsPC) was calculated, providing a forage balance metric for decision-making.

Results

The Meal Plate Index (IsPC) illustrates the forage balance, with visual indicators resembling traffic lights:

- **Brown zone:** More than 1,2, mature pasture exceeding livestock load.
- **Green zone**: Between 0,8 and 1,2. Adequate forage for livestock
- **Yellow zones**: Between 0,6 and 0,8. Alert of not reaching the objectives.
- **Red zones**: Below 0,6. Increasing risk of forage deficits

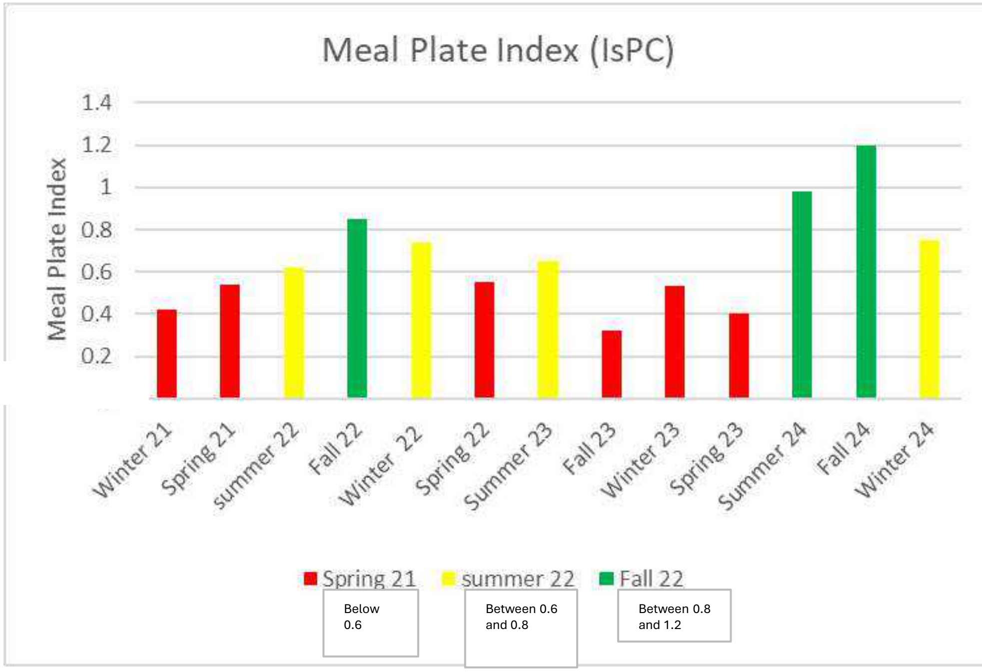

Figure 1: Meal Plate Index (IsPC) in every season that lasted the project in Las Tres Marias Ranch,

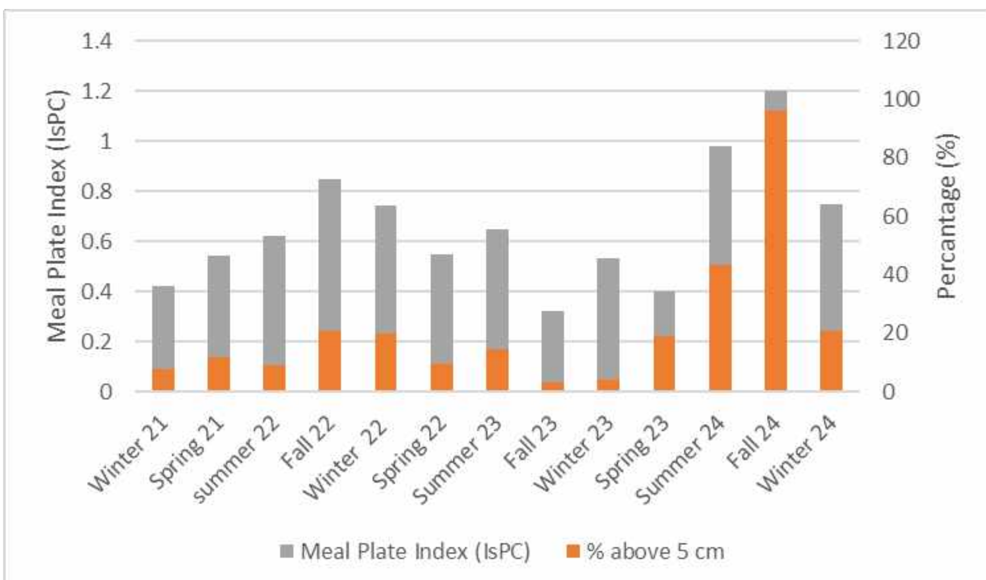

Figure 2: Meal Plate Index along with the % of grass above 5 centimetres.

The colours of the bars in Figure 1 align with the traffic light system previously mentioned: red bars indicate a risk of forage deficit, while green bars represent adequate forage availability for the livestock.

Discussion

Figure 1 illustrates the evolution of the Meal Plate Index (IsPC) over the three-year project period. Initially, the IsPC was notably low, reaching its lowest value during Fall 2023, an expected result due to a hard drought that persisted that year. A comparison of Fall 2023 data across graphics reveals that this period also had the smallest percentage of pasture area with grass taller than 5 cm.

Conversely, the highest IsPC was recorded in Fall 2024, with a value of 1.2 and 96% of the ranch exceeding the 5 cm grass height threshold. This improvement was primarily attributed to the favorable rainfall conditions during that season.

Analysis underscores a critical threshold: maintaining a high percentage of pasture with grass taller than 5 cm significantly influences both physical and economic outcomes.

The findings indicate that the Meal Plate Index is not inherently tied to seasonal patterns but is strongly correlated with the proportion of the ranch maintaining grass height above 5 cm. This emphasizes the importance of measuring grass stock and utilizing this indicator to inform ranch management and decision-making processes.

Forage Utilization and Meat Production

Figure 3 correlates meat production per hectare with the Meal Plate Index (IsPC) over three years. The data suggest a relationship between maintaining pasture height above 5 cm and achieving favorable IsPC values in the green zone, ultimately supporting higher meat production.

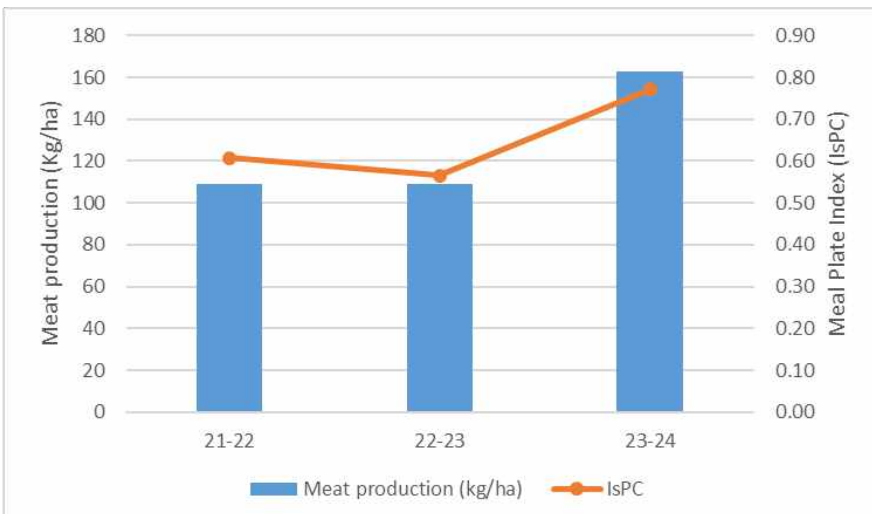

Figure 3: Meat production per hectare and Meal Plate Index (IsPC)

Species Composition Observations

An unused paddock with tall, mature grassland was transformed through targeted grazing management. A water trough and a protein supplement were introduced, and 400 cows rotationally grazed the area in small paddocks. This intervention rejuvenated the grassland:

- Mature grasses were consumed, allowing light to reach the soil.
- Initial colonization by herbs and small weeds protected the soil.
- Over time, native and non-native species (e.g., ryegrass) flourished, creating a more diverse and productive pasture.

The rejuvenated grassland provided high-protein forage in its juvenile state and evolved into a mix of cool- and warm-season grasses, demonstrating the potential for converting underutilized areas into high-quality forage systems through strategic management.

This tool had a significant impact on the Meal Plate Index (IsPC) as the pasture area increased. The newly gained hectares were predominantly of good quality, enhancing the forage available to meet the same requirements.

Conclusions

The Meal Plate Index (IsPC) has proven invaluable for quantifying forage availability and guiding management decisions. Over the three years, the project demonstrated the importance of measuring grass stock and incorporating it into decision-making processes.

Weather played a significant role, with a severe drought in the first two years followed by favorable rainfall in the final year. This variability underscored the importance of adaptive management and maintaining sufficient paddocks with grass taller than 5 cm. Understanding plant communities, their rest periods, and strategic utilization is critical for optimizing forage production and profitability.

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Balancing livelihoods and grassland sustainability: an analysis of biomass, stocking density, and income in Mongolian pastoralism

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Key words: Pastoralism; income; biomass; livestock; Mongolia

Abstract
Mongolian pastoralism, a vital traditional livelihood, faces challenges from increasing livestock numbers, grassland degradation, and socio-economic disparities. This study explores the relationships between biomass, stocking density, and livestock-based income among Mongolian pastoralists, using a pooled dataset from socio-economic surveys and ecological data from 2010 to 2019. A two-stage least squares (2SLS) regression framework is employed, with biomass as an instrumental variable for stocking density. The results reveal that biomass positively correlates with stocking density, while stocking density is negatively associated with net income, suggesting overgrazing and heightened resource competition. Other variables such as livestock number and household size are positively associated with net income, highlighting their critical role in sustaining pastoral livelihoods. Cluster analysis further shows variations based on biomass and income levels. Low-biomass regions rely more on cashmere yield, while high-biomass regions face constraints due to competing land uses. Wealthier households managing larger herds can mitigate income losses, whereas poorer households experience more significant losses due to weakness in competition. Policy recommendations include regulating livestock numbers to prevent overgrazing and promoting cashmere productivity in low-biomass regions. Future research should focus on dynamic panel data analyses and policy evaluations for sustainable livestock management.

Introduction

Mongolian pastoralism is a traditional livelihood deeply intertwined with the region's ecological systems and socio-economic structures. Despite its resilience over millennia, this practice faces increasing pressures from growing livestock numbers, grassland degradation, and socio-economic disparities, exacerbated by market demands for products like cashmere. Studies have highlighted the environmental consequences of overgrazing and the socio-economic challenges faced by pastoralist households, yet there remains a gap in understanding the intricate relationships between biomass availability, stocking density, and household income. Specifically, the interplay of ecological constraints and socio-economic factors in shaping pastoral livelihoods has been under-explored from an economic perspective.

This study seeks to fill this gap by examining what relationships biomass, stocking density, and other socio-economic variables have with livestock-based income among Mongolian pastoralists. By leveraging a pooled dataset from household socio-economic surveys and ecological data spanning 2010 to 2019, this work employs regression analyses to investigate these relationships across ecological and income clusters. The objectives are to assess the role of biomass in associating stocking density and income, explore the disparities among households based on wealth, and provide insights for sustainable livestock management and policy development in Mongolia's pastoral systems.

Methods

This study integrates data from three sources to form a pooled dataset (See details for each variable in Table 1). The primary dataset originates from the Household Socio-Economic Survey (HSES) conducted in Mongolia in 2010, 2013, 2016, and 2019. Only households actively engaged in livestock production in the 12 months preceding the survey were included. The Rangeland Production Model (RPM) is a gridded ecosystem model. It integrates the Century ecosystem model to estimate herbaceous biomass production given climate, nutrient availability, and soil properties (Kowal et al. 2021). The rangeland area size for each province used to calculate stocking density is also derived from RPM. Cashmere market price and total livestock number data by province are sourced from the National Statistics Office (NSO).

Table 1. List of the final selected variables and their definition

Data source	Variables	Description	Unit
HSEH	Net income	Yearly net income for each household from doing livestock husbandry (net income = selling animal/products - expenditure on animals)	Tugrig*
HSEH	Household size	Number of household members in each household	People
HSEH	Livestock number	Total livestock number for each household converted to goat unit (GU)	Heads of GU
HSEH	Cashmere yield	100 grams of cashmere per goat in the household for each year	100g/goat
HSEH	Other income	Pension and benefits other than revenue from livestock production	Tugrig
HSEH	Location	Dummy to indicate whether the household is located in a settlement or the countryside	Code: 0. Countryside 1. Settlement
HSEH	Water condition	Dummy to indicate main water source types, divided by whether water sources are fixed in location or not. Examples of fixed water are centralized water supplies, dug wells, and springs. Unfixed water includes tanker trucks, rainwater, surface water…etc.	Code: 0. Unfixed 1. Fixed
NSO	Cashmere price	The average market price of cashmere per kilogram in each province for each year	Tugrig/kg
RPM	Biomass	The average potential biomass production in grassland for each province in a specific year	Kg/ha
NSO and RPM	Stocking density	Total number of goat units per hectare of each province's rangeland area in a specific year.	GU/ha

*Tugrig: Mongolian currency. One US dollar is roughly equivalent to 3500 Mongolian tugrig

Biomass does not have a direct relationship with income but influences it indirectly through livestock, which depends on forage availability (Herrero et al. 2013). The quantity of grassland biomass, measured in kilograms per hectare, determines the forage availability of the grassland, which directly impacts stocking density, the total number of livestock units a grazing area can support. Biomass serves as the basis for estimating potential stocking density and acts as an instrumental variable (IV) because it is exogenous determined by environmental and climatic factors, and is strongly correlated with actual stocking density (correlation coefficient = 0.62). Meanwhile, actual stocking density is treated as an endogenous variable, influenced largely by biomass and potentially by other management and environmental factors. I assume this structure stands and employed the two-stage least squares (2SLS) method. The model is described in equations (1) and (2). I used logarithm to treat heteroscedasticity on both the dependent variable and two major independent variables, biomass, and livestock number[11].

In the first stage, regress the endogenous variable of stocking density on the instrumental variable biomass to get the predicted values of stocking density (donated as $\widehat{SD_{Jt}}$). μ is the error term.

$$\widehat{SD_{Jt}} = \pi_0 + \pi_1 \, log\big(biomass_{jt}\big) + \mu_{jt} \qquad (1)$$

In the second stage, the dependent variable $log\ (Net\ income_{it})$ is regressed on the predicted stocking density from the last stage with other variables. Where the dependent variable is the net income of livestock production for a household i at province j in year t. Cashmere price, stocking density, and biomass are at province j in year t.

$$\begin{aligned} log\ (Net\ income_{jit}) & \\ = \beta_0 &+ \beta_1 \, log\big(livestock\ number_{jit}\big) + \beta_2 \widehat{SD_{Jt}} + \beta_3 household\ size_{jit} \\ &+ \beta_4 cashmere\ price_{jt} + \beta_5 other\ income_{jit} + \beta_6 water\ condition_{jit} \\ &+ \beta_7 cashmere\ yeild_{jit} + \beta_8 location_{jit} + \epsilon_{jit} \qquad (2) \end{aligned}$$

Cluster analysis further is applied to this model. One cluster is based on biomass level and ecozones, another cluster is created based on net income and household size. Each cluster contains three groups to represent biomass and wealth status from low to high.

Results

The main results from equations (1) and (2) are summarized in Fig. 1 which are the coefficient (dots) and their confidence intervals (lines across dots). All results are significant. Except for stocking density, all other factors are positively related to it. Livestock number is most positively associated with net income. In the first stage regression, the relationship reveals that a 1% increase in biomass corresponds to a 0.005 GU/ha (0.507/100) increase in stocking density. Predicted stocking density, however, shows a negative relationship with net income in the second-stage regression. The coefficient indicates that an increase of 0.1 GU/ha in stocking density is associated with a 1.8% decrease in net income from livestock production.

[11] When doing the log transformation, I add 1 to handle zero values in those variables. By adding 1 does not change final interpretation since both net income, livestock number and biomass are large values.

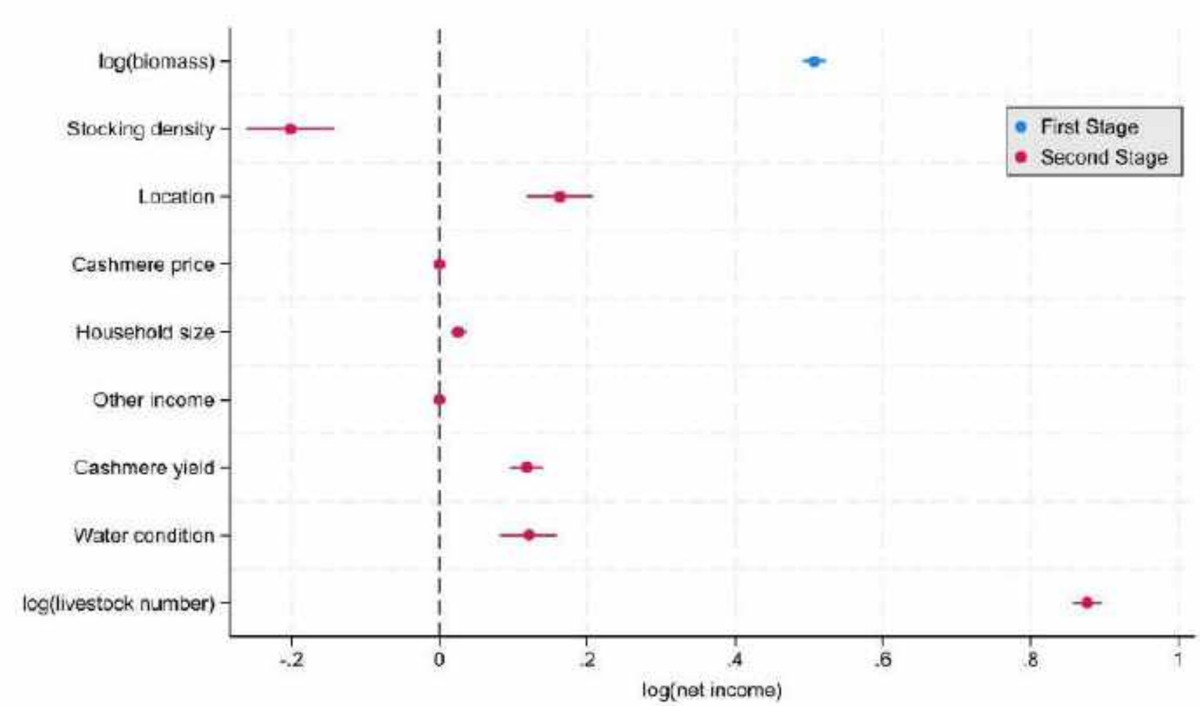

Fig. 1. General results from IV regression. Factors correlated with net income

Most results are also significant in all cluster analyses. I chose the most important variables and the main takeaway in each cluster group to be reported in Table 2. The first stage column reports the relationships between biomass and stocking density and the second stage column displays the relationship between predicted stocking density and the net income of livestock production.

Table 2. The main results from IV regressions by each biomass or wealth cluster group

Cluster group	First stage (Log (biomass) on stocking density)	Second stage (Stocking density on net income)	Interpretation of main results
Low-biomass	0.41	-0.232	Income response to cashmere yields more than other variables
Middle-biomass	0.888	0.367	Stocking density correlates positively with net income
High-biomass	-2.544	0.122	Stocking density is potentially constrained by the availability of or access to grazing land
Low-wealth	0.478	-0.169	Decreased net income is associated with stocking density increase
Middle-wealth	0.55	-0.076	Net income increases by higher biomass but possibly unreliable results due to low R squared
High-wealth	0.6	-0.03*	Stocking density is not related to net income

Note: Numbers are coefficients and * means statistically insignificant

Discussion

In the general results, the positive relationship between biomass and stocking density shows the basic idea that the more biomass, the more livestock the rangeland can support. This declining relationship between stocking density and net income is likely due to the increased demand for grass resources and heightened competition among livestock for adequate forage, reducing the per-unit livestock production. This negative association further suggests overgrazing which is a classic example of the tragedy of the commons, a concept articulated by Garrett Hardin in 1968. Increasing stocking density often leads to overgrazing since it exceeds the carrying capacity of grassland (Piipponen et al. 2022), then the degraded rangelands due to overgrazing disrupt the balance between livestock and their environment, leading to decreased livestock productivity and income, harming all users in the overgrazed areas (Silayi et al. 2024).

When breaking down the relationships by different clusters, the results suggest that regardless of the wealth status, increasing stocking density is related to less net income for livestock production. However, richer households can cope with it by keeping the larger scale of herds and having access to the market and more resources. Poorer households with less livestock will have a larger loss in net income since they are too weak to compete with richer households.

Low-biomass cluster suggests that overgrazing has happened but not for middle-biomass regions. The negative association between biomass and stocking density could mean some constraints prevent animals from grazing on land in the high-biomass group. Given the high biomass regions have the highest forest, cropland cover, and population density, lands may be turned to other uses than rangelands so fewer pastoralist households live in those areas resulting in less stocking density whereas the biomass is high.

All results suggest that livestock numbers should be regulated from overgrazing yet Mongolia currently does not have a systematic policy to control livestock numbers (ADB 2018). A higher positive association between cashmere yield and net income in low-biomass areas highlights that the decision-making in production and policy should help pastoralists focus on improving cashmere productivity instead of increasing the quantity of goats. Future studies should build on this study by using panel data to analyze effects between biomass, stocking density, and economic returns in a geographic spilite and dynamic format. Further policy analysis on livestock management and its impact is requested from this paper.

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Effect of dietary combinations on productivity and greenhouse gas emissions in lambs

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Key words: Forage combinations; methane; Production performance, Apparent nutrient digestibility

Abstract

Livestock farming is one of the main sources of global greenhouse gas emissions, particularly methane produced during the digestion process of cattle and sheep, which not only harms the environment but also results in feed energy loss. Therefore, it is essential to understand the patterns and influencing factors of livestock greenhouse gas emissions to improve feed energy efficiency and protect the environment. By feeding different combinations of roughage, production efficiency can be increased and pollution reduced. Different forage compositions lead to varying greenhouse gas emissions in lambs. Understanding the response of productivity and greenhouse gas emissions to dietary combinations, exploring green regulation methods, and focusing on low-carbon emission reduction technologies are crucial for reducing methane pollution, improving feed utilization, ensuring animal health and product safety, and promoting sustainable livestock farming. This study selected 24 healthy lambs of similar weight, randomly divided into four groups of six, and fed different combinations of diets: natural hay, oat hay + natural hay, alfalfa hay + natural hay, and alfalfa hay + oat hay. Feed intake, weight changes, and greenhouse gas emissions were measured during the experiment.

The results showed: (1) Under ad libitum feeding conditions, the dry matter intake of the alfalfa hay + oat hay group and the natural hay group was significantly higher than that of the other two groups ($P<0.05$); the protein intake of the oat hay + natural hay group was significantly lower than that of the other three groups ($P<0.05$). (2) The average daily weight gain of lambs in the alfalfa hay + natural hay group was significantly higher than that in the oat hay + natural hay group ($P<0.05$) . (3) The trend of CH4 emissions in lambs was similar to that of CO2, with the natural hay group significantly higher than the other three groups, and the emissions in the alfalfa hay + oat hay group being the lowest; the N2O emissions in the alfalfa hay + oat hay group were also significantly lower than those in the oat hay + natural hay group. This indicates that feeding natural hay significantly increases the greenhouse gas emissions of lambs .

Introduction

Livestock consumption is projected to increase by 70% by 2025 due to global population growth, urbanization, and rising incomes (FAO 2017). Meeting this growing demand will require significant improvements in animal productivity and feeding efficiency. Efficient animal feeding involves producing economically viable and safe animal products while utilizing natural feed resources effectively an Consequently, animal welfare and health, product quality and safety, and greenhouse gas emissions are critical considerations when developing strategies for precision animal husbandry. Enteric methane emissions from ruminants not only represent an energy loss from their diet (Tseten et al. 2022; van Wyngaard et al. 2018), but also contribute significantly to global warming (Yang et al. 2021). While ruminants emit carbon dioxide (CO_2) through respiration and feed fermentation, this CO_2 originates from biogenic carbon in feed (e.g., plant biomass) and is not classified as a human-induced GHG in national inventories (IPCC, 2021), as it is part of the natural carbon cycle. In contrast, nitrous oxide (N_2O) is closely linked to nitrogen conversion in faeces and urine. Although N_2O emissions are typically lower than CH_4 in ruminants, its high global warming potential (298× CO_2 equivalent) makes it a critical contributor to climate change (IPCC, 2019). Exploring the effects of different forage types on CH_4 and N_2O emissions is essential. Such research can help reduce the environmental footprint of ruminant production while improving energy and nitrogen utilization efficiency, ultimately enhancing animal productivity.

Forage plays a critical role in ruminant feeding systems due to its affordability and abundant dry matter supply. However, its low feeding value makes it insufficient to meet the nutritional requirements of animals for production when used alone (Du et al. 2019). To address this limitation, researchers have explored supplementing natural pasture-based diets with legumes, which are rich in protein and energy (Graham and Vance 2003). Some studies have demonstrated that the use of legumes as a source of roughage in ruminant diets can reduce methane emissions (Alecrim et al. 2024; Quintero-Anzueta et al. 2021). Compared to grass forages, legumes are characterized by lower structural carbohydrate content, faster physical breakdown, and quicker rumen fermentation (Niderkorn et al. 2011). Consequently, feeding legume forages increases the rate of dry matter passage, which is expected to reduce rumen methanogenic activity (Haque 2018a ; grange et al. 2021) Abreu's study showed that a 3:1 grass/legume mixed ration increased organic matter (OM) and crude protein (CP) intake and rumen ammonium nitrogen concentration compared to a diet of only grass (Abreu et al. 2004). In addition, having a higher proportion of NSC in legumes compared to grasses may drive rumen fermentation to produce more propionic acid, thereby reducing hydrogen availability to methanogenic bacteria (Wang et al. 2018). Doran 's study demonstrated that whole gut digestibility of crude and digestible protein was significantly higher in alfalfa : oats = 1:1 diets than in diets with oat hay as a source of roughage (Doran et al. 2007). Moreover, the combination of alfalfa (78%) and oats (22%) in the diet resulted in a reduction of energy loss through lower methane emissions, as compared to a diet with only graminoid forages (McCaughey et al. 1999). However, these studies focused on diets where supplementation of legumes was the only factor considered. Few studies have been conducted to explain the effects of different forage combinations on ruminants. Therefore the aim of this study was to determine the effects of adding alfalfa hay and oat hay to lamb diets on productivity, apparent digestibility of nutrients, and methane production.

Methods

Animals, diets, and study design

The experiment was conducted from June to August 2018 at Baiyinxile Ranch, Xilingol League, Inner Mongolia. The experiment involved 24 Uzhumqin crossbred lambs with an initial weight of 23.56 ± 1.54 kg (mean ± standard deviation). The experiment was conducted in a completely randomised block design with the lambs divided into four groups of six each for a period of two months. The lambs were fed natural hay (N), oat hay + natural hay (NO), alfalfa hay + natural hay (NA) and alfalfa hay + oat hay (AO), and the nutrient composition of the diets is shown in Table 1. The lambs were housed in 1m × 2m pens, dewormed from internal and external parasites and vaccinated before the trial, and pre-fed for 10 days. All lambs were given free access to water and feed samples were collected at feeding time. The daily residue was recorded and used to estimate the feed intake per animal.

Table 1 Diet conventional nutrients (air-dried basis) unit : %

Item	AO	NA	NO	N
Dry Matter （DM）	95.88	97.35	96.65	98.12
Crude Protein （CP）	9.68	10.83	6.49	7.63
Ether Extract （EE）	7.07	7.78	7.03	7.83
Acid Detergent Fiber （ADF）	36.90	47.30	50.10	60.49
Neutral Detergent Fiber （NDF）	60.57	54.66	66.40	60.49
Organic Matter (OM)	91.36	92.43	92.97	94.04

Feed intake and chemical composition

Nutrient intake is determined by the difference between the amount of each ingredient contained in the feed provided and the amount contained in the remaining species. The chemical composition of the diets was carried out at the Grass Public Laboratory, China Agricultural University. The compositions of the feed ingredients were determined by the method of AOAC (1998). The neutral detergent fiber (NDF) and acid detergent fiber (ADF) were analyzed based on the method of Van Soest *et al*. (1991) using an ANKOM fiber analyzer.

Greenhouse gas collection

Methane measurements are made using a combination of a sealed respiratory metabolism chamber, a gas collection tube and a greenhouse gas concentration analyser. The metabolic chamber allows the simultaneous measurement of methane production in two sheep. Each respiratory chamber was equipped with a trough and a water trough, and the test sheep were allowed to feed and drink freely during the test period. The animals were placed in 12 batches (2 animals/batch, 2 animals/group) 3 days before the start of the experimental period and acclimatised for 1 h. The methane and carbon dioxide production as well as faecal and urinary nitrous oxide (NOx) emissions were measured for 1 h after feeding. Emissions of methane, carbon dioxide and nitrous oxide were collected through a gas collection tube for 1 h. The gases were stored in a gas collection bag, and the collected gas samples were analysed using a greenhouse gas concentration analyser (G2308; Picarro; Beijing, China).

Statistical analysis

The experimental data were initially collated using Excel 2021. Statistical analyses were performed using SPSS 27 software and one-way analysis of variance (ANOVA) was used to assess the effect of different feeding combinations on feed intake, nutrient digestibility and GHG emissions. Duncan's multiple range test was used to compare significant differences and the significance level was set at $P < 0.05$.

Results

Feed intake and growth performance

Under ad libitum feeding conditions, the dry matter intake of AO and N was significantly higher than that of the other two groups ($P < 0.05$). The protein intake of NO was significantly lower than that of the other three groups

(P < 0.05) (Fig.1). Additionally, the average daily weight gain of lambs in NA was significantly higher than that of NO (P < 0.05) (Fig.2).

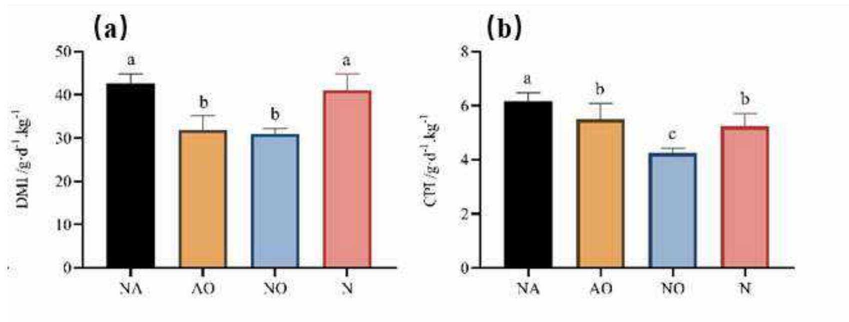

Fig.1 Dry matter and protein intake of different diet groups

Note: NA: alfalfa hay + natural hay; AO: alfalfa hay + natural hay; NO: Oat hay + natural hay; N: Natural hay；a、b、c indicates the difference between dry matter intake and protein intake between diets. Fig.1a shows the dry matter intake of different dietary groups, and Fig.1b shows the protein intake of different dietary groups.

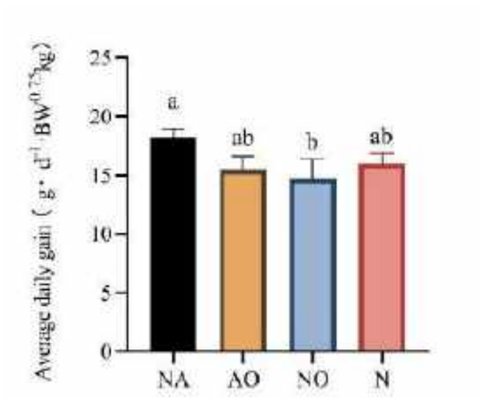

Fig.2 Effect of diet combination on average daily gain of sheep

Note: a、b、c indicates the difference between average daily weight gain of lambs between diets

Apparent digestibility of nutrients

Table 2 shows the effect of different roughage combinations on the apparent digestibility of nutrients in lambs. No significant differences were found between the four roughage combinations in terms of digestibility of dry matter, organic matter and neutral detergent fibre. However, N significantly increased the intake of ADF by lambs (P < 0.05). In addition, ADF digestibility was 26.83% and 19.84% higher with N compared to NA and AO, respectively. In addition, crude protein digestibility was significantly lower (P < 0.01) in N than in the other three treatments.

Table 2 Effects of diet groups on apparent digestibility of nutrients in sheep

Items	NA	AO	NO	N	P-value
Dry matter					
Intake/（g/d）	815.09±33.24	784.16±41.25	707.95±21.64	229.67±20.54	0.277
Feces outpu（g/ d）	356.01±18.66	330.54±20.55	306.83±31.76	331.09±12.00	0.580
Apparent digestibility (%)	22.75±3.63	47.82±1.74	56.71±2.93	56.93±4.09	0.976
Orangic matter					
Intake/（g/d）	753.29±20.71a	716.40±25.41ab	658.19±13.56b	733.30±12.78a	0.047
Feces output（g/ d）	310.11±11.20	277.50±12.66	269.28±15.30	278.65±18.77	0.232
Apparent digestibility (%)	58.29±2.34	61.24±1.27	59.13±1.94	61.43±2.57	0.650
Neutral detergent fiber					
Intake/（g/d）	418.94±11.52	499.89±15.96	447.63±9.22	446.40±19.96	0.412
Feces output（g/ d）	199.48±7.49a	170.66±9.48b	163.39±9.53b	174.0±10.93ab	0.053
Apparent digestibility (%)	58.29±2.34	61.24±1.27	59.13±1.94	61.42±2.57	0.650
Acid detergent fiber					
Intake/（g/d）	277.3±11.39b	262.58±13.23b	255.97±12.66b	340.62±37.42a	0.032
Feces output（g/ d）	117.67±6.97a	104.68±6.70ab	84.86±9.82b	90.25±4.09b	0.015
Apparent digestibility (%)	56.25±3.79bc	59.53±2.44c	66.52±3.73ab	71.34±1.77a	0.007
Crude protein					
Intake/（g/d）	98.21±3.48b	114.33±3.14a	87.18±1.80c	77.04±3.45d	＜0.001
Feces output（g/ d）	43.22±1.06	41.55±2.12	38.96±1.87	40.96±3.07	0.577
Apparent digestibility (%)	61.73±1.77a	57.73±1.58a	55.35±1.73a	45.85±3.97b	＜0.001

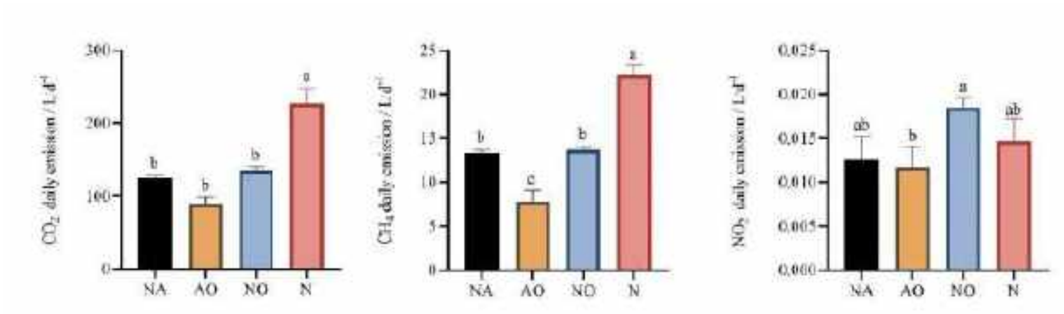

Fig.3 Effects of dietary combination on greenhouse gas emissions of sheep

Greenhouse gas production

The CH_4 emission pattern of lambs was the same as that of CO_2, and N emissions were significantly higher than those of the other three groups. AO emissions were the lowest among the groups. In addition, N_2O emissions were significantly lower for AO than for NO.These results suggest that feeding natural hay significantly increased GHG emissions from lambs ($P < 0.05$) (Fig. 3).

Discussion

Feed type and composition play a crucial role in grazing livestock production systems, significantly influencing nutrient utilization efficiency, animal performance, and greenhouse gas emissions (Schils et al. 2007). Studies have shown that the addition of alfalfa hay significantly improves the nutritional quality of roughage combinations, thereby promoting the daily weight gain of lambs (Wang et al. 2020; Wang et al. 2023). Alfalfa hay, with its high crude protein and low fiber content, provides lambs with sufficient energy and nitrogen to enhance rumen microbial activity and nutrient absorption efficiency (Ishaq et al. 2019). This superior nutritional profile not only improves the nutrient metabolism of lambs but also significantly boosts their growth performance in a shorter time (Ren et al. 2024). In contrast, the oat hay + natural hay group, whilst demonstrating a role in meeting the basic nutritional requirements of lambs, may have limited further improvements in growth performance due to low protein levels (Xiao et al. 2021). In particular, the low nitrogen content of oat hay leads to limited microbial activity in the rumen, which reduces the efficiency of protein catabolism and indirectly affects lamb performance (Kittelmann and Janssen 2011). In addition, although feeding natural hay alone has a higher utilization rate of ADF, its overall protein supply capacity is insufficient. This limitation indicates that relying solely on natural hay as a feed may not meet the growth requirements of lambs, and supplementation with high-protein feeds, such as alfalfa hay, is necessary to compensate for the deficiency (Huang et al. 2021).

The primary greenhouse gases emitted by ruminants include methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O), and their emission levels are strongly influenced by feed composition (Broucek 2014).This study further highlights significant differences in greenhouse gas emissions among various feed combinations (Haque 2018b). Methane, the primary greenhouse gas produced during rumen fermentation, is influenced by the type of feed and its fiber content. High-fiber feeds typically result in longer fermentation times in the rumen, promoting the growth of methanogenic microbes (Bharanidharan et al. 2021 ; Bhatta et al. 2017). In this study, lambs fed natural hay exhibited significantly higher CH_4 emissions compared to other groups. This is attributed to the higher levels of neutral detergent fiber (NDF) and acid detergent fiber (ADF) in natural hay, which provide ample substrates for rumen microbes, thereby increasing methanogenic activity (Wallace et al. 2015). Conversely, the AO group had the lowest CH_4 emissions due to the feed combination's low fiber and high protein content. High-protein feeds pass through the rumen more quickly, reducing fermentation time for methanogens and effectively lowering CH_4 emissions (Pepeta et al. 2024). The CO_2 emissions of the natural hay group were significantly higher than those of other groups, primarily due to increased energy metabolism driven by the high fiber content. Ruminants expend more energy breaking down fiber, and the fermentation process releases greater amounts of carbon-based volatile compounds, further exacerbating CO_2 emissions (Ungerfeld 2020). N_2O emissions from ruminants primarily result from nitrogen transformations in manure and urine, which are influenced by feed nitrogen content and ammonia volatilization (Zhao et al. 2023). This study found that the AO group exhibited significantly lower N_2O emissions compared to the NO group, likely due to the higher protein content of alfalfa hay. This allows for more efficient nitrogen absorption and utilization by the lambs, reducing the accumulation of residual nitrogen in manure.

These findings provide valuable insights for feed management and low-carbon livestock practices in pastoral areas. By reducing fiber content and supplementing with easily digestible, low-fiber feeds (such as alfalfa hay), methane emissions from rumen fermentation can be reduced. Additionally, increasing protein levels and optimizing the inclusion of high-protein feeds in the diet improves nitrogen digestion and absorption efficiency, reducing ammonia volatilization and N_2O emissions. In areas dominated by natural hay, increasing the use of alfalfa and oat hay can enhance livestock productivity while effectively reducing greenhouse gas emissions. Encouraging scientific feed combinations will bring both economic and environmental benefits.

Acknowledgements
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Commercial-scale implementation of wet season spelling for Mitchell grass recovery

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Key words: wet season spelling, Mitchell grass, grazing management, seasonal variability

Abstract

Mitchell grasses (*Astrebla* spp.) are the dominant component of the alluvial cracking clay grasslands of the Barkly Tablelands region in the Northern Territory, Australia. Mitchell grasses are native palatable, productive and perennial grasses that contribute significantly to cattle diet quality and quantity in the region. Several years of below-average rainfall resulted in a noticeable reduction in Mitchell grass tussocks in 2022. The Barkly Region component of the Rain Ready Rangelands (RRR) project trialled the commercial-scale application of wet season spelling to promote Mitchell grass recovery.

The pastoralist-led demonstration used four paddocks on a demonstration site 440km north east of Tennant Creek, Northern Territory. Three paddocks were used in a wet season spelling rotation, with one paddock continuously stocked as a control. Farmbot™ telemetry units were used to record daily rainfall data remotely. Using the Botanal field sampling methodology (Tothill et al. 1992) data were collected from each paddock before and after the 2023/24 wet season inside and outside of new 100m by 100m cattle exclosures in each trial paddock.

Changes in vegetation throughout the trial period were strongly influenced by successive high rainfall years, biomass increased in all paddocks both inside and outside of the exclosures regardless of management strategy. However, despite the high rainfall and moderate to low pasture utilisation, there was a tendency for a greater increase in total perennial grass basal area inside exclosures than in grazed areas. There was some early evidence from vegetation monitoring that recovery was enhanced inside exclosures and reduced in the poor (C) condition areas where there were very few pre-existing perennial grass plants. There was also a higher pasture growth response at the better land condition site with the same rainfall and grazing impact. This provides evidence of the benefits of promoting land condition recovery. We aim to continue to monitor the impacts of wet season spelling on Mitchell grass health in these paddocks through time.

Introduction

Wet season spelling is a grazing management strategy that can assist in the recovery of palatable perennial pastures by removing selective grazing during the growing phase and enabling palatable, perennial tussocks to establish and rebuild root reserves (Ash et al. 2011, O'Reagain and Scanlan 2013, O'Reagain et al. 2014, Scanlan et al. 2014). Without perennial pastures, annual grasses and forbs can become dominant leading to lower pasture biomass, higher detachment and feed shortages during the dry season. This can have a cumulative impact in years with low rainfall.

Understanding the impacts of grazing management changes can be difficult to measure when combined with highly variable rainfall. Land condition change can be both slow (for most years) and then fast and sudden when rainfall, low grazing pressure and seedbank availability combine to provide the best conditions for establishment of new plants (Watson et al. 1996). Establishing sites that can be monitored long term, with and without grazing across variable years is needed to observe and measure changes.

This demonstration was designed to provide the information that may increase pastoralist confidence in implementing wet season spelling to promote Mitchell grass recovery. The objective of the project was to test the efficacy and practical implementation of wet season spelling to promote the recovery of Mitchell grass at the commercial scale.

Methods

The demonstration site included four paddocks ranging in size from 67 to 125 km^2 on Anthony Lagoon Station in the Barkly Tableland region of the Northern Territory. Three paddocks were part of a wet season spelling rotation (No. 5 East, No. 5 West, No. 6), with one paddock (No. 4) continuously grazed as a control. At the start of the project, the carrying capacity (AE/km^2) (AE = 450kg steer) of each paddock was calculated using regionally calibrated modelled pasture growth and safe utilisation rates for the land type (Pettit, 2011; Rickert et al. 2000; McLennan et al. 2020). Cibo Labs land condition spatial data (provided by the property owner) was used to adjust total modelled pasture growth for each paddock to better reflect potential pasture growth. To calculate the short-term stocking rates in the grazed paddocks carrying capacities were converted to AE/day. Decisions about cattle movements and which paddocks were grazed or spelled were determined by the property manager with advice from the project team. Thus, No. 5 East was wet season spelled with all cattle from No. 5 East and West going into No. 5 West on 18 December 2023.

In each paddock, a 100m by 100m exclosure was erected to exclude grazing for comparison to the surrounding continuously grazed and rotationally spelled paddocks. Site locations were selected between 1 and 2 km from a water point where Mitchell grass was present but in poorer condition. Four transect lines, 87m in length were established inside each exclosure. Four additional transect lines of the same dimensions were established parallel to the exclosure in an area most representative of species' composition and biomass (control treatment). An additional unfenced monitoring site with 4 transect lines was established in an area of good (A-B) land condition in Paddock 5 West where Mitchell grass was dominant. Fifteen $1m^2$ quadrats were assessed for vegetation composition, pasture biomass, ground cover and perennial grass basal area along each transect line in October 2023 and May 2024.

Results

The rainfall in No. 4 and No. 6 Paddocks during the 2023-24 wet season was well above average (in the top 95% of all years) with 1132mm received. The October 2023 baseline pasture assessments highlighted a natural variation in pasture yield between paddocks (Fig. 1). Total standing dry matter (TSDM) inside and outside of the exclosures were similar in each paddock in October 2023. TSDM increased at all sites between October 2023 and May 2024. The average increase in TSDM was consistent in all exclosures (2010 kg/ha ± 112). Outside the exclosures, TSDM varied depending on the grazing treatment and pasture type. The good land condition site in No. 5 West paddock increased TSDM by 1653kg/ha between October 2023 and May 2024, compared to No. 5 West outside exclosure site which increased by 896kg/ha, despite both being in close proximity and the good land condition size having higher grazing scores.

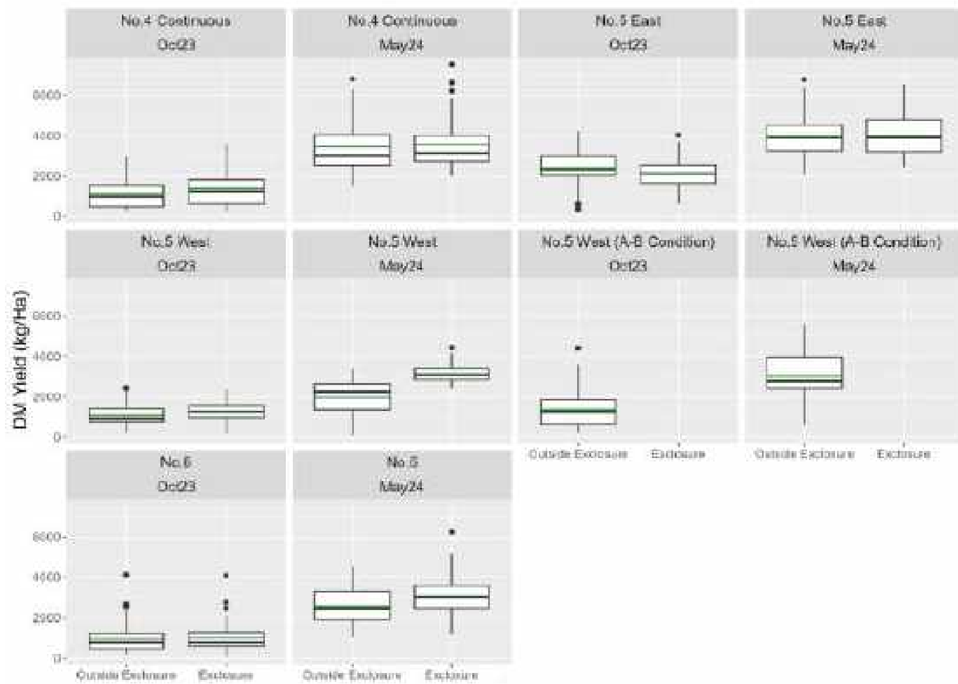

Figure 1: Total yield (kg dry matter/ha) inside and outside of exclosures, October 2023 and May 2024. Mean (green line), median (black line), middle 50% of data (box), min and max (whisker), outliers (dots)

The combined *Astrebla elymoides*, *Astrebla pectinata* and *Astrebla squarrosa* (Mitchell grasses) yield is shown in Fig 2. *Astrebla* species yield increased between October 2023 and May 2024 in all exclosures except No. 5 East. No. 5 West had the lowest yield of *Astrebla* species with no *Astrebla* spp. in the outside exclosure site in October 2023 and a small increase by May 2024 (4kg/ha). The No. 5 West good land condition site had the highest Mitchell grass yield of all sites in May 2024 (1848kg/ha, 61% of TSDM).

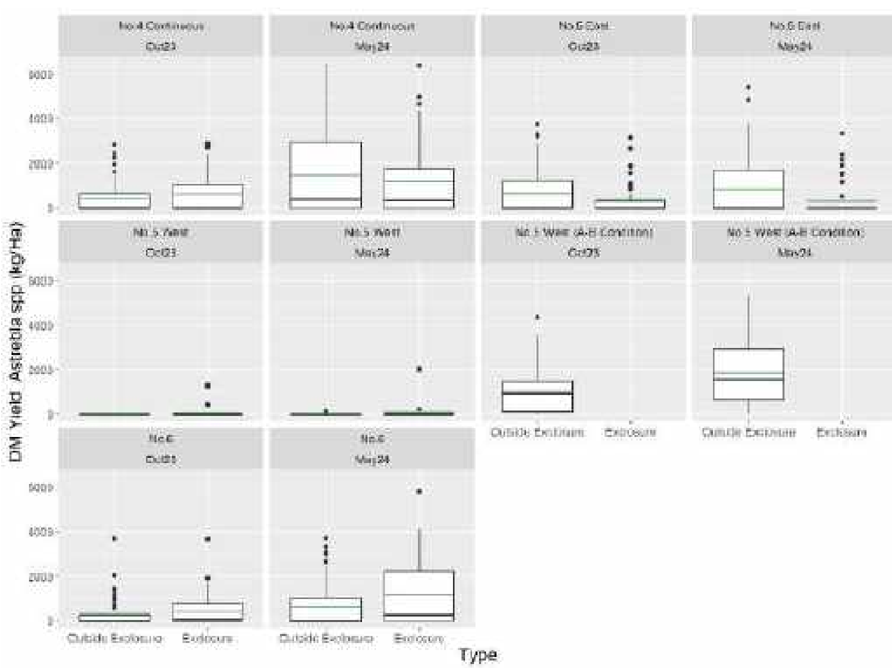

Figure 2: Total yield (kg/ha) contribution of grouped Astrebla spp. inside and outside of exclosures, October 2023 and May 2024. Mean (green line), median (black line), middle 50% of data (box), min and max (whisker), outliers (dots)

There was a high level of variation in grass basal area of *Astrebla* species across all paddocks and treatments (Fig. 3). Grass basal area of *Astrebla* species increased over the wet season at all sites in No. 4 paddock and in the exclosure of No. 6 Paddock.

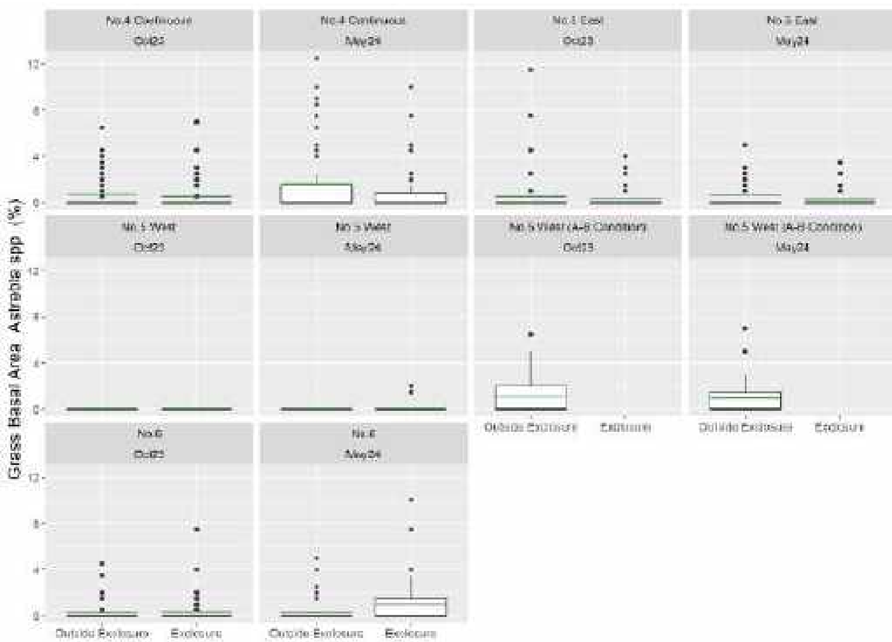

Figure 3: Grass basal area of *Astrebla* spp. in October 2023 and May 2024. Mean (green line), median (black line), middle 50% of data (box), min and max (whisker), outliers (dots)

Grazing scores (defoliation) outside exclosures were low to moderate across all paddocks in May 2024 but were higher in No. 5 West and the good condition site in No. 5 West. This was due to the additional cattle from the spelled No. 5 East paddock on the 18th of December 2023.

Discussion

The initial differences found inside and outside of exclosures and between paddocks in October 2023 (Fig. 1) were due to the underlying variability in soils, vegetation and grazing history, as the exclosures had only been recently established. Results highlighted the natural variance in pasture composition and yield.

Changes in vegetation throughout the trial period were strongly influenced by rainfall. Generally, in high rainfall years yield increased in all paddocks both inside and outside of the exclosures regardless of management strategy. However, yield increase was lower outside No. 5 West exclosure, presumably due to the higher stocking rates in the paddock (supported by the higher observed defoliation). The two outside exclosure sites in No. 5 West had the same grazing treatment and distance from water effects, however they had different pasture growth responses. The total yield increase in the good (A-B) land condition site was close to double the yield increase in the adjacent No.5 West outside exclosure site that began in C condition. While not unexpected, this provides “seeing is believing” evidence of the impact grass basal area has on biomass production and the importance of promoting perennial grass recovery for a climate resilient feedbase.

Astrebla spp (Mitchell grass) biomass increased over the wet season in all paddocks and sites except the No. 5 East exclosure. The low grass basal area of *Astrebla* spp. in No. 5 West C condition site may mean recovery will take longer to occur, with few plants present to provide a local seed source for establishment of new plants.

Changes in land condition and Mitchell grass recovery are unlikely to be observed after just one year in rangelands where land condition change is slow and episodic (Watson et al. 1996). However, after successive high rainfall years, there was some early evidence from vegetation monitoring that recovery was enhanced inside exclosures, and reduced in the C condition areas where there were very few pre-existing perennial grass plants to build upon. There was also a stronger pasture growth response at the better land condition site with the same rainfall and grazing impact, which provides evidence of the benefits of implementing grazing strategies that promote grass basal area recovery and better land condition. Longer term monitoring is required to see if the wet season spelling strategy has advantages over the continuously grazed paddock when both are grazed at recommended stocking rates. The project has established baseline data across the demonstration site to compare future seasonal conditions and impacts of wet season spelling.

Acknowledgements
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Multipurpose shrub and tree legumes for Northern Australian rangelands

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Key words: Ecosystem services, shade, shelter, Mitchell Grass Downs

Abstract
The vast open rangelands of Australia's Mitchell Grass Downs Bioregion as depicted in Figure 1 are a significant producer of livestock and the region is dominated by the *Astrebla* grass species. Multipurpose shrub and tree legumes could play an important role in providing many ecosystem services such as drought fodder, shade, shelter, N fixation, carbon sequestration, biodiversity, habitat, and they may also potentially contain novel compounds that could have useful phenolic and or antioxidant, anti-methanogenic properties which could benefit animal production and the environment.

As part of CRC P 58599 project "Legumes for the north" the seeds of a range of native and exotic shrub and tree legumes were sourced from across North Queensland, grown as tube stock and then transplanted at five sites across the region to evaluate their adaptability to the region. The mix of species included fast and slow growing, long lived and short-lived perennials including species of *Acacia, Adenanthera, Albizia, Bauhinia Cajanus, Gliricidia, Peltophorum, Pongama, Sesbania, and Vachellia.* Most of these species were planted at each site on vertosol soils in semi-arid locations with mean annual rainfall from 400mm to 580mm, and irregularly watered by artisan bore water until well established.

After three years of growth, initial observation of the establishment phase and persistence indicates that several species across the sites show agronomic promise including but not limited: *Albizia lebbeck, Gliricidia sepium, Peltophorum pterocarpum.* Several species failed to persist or have had poor growth at least at some sites including *Cajanus cajun*, *Sesbania sesban* and *Adenanthera pavonina*.

It is envisaged that the successful species could be planted as mixed species plantings on the open treeless grasslands radiating out along fence lines from existing bores/farm dams with simple trickle irrigation likely to be essential for at least the establishment phase. Once established the shrubs and trees would provide many of the ecosystem services outlined above.

Introduction

Shrubs and trees have long been considered important for the nutrition of grazing and browsing animals in Australia, particularly in the north where the quantity and quality of pastures is poor for long periods. Over 70% of Australia falls within the arid and semi-arid climatic zones where extensive grazing of livestock is the dominant land use (Lefroy *et al* 1992.) This includes the vast open, mainly treeless (Fig 1) rangelands of the Mitchell Grass Downs Bioregion which are dominated by the *Astrebla* grass species. The climate of the region is severe as is the edaphic environment with vertosol soils. These rangelands are dominated by C4 grasses noted for their resilience but are of poor nutritive value and decline in quality with maturity (Minson 1981). Lowry *et al* (1993) suggest that the introduction of legumes may increase production not only through an increase in total edible dry matter but by acting as a supplement to promote the utilisation of the lower quality diet. To date, the introduction of sown legumes has proved difficult, with few, if any, being successful (Gardiner 2016). However, adapted and resilient shrubs and trees may be an option and could potentially contribute to nutrition and other facets of animal production. During drought, top feed/browse species become of important (Chippendale and Jephcott 1963, Everist 1985). These authors and Newton (1970) and Guttridge and Shelton (1994) list many native and introduced shrub and tree species as having potential in northern grazing systems including *Acacia, Albizia, Bauhinia, Capparis, Desmanthus, Eucalyptus, Gliricidia, Geijera, Leucaena, Owenia, Sesbania* and *Vachellia* among others. Dynes and Schlink (2002) however note that investigations of the potential of native shrubs and trees (particularly *Acacias*) as fodder sources for livestock in Australia have been limited to the more widespread better-known species such as Mulga (*Acacia aneura*).

There are few shade trees in the region and temperatures are high, with mean maximum temperatures exceeding 35ºC for many months per year. For example, Camooweal in Western Queensland has on average 155 days per year with temperatures >35ºC, and 37 days per year >40ºC (BOM 2024, McCosker 2023). The importance of heat stress in limiting potential animal production in NW Australia was noted by Petty (1997, and lack of shade can be detrimental to survival of newborn calves and lambs (Schmidt 1969 cited by Orr and Holmes 1984). Tunkala *et al* (2023) studied the *in vitro* characteristics of several of the aforementioned species and found that *Gliricidia* and *Vachellia* have a slowly degradable protein content while *Bauhinia* emerged as a candidate to assist protein protection in the rumen and reduce methane emissions.

Multipurpose shrub and tree species could play a role in providing many ecosystem services such as drought fodder, shade, shelter, N fixation, Carbon sequestration, biodiversity, habitat, and they may potentially contain novel compounds with useful phenolic, antioxidant and/or anti-methanogenic properties of benefit to animal production and the environment.

This study set out to screen several well adapted shrubs and tree species that may then progress to (if not already) domestication and planting out as multipurpose species (Figure 1). These mixed shrub and tree plantings (including tall, short, fast growing, slow growing, palatable, not palatable species) would radiate out along fence lines from existing bores and farm dams or to nearby shelterbelts or groves with low-cost trickle irrigation to aid establishment.

Fig 1. A schematic concept diagram of before and after planting multipurpose species on the near treeless Open Mitchell Grass Downs utilizing existing bores and fence lines.

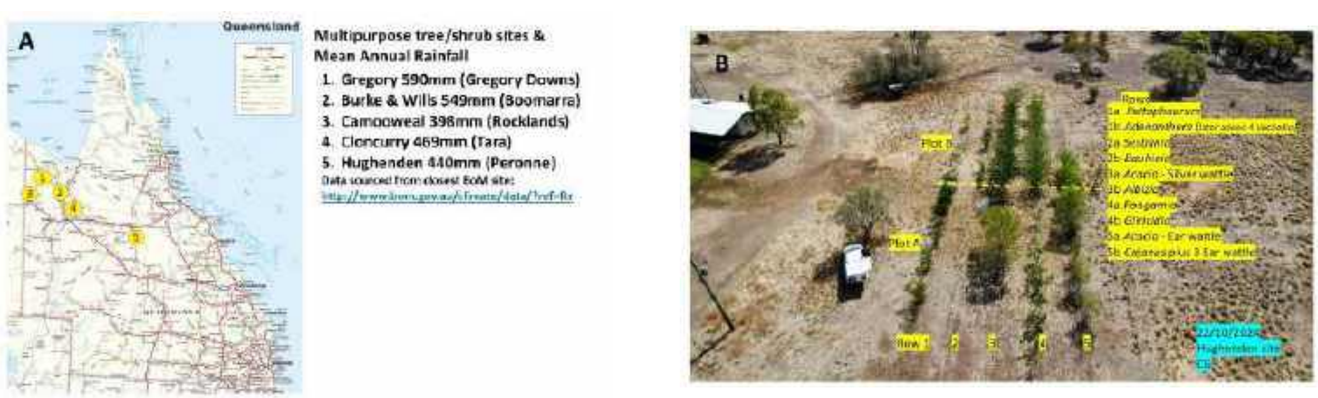

Fig 2. A) The location of the shrub/tree evaluation sites and mean annual rainfall of the sites. B) Aerial view of the layout and surviving species at the Hughenden trial site as of October 2024.

Methods

As part of CRC P 58599 project "Legumes for the north" and during COVID 19 pandemic period,(limiting travel and access to the remote sites) in 2020 seeds of a range of native and exotic shrub and tree legumes were sourced from across North Queensland. They were selected based on availability of seed and desirable traits such as drought tolerance, fodder production, edaphic adaptability, grown as tube stock in a commercial nursery and then transplanted to five sites across the region in mid-2021 (Figure 2). The aim was to evaluate the adaptability of the species to the region. The mix of species included fast and slow growing, long lived and short-lived species *Acacia auriculiformis, A.holosericea, Adenanthera pavonina, Albizia lebbeck, Bauhinia hookeri, Cajanus cajun, Gliricidia sepium, Peltophorum pterocarpum, Pongamia pinnata, Sesbania sesban,* and *Vachellia sutherlandii.* These species were planted at each of the five sites, except for *V. sutherlandii* (due to scarcity of seed) on vertosol soils in semiarid locations with mean annual rainfall ranging from 400mm to 580mm (Fig. 2). Plants where at least initially watered via a trickle irrigation system with water sourced from artesian bores/dams. The frequency of watering and maintenance of the plots varied across the sites. Infrequent watering occurred until the plants were well established. Where available, 13 seedlings of each species were planted 2m apart within rows with 4m between rows. The plots were inspected occasionally, with reports and images from station managers collated. Data presented here are for the Hughenden site only but reflect observed results across the region. At the Hughenden site data were collected on plant survival, height, diameter at breast height (DBH), and the general status of the plants was recorded in October 2024.

Results

After three years growth, initial observation of the shrub and tree establishment phase and persistence indicated that several species showed agronomic promise across the sites including: the *Acacia* species*, Albizia lebbeck, Bauhinia* hookeri*, Gliricidia sepium, Peltophorum pterocarpum* and *Pongamia pinnata.* Survival and growth (some to >4m tall, Table 1) varied across sites, with several short-lived species such as *Cajanus cajun and Sesbania sesban* displaying rapid initial growth and then tended to die at most sites. *Adenanthera pavonina* performed poorly at all sites.

Table 1. Shrub/treegrowth data from Peronne Station (Hughenden, NW Queensland) October 2024

Species	% survival	Mean DBH (cm)	Mean Height (cm)	Notes * = native
Acacia auriculiformis*	69	5.2	317	Dense foliage
A.holosericea*	23	4.4	438	Survivors are robust
Adenanthera pavonina*	15	N/A	100	Poorly adapted
Albizia lebbeck*	100	2.6	335	Leafy, good canopy, well grown
Bauhinia hookeri*	77	2.5	114	Slow growth but good survival
Cajanus cajun	0	0	0	Short lived species, initially good
Gliricidia sepium	100	4.84	302	Leafy, multi branched, thriving
Peltophorum pterocarpum*	100	6.7	177.6	Leafy, thriving
Pongama pinnata*	84	1.46	164	Slow growth but good survival
Sesbania sesban	0	0	0	Initially good, but short-lived
Vachellia sutherlandii*	50	1.6	252.5	Limited seed for planting

A video overview of the concept of multipurpose shrub and trees for the open downs, the Hughenden site and various species is available at: https://www.youtube.com/watch?v=VGvAVjgX7FU

Discussion and conclusions

Albizia, Gliricidia and *Peltophorum* have been particularly successful to date at all sites, with 100% survival and good growth at the Hughenden site. The *A. auriculiformis, Bauhinia, Pongamia,* and *Vachellia* species are promising. The short-lived species such as *Cajanus* and *Sesbania* can potentially provide good quick fodder, habitat, and cover while other species establish, but generally failed to persist, although at other unrelated locations they have been noted to recruit from seed. There are many other species (including non-legumes) that should be investigated, for example Everist (1986), with local native ecotypes most likely to be successful and having some social licence in the community. It is envisaged that the successful species could be planted as mixed species plantings on the open treeless grasslands radiating out along fence lines or in shelterbelts or groves from existing bores/dams with simple trickle irrigation which is likely to be essential for at least the establishment phase. On-going long-term monitoring of these plots is required to evaluate among other attributes their response to lopping/grazing, shade, nutritional value. Further research is also essential to select and evaluate other adapted and appropriate species, develop suitable agronomic and management practices for the establishment, longevity and utilisation of the species, and evaluate the costs and value of both shrubs and trees to livestock production, animal welfare and the environment. Once established these multipurpose shrub and tree species could potentially provide many of the ecosystem services outlined above benefiting the environment, animal welfare and production.

Acknowledgements
The ongoing care of the tree plots by the various station managers and staff is much appreciated as is the contribution of Agrimix staff, JCU, and the CRC P 58599 project for funding. Thanks to Jirapun Kota for assistance with field data collection.

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Soil carbon stock of *Morus-Lepidium* based Agroforestry system on application of different nutrient sources in Western Himalayas

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Keywords: Carbon stock; *Lepidium sativum*; *Morus alba*; Organic manures; Jeevamrut

Abstract

Lepidium sativum is a fast growing annual herb belonging to the Brassicaceae family and possesses the galactogogue effect that promote milk synthesis and production. Study was conducted at the experimental farm of Dr. Y. S. Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.) to evaluate the effect of planting condition and different nutrient sources on soil physicochemical properties and carbon stock of Morus based Agroforestry system. The study consisted two structural and functional components *Morus alba* fodder tree as woody perennial and *Lepidium sativum* as intercrop. There were eight treatments *i.e.*T_1: Lepidium + *Morus* +FYM@ 4 tonnes ha^{-1}, T_2: Lepidium + *Morus* +Vermicompost@ 1.12 tonnes ha^{-1}, T_3: Lepidium + *Morus* +Jeevamrut@ 500Litre ha^{-1}, T_4: Lepidium + *Morus* +No Manure, T_5: Lepidium + FYM @ 4tonnes ha^{-1}, T_6: Lepidium + Vermicompost @ 1.12 tonnes ha^{-1}, T_7: Lepidium + Jeevamrut@ 500Litre ha^{-1}, T_8: Control (without *Morus* and no Manure). Jeevamrut liquid organic manure made up of cow dung, cow urine, jaggery, gram flour, soil and water. It acts as an agent to increase the microbial count. The present study revealed that the tree proximity and nutrient sources significantly affected the soil physicochemical properties and carbon stock of the system. The results of the study indicated that the highest soil, bulk density (1.35 g cm^{-3}), available Nitrogen (344.60 kg ha^{-1}), Phosphorus (91.76 kg ha^{-1}) Potassium (539.52kg ha^{-1}), organic carbon (10.50 g kg^{-1}), and soil organic carbon stock (21.31 Mg ha^{-1}) was recorded in treatment T_2*i.e. Lepidium sativum*+ *Morus alba*+ Vermicompost @ 1.12 tonnes ha^{-1} while the lowest was recorded in treatment T_8*i.e.* Control (without *Morus* and no Manure). Maximum seed yield (1613.07 kg ha^{-1}) was observed in treatment T6 while the lowest was recorded in treatment T4. The treatment T_3 (*Morus*+ Lepidium+Jeevamrut) resulted in higher net return (1021.85 USD ha^{-1}) and B:C ratio (2.44) when 500 litres $hectare^{-1}$ Jeevamrut was applied as organic manure.

Introduction

Agroforestry is a sustainable land use a system whereby a deliberate integration is done to manage the agriculture as well as forest resources on the same piece of land in order to harvest the diversified products. It is an intensive farming and forest management shaped by intentional introduction of multiple productive species and management of their complex agroecological interactions to increase marketable yields and provision of ecological services (Gold et al. 2009, Garrett 1997). *Morus alba* (Mulberry) is a multipurpose agroforestry tree species belonging to family Moraceae. It grows in sub-tropical region and up to higher altitudes in the Himalaya-Hindu Kush region (Imran et al. 2010). Mulberry foliage is an excellent source of crude protein (20-24%) and is Morus leaves are feed as a part of mixed ration used to animals in lean period. *Lepidium sativum* (Chandarshoor) belongs to family Brasicacae and is widely cultivated in tropical and subtropical zones of India. The plant has its origin in Egypt and Southwest Asia but is now cultivated throughout the world for its seeds (Manohar et al. 2012). Considerable attention has been given to the use of chemical fertilizers in conjunction to maintain soil health and quality. Improvement of environmental conditions and public health are important reasons for advocating increased use of organic materials (Seifritz 2011). Apart from using conventional farm based products there is an increasing demand for improved materials like Jeevamrut which is liquid organic manure prepared from cow dung, cow urine, unpurified sugar, chickpea flour and soil from underneath the wild trees and water. It acts as an agent to increase the microbial activity and if used consistently, it minimizes the need of chemical fertilizers (Palekar 2006). Jeevamrut is low cost improvised preparation that enriches the soil with indigenous microorganisms required for mineralization of the soil. Application of vermicompost to crop has also been reported to improve early root initiation, increased root biomass, enhanced plant growth and development. It is considered as one of the important indices of sustainable land management, which contributes to improve soil quality and crop productivity. Himachal Pradesh being a north-western region of Himalayas is generally considered as a good site for soil organic carbon sequestration. Emerging evidence indicated that integrated soil fertility management in which both organic and inorganic resources is a feasible approach to overcome the soil fertility constraints. Therefore, to understand the hypothesis, the objectives of the study were to determine the effect of planting condition and different nutrient sources on soil physicochemical properties and carbon stock of *Morus* based Agroforestry system.

Methods

The experimental farm is located at 30° 51' N latitude and 76° 11' E longitude with an elevation of 1200 m above mean sea level and slope of 7-8 % which falls in subtropical sub-humid temperate agro-climatic zone of Himachal Pradesh. The area receives an annual rainfall varying from 1000 to 1600 mm and 75 % falls during monsoon season (July- September). The climate data of the study area shown in fig 1 (Source: Meteorological observatory, Department of environment science, Dr Y S Parmar University of Horticulture and Forestry, Nauni, Solan, HP 173230).

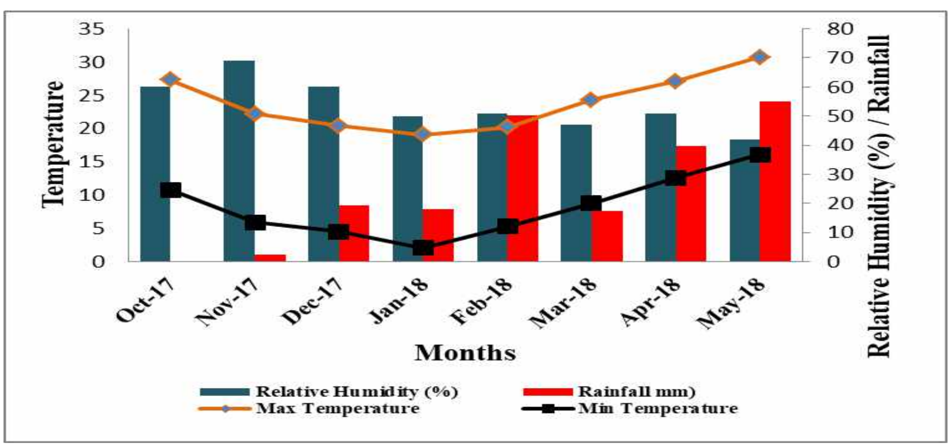

Fig1. Mean monthly temperature (°C), rainfall (mm) and relative humidity (%) during cropping season

Trees rows of *Morus alba* tree consisting of spacing 3×3 m with rows running in East to West direction. The study was conducted in a Randomized Block design factorial with three replications and comprising of four treatments *i.e.* T_1: FYM @ 4 tonnes ha^{-1}, T_2: Vermicopost @ 1.12 tonnes ha^{-1}, T_3: Jeevamrut @ 500Litre ha^{-1} and T_4: No Manure. According to Palekar (2006) Jeevamrut is prepared by mixing cow dung (10.00 kg) with cow urine (10.00 litres), jaggery (1.5 kg), pulse flour (1.5 kg), 1 kg of soil brought from the bunds of the field where cultivation is to be taken up and add 200 litres of water. Bed sizes of 4 × 2m were made and line sowing was done. Before the sowing of seeds N_{20}: P_{40}: K_{10} Kg hectare^{-1} was applied in the form of FYM and Vermicompost in the individual plots. Jeevamrut is applied as soil drench @ 0.4 litre per plot diluted in 7.6 litre water one time before sowing of seeds and 4 times after sowing at an interval of 15 days. The plants were harvested after five months from the date of sowing of seeds in the main field. Soil samples were taken from surface layer (0–15 cm depth) after harvesting to study the soil physical and chemical properties organic carbon and soil carbon stock.

Five random samples were collected per plot and 500 g of composite sample was taken. Collected soil samples were placed in ziplock bags with proper tags and transported to the laboratory for further analysis. The soil samples were air dried and crushed with mortar and pestle to make them pass through a 2 mm sieve. The crushed samples were then stored properly for use in subsequent analysis. The bulk density of the samples (replicated thrice) was estimated using a core sampler by oven drying the samples at 105° C till constant weight. The dried soil sample were prepared for the estimation of SOC by adopting frequently used method of Walkley and Black (1934), available nitrogen by Alkaline potassium permanganate method (Subbiah and Asija, 1956), available phosphorus by (Olsen's et al. 1954), and available potassium by (Merwin and Peach 1951) method. Soil pH were analysed using soil:distilled water (1:2.5) (Jackson, 1973). The selected parameters were analyzed for understanding their variability through analysis of variance (ANOVA), one way design, as specified by Gomez and Gomez using statistical package R Studio Team (2022) for testing the significance of treatments (Į=5%), The packages used were "ggpubr" for line plot using function ~ggline, whereas bar plots were computed using ggplot2 underlying function ~ggbarplot.

Results

The present study revealed that the tree proximity and nutrient sources, significantly affected the soil physicochemical properties and carbon stock of the system (Fig 2). The results of the study indicated that the highest soil, bulk density (1.35 g cm^{-3}) available Nitrogen (344.60 kg ha^{-1}), Phosphorus (91.76 kg ha^{-1}) Potassium (539.52kg ha^{-1}), organic carbon (10.50 g kg^{-1}), and soil organic carbon stock (21.31 Mg ha^{-1}) was recorded in treatment T_2 *i.e.Lepidium sativum*+ *Morus alba*+ Vermicompost @ 1.12 tonnes ha^{-1} followed by T_1: FYM @ 4 tonnes ha^{-1} with the corresponding values (1.33 g cm^{-3}), (330.02 kg ha^{-1}), (85.39 kg ha^{-1}), (529.393 kg ha^{-1}), (9.03 g kg^{-1}) and (18.00 Mg ha^{-1}) while the lowest was recorded in treatment T_8*i.e.* Lepidium+No Manure with the corresponding values (1.22 g cm^{-3}), (305.87 kg ha^{-1}), (60.24 kg ha^{-1}), (504.507 kg ha^{-1}), (5.61 g kg^{-1}) and (10.33 Mg ha^{-1}).

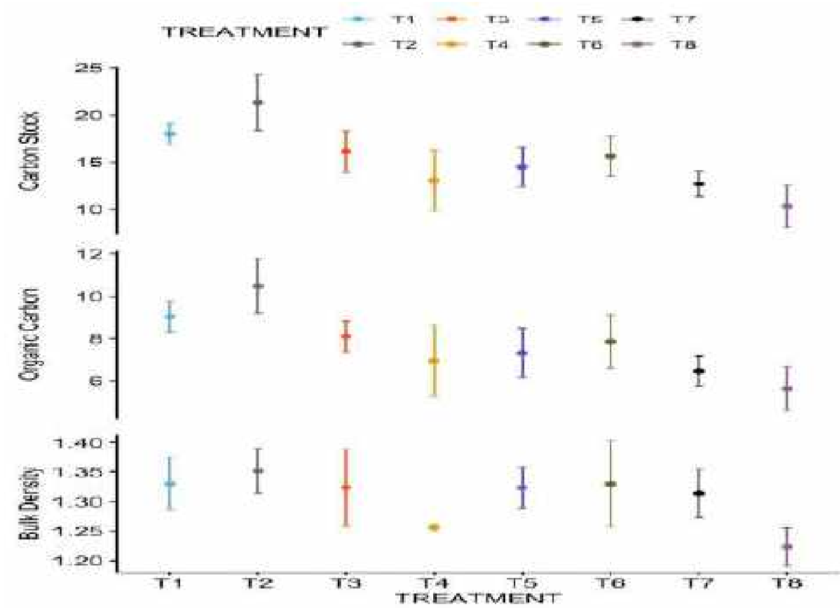

Fig: 2 Effect of planting condition, intercropping patterns and nutrient sources on soil bulk density (g cm^{-3}), organic carbon (g kg^{-1}) and carbon stock (Mg ha^{-1}) under Morus based Agroforestry System.

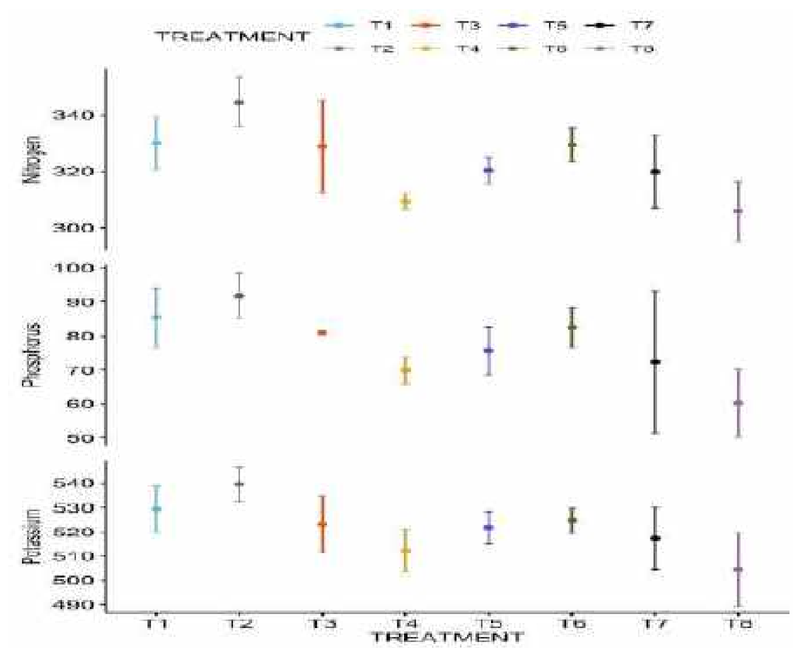

Fig: 3 Effect of planting condition, intercropping patterns and nutrient sources on soil available nitrogen (kg ha^{-1}), phosphorus (kg ha^{-1}) and potassium (kg ha^{-1}) under Morus based Agroforestry System.

Maximum seed yield (1613.07 kg $hectare^{-1}$) was observed in treatment T6 while the lowest was recorded in treatment T4. Under open condition the maximum seed yield kg per hectare (1613.07 kg $hectare^{-1}$) was recorded in treatment T_6 (Lepidium+Vermicompost) which was statistically at par with the T2 (Morus+ Lepidium+

vermicompost). Whereas, minimum seed yield kg per hectare (752.23 kg hectare^{-1}) were observed in treatment T_4 (Morus+Lepidium+No manure). The mean seed yield kg per hectare of *Lepidium sativum* was significantly influenced by different types of organic manures. The maximum seed yield (1460.57 kg hectare^{-1}) was observed in application of vermicompost which was statistically at par with the application of Jeevamrut (1395.26 kg hectare^{-1}) and farm yard manure (1291.66 kg hectare^{-1}) whereas; minimum (834.74 kg hectare^{-1}) was recorded in control where no manure was applied.

Discussion

There have been other reports of increase of N in soil after application of vermicompost (Nethra et al., 1999). Favourable soil conditions as viz. porosity, organic carbon content, biological activities and water holding capacity might have helped in mineralization process of soil nitrogen thereby leading to build-up higher available nitrogen (Kushwala *et al.,* 2017). Findings of the present study are in line with the studies of Nkechi *et al*. (2013) and Singh *et al*. (2017). The continuous inputs of P to the soil were probably from slow release from vermicompost and release of P was due largely to the activity of soil microorganisms (Arancon et al., 2006). Marinari et al. (2000) showed similar increases in soil P after application of organic amendments. The selective feeding of earthworm on organically rich substances which breakdown during passage through the gun, biological grinding, together with enzymatic influence on finer soil particles, were likely responsible for increasing the different forms of K (Rao et al., 1996). The results in the present study are in agreement with the previous studies of (Kumar and Singh, 2017) who observed that the higher seed yield per plant in mustard (*Brassica juncea*) was recorded in combined application of RDF+vermicompost. Theunissen et al. (2010) reported that the vermicompost contains most nutrients in plant available form such as phosphates, exchangeable calcium, soluble potassium and other macronutrients with huge quantity of beneficial microorganisms, vitamins and hormones which influence the growth and yield of plants. This may be due to the fact that application of vermicompost results in improving the physical, chemical, and biological properties of soil and also provide N, P, and K to plants (Baziramakenga and Simard 2001). Based on both analytical data and field observations, it can be concluded that application of Vermicompost @ 1.12 tonnes ha^{-1} under *Morus alba* based agroforestry system had a synergistic effect on improving soil physical as well as chemical properties over control (without any manure under open condition). Application of organic manures in the form of vermicompost resulted into better yield parameters of *Lepidium sativum* as compared to other organic manures. Organic farming and agroforestry can be enhanced to drive greater environmental sustainability, increase crop productivity, and strengthen soil health, thereby creating more resilient agricultural systems capable of addressing global challenges like climate change and soil degradation.

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Supporting of cattle grazing in high nature value areas by virtual fencing technology

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Key words: grazing; high nature value areas; suckler cows; virtual fencing

Abstract

Evolution of virtual fencing designed for grazing beef cattle opens up new opportunities for available rangeland and grassland areas. Virtual fencing has the potential to reduce the amount of labour required for fencing, increase the flexibility of fencing to adapt to changing pasture conditions, improve precision and efficiency, and provide more options for grazing management. Taking into account this promising perspective, we have started the project ProEcoFarm which main objective is to produce top-quality culinary beef based on a model of farming suckler cows in a pasture-based feeding system on extensive grasslands located in high nature value areas using an Internet of Things (IoT) system. The experimental pasture is located in the Middle Odra Valley in Western Poland in the complex of semi-natural grasslands under protected area of Natura 2000. The study has been carried out from 2022. The grazed area of 27.5 ha is characterized by high diversification of botanical composition as a consequence of mosaic soil habitats of the pasture. We noticed occurrence of 48 species and 7 grass communities. Based on the monthly monitoring of the pasture during vegetation periods the biomass yield ranged from 0.8 to 2.7 t DM per ha, depending on the grass community. The study area is grazed by Limousine suckler cows by stocking density below 0.5 LU per ha. We conclude that for cattle grazing in high nature value areas the building of conventional fences are often impossible or/and not welcome. The remote control of the cattle herd using collar-mounted devices will make it possible to exclude areas with protected plant or animal species from grazing without building physical barriers. It is worth noting that an essential part of the technological innovation is determining grazing areas according to the cattle's feeding group classification.

Introduction

High quality culinary beef is obtained in pasture feeding conditions (Horn and Isselstein 2022). Young beef cattle are predisposed for this purpose, and above all the technology of suckler cows, from which weanlings are valuable slaughter raw material or can be further fattened to obtain a greater mass (Goliński et al. 2023). The use of pasture sward in the feeding of beef cattle has a very beneficial effect on the quality of meat (Daley et al. 2010; Stanton et al. 2018). Unlike feeding cattle with silage and concentrated feed, meat obtained from animals grazing on pasture has an increased content of unsaturated fatty acids, as well as minerals (O'Callaghan et al. 2016). In many countries in Europe and around the world, consumers are looking for this type of beef as a health-promoting food product ("green beef"). This aspect, as well as animal welfare, speaks in favour of greater use of pastures in animal husbandry, which has become one of the priorities in the agricultural policy of the European Union (Guyomard et al. 2021). Pastures provide natural, valuable feed that is adapted to the digestive physiology of ruminants. Organizing effective feeding of pasture beef cattle is not easy, however it requires knowledge and material inputs. Current trends in the use of pastures consist in the application of innovative decision-support tools, mainly through grazing control using the IoT system (Internet of Things). Its key element is the use of virtual pasture fences (Anderson et al. 2014; Campbell et al. 2019; Goliński et al. 2023). Thanks to GPS technology and wave signal receivers mounted on the necks of animals, it is possible to use innovative technology for pasture feeding of cattle by controlling the herd for better planning and organization of grazing. The objective of the paper is to present the innovative technology of keeping suckler cows using the IoT system based on virtual fencing to control the herd for the purpose of extensive grazing of grasslands located in high nature value areas.

Methods

The study has been carried out from 2022 and is still running. The experimental pasture is located in the Middle Odra Valley (52º04' N, 14º97' E) near to Czarnowo village (Western Poland) in the complex of semi-natural grasslands under protected area of Natura 2000. Its character is of rangeland areas because no fertilization or other agricultural practices have been used there for many years. The grazed area of 27.5 ha is characterized by high diversification of botanical composition as a consequence of mosaic soil habitats of the pasture. The study area is grazed by Limousine suckler cows in the continuous grazing system by stocking density below 0.5 LU per ha (ranging during three year of the study from 0.37 to 0.46 LU per ha). Each year, at the end of the vegetation period, a cleaning cut was carried out to chop up the biomass residues after grazing. In the first stage of the study we assessed the sward yield and its nutritional value using the Crabbe et al. (2019) method. Samples were taken from the designated homogeneous pasture patches, where a 30 m × 30 m plot was randomly selected for in-situ ground measurements. The sward yield was determined using a quadrat frame method collecting biomass each three weeks during vegetation season from May to October. After cutting, the biomass was weighed, dried in the Binder chamber and subjected to laboratory analyses to assess the chemical composition of the sward (ash, crude protein, crude fat, crude fibre, NDF, ADF, β-carotene) using commonly applied methods. Additionally, the botanical composition of the sward using the Klapp method was estimated. Detailed studies of the sward, which constitutes the feed base for suckler cows, were necessary, because the supporting of cattle grazing is carried out on natural meadow complexes in the river valley, the characteristic feature of which is the diversity of plant cover and soil substrate determining the heterogeneous feed potential of the facility. In the next step, based on the collaboration with IT company within the ProEcoFarm project, the concept of supporting of cattle grazing in high nature value areas by virtual fencing technology was elaborated. The idea was to use our own materials and solutions that would make the system more accessible to Polish farmers, mainly from an economic point of view.

Results

Forage potential of the pasture

Studies on the botanical composition of the pasture sward revealed great diversity. In the sward of the analysed pasture, 48 species were recorded, including 11 grasses, 5 other monocotyledonous plants, 5 legumes and 27 other dicotyledonous herbs and weeds. Seven characteristic meadow communities were distinguished: No. 1/ *Poa pratensis-Festuca rubra*, No. 2/ *Alopecurus pratensis-Poa trivialis* with a significant share of legumes and dicotyledonous plants of moist habitats, No. 3/ *Alopecurus pratensis*-*Carex sp.* with a significant share of dicotyledonous plants of moist habitats, No. 4/ *Carex gracilis* community with a significant share of dicotyledonous plants of moist habitats, No. 5/ *Alopecurus pratensis-Agrostis stolonifera* with a significant share of dicotyledonous plants of moist habitats, No. 6/ *Alopecurus pratensis* dominating grass community, No. 7/ *Alopecurus pratensis-Festuca rubra* with a large share of dicotyledonous plants. In the identified communities, the share of grasses in the botanical composition ranged from 2 to 69%, other monocotyledons, including sedges, from 4 to 69%, legumes from 0 to 19% and other dicotyledonous meadow plants from 15 to 32%.

Based on the monitoring of the pasture during vegetation periods within investigation years the biomass yield available for cattle ranged from 0.8 to 2.7 t DM per ha, depending on grass community (Fig. 1).

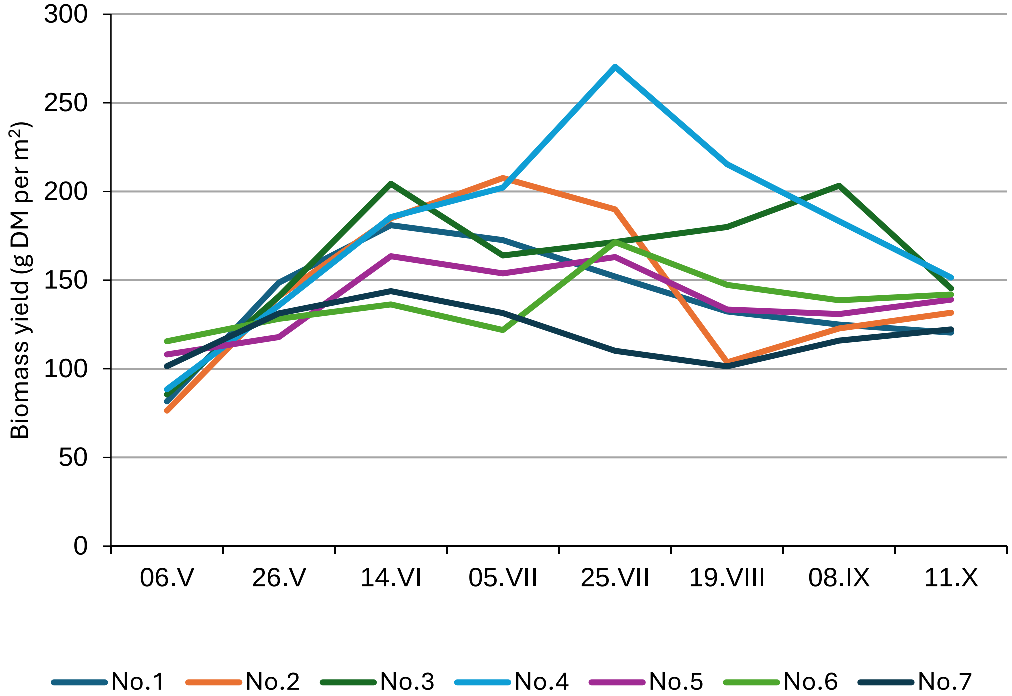

Figure 1. Changes in biomass yield available for grazing of suckler cows during vegetation period (explanation of the No. 1-7 communities given in the main text)

The community of *Carex gracilis* (No. 4) was the least attractive to grazing cows. From the beginning of the vegetation period to the end of July, the sward of this community was grazed very rarely, which caused the biomass yield to increase. In the second part of the vegetation period, suckler cows also grazed the sward available from this community. A similar trend was observed in the *Alopecurus pratensis*-*Carex sp*. Community (No. 3). The lowest yields throughout the vegetation period were found in the *Alopecurus pratensis-Festuca rubra* community (No. 7), because it was the most attractive to grazing animals.

The chemical composition of the pasture sward varied depending on the community (Table 1). The best quality, especially in terms of higher concentration of crude protein, crude fat, β-carotene, and lower ADF, was noted in the *Poa pratensis- Festuca rubra* community (No. 1). Low quality was found in the communities No. 3 and No. 4 with a large share of hygrophilous species, particularly of the genus *Carex*.

Table 1. Chemical composition of the sward communities occurring in the pasture (average values)

Plant community*	Ash g/kg DM	Crude protein g/kg DM	Crude fat g/kg DM	Crude fibre g/kg DM	NDF g/kg DM	ADF g/kg DM	β-carotene mg/kg
1	47.4	122.6	16.5	224.0	548.9	289.0	676.9
2	43.4	114.6	12.4	219.5	526.2	289.5	533.7
3	43.5	109.0	13.7	228.6	559.2	295.8	419.9
4	43.8	110.7	10.7	225.4	571.3	292.8	522.0
5	53.9	113.0	13.9	225.8	554.1	291.9	583.0
6	57.9	102.5	14.8	225.3	515.9	297.5	554.9
7	50.9	107.8	15.2	227.5	561.6	295.1	519.1

*explanation of the 1-7 communities given in the main text

Virtual fencing to support grazing of suckler cows

Recognition of the forage potential of the pasture was the basis for preparation of the map with logical connections into IoT system. In this stage, a virtual pasture in the IoT system on a satellite map was marked up, maintaining its extensive character, as well as developing a grazing schedule, taking into account the parts dedicated to suckler cows and calves, which is the basis for the innovation of the technology. The developed grazing schedule in the river valley complex also included valuable natural and wetland enclaves, to which access of grazing animals will be periodically excluded. The virtual fence was implemented using the same principle as in commercially available systems, where a GPS collar constantly tracks the animal's position and compares it with virtual boundaries set by the farmer and collected from the collar. If the animal approaches the virtual border, the collar will produce an audio signal whose intensity and tone scale increase when the animal comes closer to the border. If the animal does not respond to the audio signal, it will receive an electric pulse. The pulse has about 30 to 50 times less energy compared to a traditional electric fence, but still, it is enough for the animals to be considered unpleasant. The cycle of the audio signal followed by the electric shock is repeated one to two more times if the animal does not respond, the animal is indicated as 'escaped'. The scheme used in our system is presented in the Figure 2. A key element of virtual fencing technology are collars equipped with built-in solar panels that charge the batteries during the day.

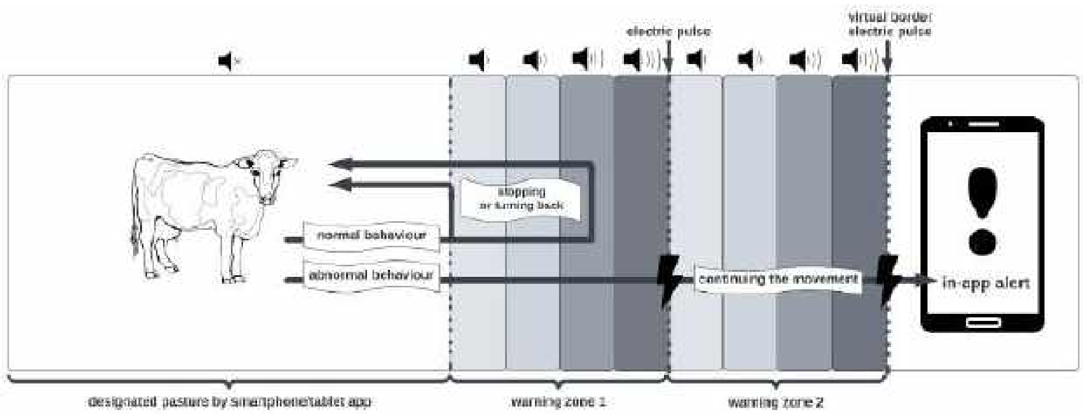

Figure 2. Scheme of possible response of grazing animals to virtual fencing in the IoT system

The next steps for developing of the technology were: field tuning of IoT system components, work on creating a virtual knowledge base, preparation of camera stations, setting camera parameters and including them in the IoT system and programming work. In 2024 the adaptation of grazing animals is in progress and the results are promising. Parallel, the zootechnical studies are conducted, which include physical monitoring of the herd, studies of the nutritional activity of suckler cows and calves in virtual quarters, ethological studies of animals, body temperature tests to detect animal diseases. Every two months from the beginning of grazing the assessment of animal weight gains during the grazing season are conducted. The IoT system supporting the technology of grazing suckler cows in high nature value areas by virtual fencing will be complemented by the analysis of the meat quality of weaned calves after slaughter. Special attention is given in preparation of the physical location and configuration of the energy storage and photovoltaic installation.

Discussion

Grass communities located in the river valleys are of both socio-economic importance (production of animal feed and products, most important elements of the natural landscape), as well as ecological importance, because as habitats for a huge number of plant and animal species, they constitute one of the most important reservoirs of biodiversity in Poland. The results of our study focusing on determination of forage potential of the studied pasture in the Middle Odra Valley confirmed that high nature value areas can be used for cattle grazing. The technology of suckler cows is particularly suited for this purpose. The premise for maintaining the high natural values of those meadow complexes is their utilization. It was confirmed by many authors, e.g. Horn and Isselstein (2022). The using of the IoT system based on virtual fencing support grazing of suckler cows in high nature value areas, where it is often impossible to build conventional fences and constantly monitor the daily activity of animals. Furthermore, remote control of the cattle herd using collar-mounted devices will also make it possible to exclude areas with protected plant or animal species from grazing without building physical barriers. The benefits of directing grazing animals to appropriate landscape niches were also highlighted by Campbell et al. (2020) and Stevens et al. (2021) to virtually exclude from grazing landscape elements of high natural value or habitats of rare and protected species, in particular areas excluded from use in a given year in accordance with the conducted agri-environmental programs. The potential for environmental protection in the aspect of implementing the tested IoT system on similar meadow objects, due to their large area in our country, is therefore very large.

Acknowledgements

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Pastoralism in the Sahel: Perceptions and adaptation strategies of pastoralist youth

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Key words: Youth pastoralists; Rangeland; Pastoralism; Senegal

Abstract
Our study examines how young people in the Senegalese silvo-pastoral zone perceive and engage in pastoral livestock farming. Nowadays, pastoralism remains a significant cultural element, however traditional practices such as transhumance are perceived as very rigorous. Young people consider livestock farming as a means of saving money but face challenges such as pasture degradation and limited State support. They advocate for reforms to modernize pastoralism and improve their living conditions. While many diversify their income sources, they are reluctant to pass these practices on to their children.

Introduction
Pastoralism is recognized as a sustainable way of utilizing pastoral ecosystems (grazing lands and water points) that promotes the maintenance of biodiversity (Andreas et al. 2017). In pastoral communities, young people (under 40 years) play a crucial role in livestock management and provide reliable support in all pastoral activities, including transhumance, watering, and herd monitoring. Caught between the pull of modernity and traditional pastoral practices, these young people strive to maintain the pastoral culture inherited from their parents while adapting to a modern lifestyle (Korbéogo 2016), made possible by the opening of rural areas to urban influences and the exchange of lifestyles through rural-urban migration, commercial trade, and human interactions facilitated by the improvement of roads (Macia et al. 2023).

In the Sahel, the Senegalese silvopastoral zone provides an excellent setting to study these current social phenomena upon which the future of pastoralism depends (Mauclaire 2019; Mugelé et al. 2023). Young people's perception of pastoral practices deserve analysis to understand how they perceive the future of pastoralism. In Senegal, many young people explore new income opportunities in urban areas. These alternative income sources may eventually lead to visions and ambitions shifts. While such shifts might offer young people socio-economic stability, they could influence or destabilize pastoral activities (Ancey and al. 2020), which, as mentioned, heavily rely on the energy and vitality of youth. This could result in a transformation from traditional pastoralism to modern livestock farming, as well as changes in rangelands, both biophysical and in terms of the way they are used.

This study aims to explore how young people from pastoralist families view traditional livestock practices, particularly in comparison to urban income-generating activities. It will examine the influence of education (both conventional and Quranic) on this shift, and how access to digital technology is reshaping pastoralism and creating new economic opportunities. The focus is on understanding what motivates young people to continue pastoral livestock farming despite the availability of other professional options.

Methods

We developed a concise questionnaire to collect qualitative data on young people's perceptions of pastoral livestock farming. We did not employ a sampling method, as our objective was not to conduct an exhaustive study but rather to explore preliminary insights that could serve as a basis for further investigation. The questionnaire was designed based on our field experience over the past few years of research in pastoral areas. Consequently, we included predominantly open-ended questions to broaden the scope of possible responses. To construct and deploy the questionnaire, we utilized the data collection tool **KoboToolbox**, which allowed us to design the survey and distribute it on platforms like smartphones. This approach enabled us to share the questionnaire via a simple link in unlimited quantities. By leveraging this method, we distributed the link as widely as possible and encouraged recipients to share it further. Through this snowball sampling strategy, we received referrals from participants who had already completed the questionnaire.

We also opted to share the link through social networks, particularly WhatsApp groups and direct contacts. This allowed anyone with basic literacy skills to complete and submit their responses. Additionally, we conducted several interviews via phone calls with herders whose contact information was shared with us but who could not read, write, or use WhatsApp. The collected data was stored on a **KoboToolbox server**, enabling secure storage during the collection process. These data were later downloaded in **XLS** format for processing in Microsoft Excel.

How young people perceive the pastoral livestock farming

Young people perceive pastoral livestock farming as offering limited prospects. Income during the dry season is low, mainly spent on livestock feed, while the rainy season provides slightly higher earnings, though still lower than urban jobs. This makes livestock farming less economically appealing compared to city employment, as highlighted by (Magrin and Raimond 2024) in other Sahelian cities. Incomes during the dry season are under 50,000 FCFA (*local currency*) per month (76 Euros or 83 USD), rising to 100,000 FCFA (152 Euros or 166 USD) in the rainy season. These earnings fluctuate based on season and family needs. Small ruminants are sold weekly, while larger ones are sold occasionally, often to cover feed costs. Thus, livestock income is unpredictable and doesn't provide stable financial security or savings.

For young herders, financial stability depends on herd size, which allows income diversification. Some with large herds or seeking alternatives secure steady income through livestock trading. Experienced herders engage in trading, either as intermediaries or resellers, often reinvesting profits to grow their herds. Trading is seasonal, particularly during the dry season, to cover feed costs. Livestock traders tend to be young people with strong negotiation skills from interactions with urban communities during Quranic studies. As in their early life in quranic schools, these young students spent mornings and evenings begging from passers-by in cities for their Quranic teacher, throughout their entire study period, which could last several years. In this way, they develop great ability to interact and negotiate with urban people. However, rural youth face challenges in urban environments, such as language barriers and unmatched attitudes, from the view of the urban habitants. Only those accustomed to urban life adapt successfully.

Moreover, many pastoral youths have diversified their income through other professions, such as working for international research institutions, accounting, teaching, and consulting, while maintaining their identity as pastoral herders. This diversity of activities encourages further analysis of what keeps young people engaged in livestock farming

Understanding what motivates young people from herding
Understanding the motivations of young people from herding families is crucial for predicting the future of pastoral livestock farming. Our research reveals that young people are drawn to pastoral livestock farming due to its deep connection to their cultural identity. Terms such as "tradition," "culture," and "Fulani" were often mentioned, reflecting the significance of this practice as a cultural heritage. Phrases like "It's about the cultural aspect and honoring our parents" highlight the pride in continuing a family tradition. This cultural identity, shaped by parental involvement in livestock farming, continues to be a source of pride for young people (Luque 2002), ensuring that pastoral practices are maintained across generations.

However, certain pastoral practices, particularly transhumance, face increasing criticism for their economic, physical, and social impacts. Transhumance restricts participation in community activities and prevents children from accessing education and families from receiving medical care. The need to find alternatives to moving entire families with herds has become urgent. Basic services such as schools and healthcare facilities must be accessible to these families.

Most young people interviewed, regardless of education, expressed the intention that their children would not follow in their footsteps due to the harsh realities of pastoral life and lack of access to essential services. This trend suggests that, without reform, pastoral livestock farming in the Senegalese silvo-pastoral zone may decline in the coming generations. However, as Ba (2023) suggests, adaptive changes in livestock farming practices could help sustain this system, despite the numerous challenges posed by agricultural expansion, grazing land shortages, and inadequate state support.

Discussion
The Fulani identity remains closely linked to pastoral livestock farming among young people, serving as a source of pride, as noted by Botte et al. (1999). However, many young people express a desire to transform pastoral practices, particularly transhumance, to improve their quality of life. This includes providing better living conditions for their families, which is difficult in remote, sparsely populated areas where transhumant herders must reside. The traditional "good herder" identity is gradually being replaced by a more modern identity focused on technology, urban networks, and material wealth, as observed by Macina et al. (2023).

State investments in pastoral hydraulics, like the densification of boreholes, have made new areas accessible, but they have also led to overgrazing due to an increase in livestock numbers. Many herders noted that the availability of water in the region has exacerbated the lack of pasture, a trend highlighted by Véron (2014). Degradation of grazing lands, proliferation of invasive species, and overexploitation of communal resources are major concerns. Combined with rising livestock populations and improved veterinary care (Véron 2014), these factors contribute to the environmental challenges facing the Senegalese sylvo-pastoral zone, as noted by Ba (2023).

Results statement: Youth in Senegalese silvo-pastoral zone believe pastoral practices must change to improve the quality of life for families and children, ensuring access to basic services.

Conclusion
Pastoral livestock farming in the Senegalese silvo-pastoral zone is viewed by young people as an activity tied to their "Fulani" identity, yet its restrictive practices hinder participation in community life. While large-scale herders can earn significant incomes, young people see the potential to build "savings herds" with family or hired help, benefiting from rising livestock demand for festivals. With challenges like land degradation and shrinking pastures, young people express reluctance to continue these practices, questioning their long-term viability. However, we advance the need for a larger and quantitative study to gain a clearer understanding view of youth perceptions on the pastoral lifestyle and the pastoralism in the future.

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Can spatial distribution of cattle manure be controlled? Relationship between cow location and dung pats

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Key words: cow location; deep learning; dung pats; unmanned aerial vehicle (UAV)

Abstract

Controlling the spatial distribution of cattle dung pats in a pasture can enhance nutrient utilization and mitigate greenhouse gas emissions resulting from dung in grazing management. Dung pats are distributed in accordance with cattle behavior and location in a pasture, thus frequent monitoring of cattle location and dung distribution is essential for effective dung control. Recently, the detection of dung pat distribution has been achieved using unmanned aerial vehicle (UAV) images. Additionally, a global positioning system (GPS) can provide continuous monitoring of cattle locations. Therefore, in this study, we monitored the effect of cattle location on dung distribution under strip stocking using UAV images and a deep learning approach. Five dairy cows, equipped with GPS collars, grazed for five days under a strip stocking condition. A 3.5 ha pasture was divided into four paddocks, one of which was expanded each day. UAV images were captured before grazing each day. The training data generated were used to estimate dung pat distribution using YOLO (YOLOv8x), an object detection algorithm. The accuracy of the dung distribution was assessed using the confusion matrix. The paddock was further divided into 10 m grids, and a generalized linear model was employed to evaluate the relationship between cow location and dung pat count within each grid. The detection accuracy of dung distribution was 0.793 (precision), 0.222 (recall), 0.210 (accuracy), and 0.347 (*F*-value), indicating the need to improve the accuracy of detecting undetected dung pats. As the pasture area increased, the cows spread out their location, resulting in an expanded dung distribution. However, the cow location did not correlate with the dung location ($R^2 = 0.053$). This is presumably due to the insufficient recall of the dung distribution estimates. Additionally, not only the location, but also the cow's behavior, such as resting and lying, should be assessed.

Introduction

Cattle play a critical role in nutrient cycling within grazing ecosystems by consuming plants and redistributing nutrients back into pastures through excretion (Hirata et al. 2011). However, the spatial distribution of excreta across pasture is often uneven (Hassan-Vásquez et al. 2022). Consequently, nutrient levels within a pasture can vary significantly, with some areas becoming nutrient-rich or even overloaded, while others remain nutrient-deficient. Moreover, in areas with high concentrations of manure, dung patches are formed (Takigawa et al. 1996), which may reduce the efficiency of grassland utilization (Klootwijk et al. 2019). Recently, cattle dung has also been recognized as a source of greenhouse gas emissions, with nitric oxide and nitrogen dioxide being emitted from dung (Osada 2001). Thus, efforts to reduce greenhouse gas emissions, such as the application of nitrification inhibitors, are required (Cahalan et al. 2015). However, the widespread application of nitrification inhibitors across an entire pasture represents a substantial cost and is a labor-intensive endeavor.

Controlling the spatial distribution of cattle dung pats in a pasture would contribute to solving the above problems and is important from the perspective of grassland management and environmental conservation. Since cattle behavior and location are closely linked to dung distribution, frequent monitoring of cattle movements and dung deposition is essential for effective management. In recent years, global positioning systems (GPSs) or global navigation satellite systems (GNSS) have facilitated continuous monitoring of cattle locations (Yoshitoshi et al. 2020). Moreover, the detection of dung pat distribution has been accomplished through unmanned aerial vehicle (UAV) images, employing deep learning approaches that can accurately recognize images and detect objects. In this study, we monitored the effect of cattle location on dung distribution under strip stocking conditions using UAV images and a deep learning approach. Grazing insight into this relationship can inform the development of targeted strategies to manage dung distribution, enhance pasture utilization, and mitigate environmental impacts.

Methods

The grazing trial was conducted for five days from June 26, 2023, in a 3.5 ha grass-legume mixed pasture located in the eastern region of Hokkaido, Japan (N42°33', E143°14'). The pasture had a single gate in its northeastern part and tree sheds along the fence from the east to the northeast in the pasture. The pasture was divided into four paddocks, and strip grazing was implemented. On the initial day, the entire pasture was utilized for grazing, followed by the sequential opening of one paddock per day, starting with the easternmost paddock on the second day.

A total of 53 cows (47 Holsteins and 6 Jerseys cows) were grazed for approximately 8 hours from 7:30 am. to 3:30 pm. The cows were milked twice a day, once before and once after grazing, and were provided supplementary feed in the barn. Five cows (three Holsteins and two Jerseys), selected based on age (3.6 ± 2.9 years) and breed, were fitted with GPS collars to track their movements during the grazing.

Aerial photography was conducted on four of the five grazing days, excluding June 28 due to rain. An UAV (Parrot, Anafi, France) equipped with a camera (4K HDR) was used for aerial photography. Four Ground Control Points (GCP) were set up to perform geometric corrections prior to aerial photography. The UAV was operated using the Pix4D capture flight management application. The flight altitude was 35 m, the camera angle was 80°, the overlap setting of 80% for forward movement and 60% for lateral movement, and the image resolution was 1.3-1.5 (cm/pixel).

To validate the dung distribution data, three 10 m × 10 m plots were established in the pasture. The dung distribution estimated via aerial imagery was compared to data obtained through direct observation using a Real-Time Kinematic GNSS (RTK-GNSS). Aerial images were geometrically corrected and orthorectified using Agisoft Metashape (Agisoft LLC, Russia).

For the creation of training data, annotations were performed using the Makesense tool (https://www.makesense.ai/). Training was conducted using YOLOv8x (https://github.com/ultralytics/yolov8), a real-time object detection algorithm YOLO (You Only Look Once). The dataset included 3,284 annotations, combining data from the present study and our previous study (Kawamura et al. 2024) conducted at a different location.

Statistical analyses were performed using R version 4.3.2 (R Core Team, 2023), except for estimating cow dung distribution. The accuracy of dung distribution detections was assessed through a confusion matrix. The logarithm of GPS point counts was used to evaluate cow movement patterns. A Poisson regression model (GLM) was used to examine the relationship between cow location and dung distribution. The number of GPS points within each grid of the pasture served as the explanatory variable, while the number of dung detections represented the response variable. The predictive accuracy of dung counts, estimated from the regression equations, was assessed using R^2 (coefficient of determination), RMSE (root mean square error), and AIC (Akaike Information Criterion).

Results

The average vegetation coverage was 62.0%, with meadow fescue (*Festuca pratensis* L.), white clover (*Trifolium repens* L.), and orchard grass (*Dactylis glomerata* L.) as the dominant grass species. The detection accuracy of dung distribution was 0.793 (precision), 0.222 (recall), 0.210 (accuracy), and 0.347 (*F*-value). GPS data were obtained from all five cows on one day, four cows on three days, and three cows on the remaining day.

Figure 1 illustrates the daily counts of GPS points and the cumulative total of detected cow dung. The spatial distribution of cow increased as the grazing paddock expanded, leading to a wider spread of manure distribution. However, despite the paddock expansion, cow tended to concentrate their activities near the tree shades in the southeastern part of the pasture.

The relationship between the time spent by cows in each area and the number of dung was analysed using Poisson regression (GLM), as shown in Figure 2. The regression equation is as follows:

Number of dung = exp (0.37+0.19×log [GPS points]): R^2=0.053, RMSE=2.403, AIC=1600.186

The low R^2 value indicates that cow locations accounted for less than 5% of the variation in the dung distribution.

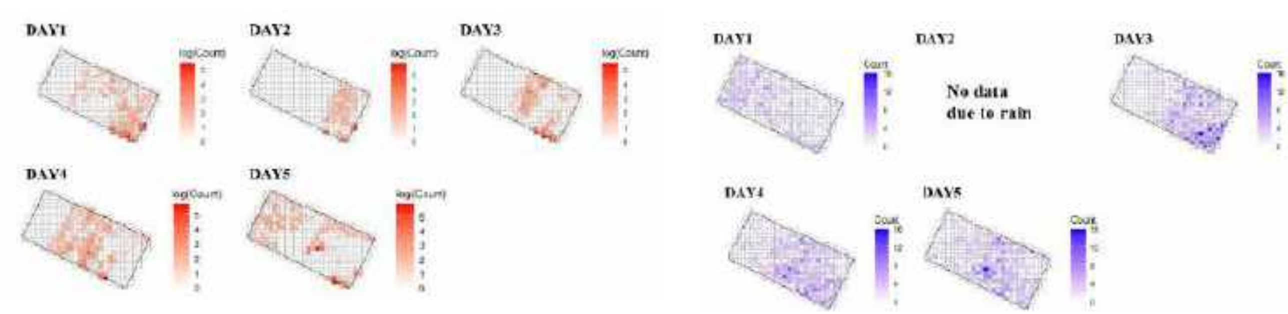

Fig. 1 Cattle location (left) and estimated dung distribution (right) in the strip stocking pasture

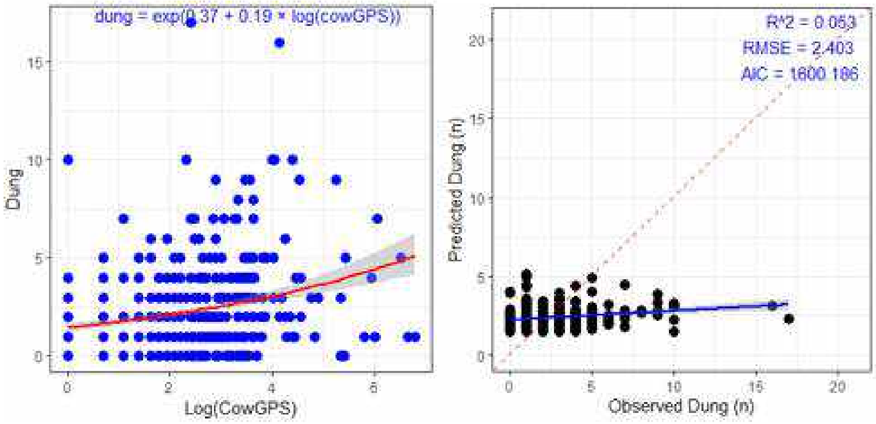

Fig. 2 The regression equation and graph obtained through Poisson regression, based on the number of GPS counts within the grid and the detected number of cow dung (left). The accuracy of the regression equation is evaluated by comparing the number of cow dung estimated from the equation with the actual number of dung detected (right).

Discussion

Strip grazing influenced cattle behavior significantly. As the pasture area increased, cows spread out their location, resulting in an expanded dung distribution. However, the cow location did not correlate with the dung location (R^2 = 0.053). This low correlation may be attributed to the low detection rate of cow dung in aerial images (recall: 0.222), which highlights the need for improvement. The resolution of the aerial images, approximately 1.3–1.5 cm/pixel, was coarser than that used in a previous study by the authors (0.9–1.0 cm/pixel), potentially causing smaller dung patches to go undetected. Kawamura et al. (2023) recommend a drone flight altitude of 40 m (resolution: 2 cm) or lower for efficient surveying in large fields. However, achieving higher-resolution images at lower altitudes may be essential for accurate detection in a pasture.

Machine learning models demonstrate enhanced accuracy with larger and more diverse training datasets, thus augmenting their practical applicability (Oki et al. 2019). Therefore, in addition to optimizing aerial photography conditions, it is crucial to enhance detection model accuracy by expanding the variety of supervised data for cow dung images, particularly given the challenges in distinguishing them from their surroundings.

Regardless of the expanded grazing paddocks, cow activity was concentrated in specific areas. This behavior likely reflects cows exploring and grazing in newly opened paddocks but returning to shaded areas for rest and ruminating. Research has indicated that cows defecate less frequently when lying down or foraging and more frequently after standing up and feeding (Suzuki et al., 1983). To enhance the predictability of cow dung distribution, it is essential to analyze not only the duration of stays but also grazing, ruminating, and resting behaviors at each location.

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Optimizing subsoiling tillage and nitrogen rates for fodder productivity and ethanol production of sorghum *(Sorghum bicolar* L.) in Northern Himalayas

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Keywords: Conventional tillage, Fertilizer, HCN**,** Rotavator, Subsoiling, Sugar yield

Introduction

In India, sorghum occupies 4.09 million ha area with production and productivity of grain about 3.48 million tons 849 kg grain/ha, respectively (Agricultural Statistics at a Glance, 2020). Presently sweet sorghum (*Sorghum bicolar* (L.) Moench.) is gaining popularity among farming communities mainly because of its fast growing habit, wide adaptability, tolerance to abiotic stress, higher grain productivity, good quality of green fodder and moreover the potential source of energy. Its stalk contains 15-17% fermentable sugars, 47% juice with 7.24% sugar content (Hugar, 2010). Besides, single cut sweet sorghum produced 35-50 t ha^{-1} stalk, 1.5-2.5 t ha^{-1} grain and 2760 lakh ha^{-1} ethanol (Ratnavathi *et al*., 2004). Sweet sorghum is a promising source of biofuel like ethanol, jaggery and syrup that can produce nearly 2000-2800 lha^{-1} and grains can also be used for making potable ethanol with a recovery rate of 400 lt^{-1} of grain (Singh, 2010). In general, sorghum plant attains height up to 3.50m, leaves are broad ~12 cm and long ~125cm and the stalk contributes 70-80% to biomass.

Tillage and balanced fertilization are two basic indices for sustainable crop production. The heavy tillage with regular use of disc harrow has now been obsolete in view of conservation tillage mainly because traditional tillage pulverizes top 15 to 20 cm soil leading to formation of hard pan (Kumar, 2003) resulting into reduced percolation. Hence water stagnation creates a reduced rhizosphere which is unfavorable for nutrient absorption and root growth. Subsoiling and differential rate of deep tillage along with fertilizer application have proved the suitability for not only breaking the hard pan but also making nutrients available at different depths for higher crop productivity (Manoj *et al*., 2022). Chen and Haung (1972) reported that differential rate of subsoiling at a depth of 25-30 and 60-90 cm improved the yield of autumn planted cane.

Fertilizer broadcasting results in low fertilizer use efficiency due to various losses (Rababi, 2006) as surface applied nitrogenous fertilizers are more prone to volatilization. That is, 40 to 50% of applied nitrogen and only 22 to 30% of applied phosphorus and potassium fertilizers are effectively used by the crop and the remaining get either washed away, volatilized, leached to ground water or get fixed with soil (Rowse and Stone, 1980).

Broadcasting is a common method of fertilizer application just before last tillage or seeding. These fertilizers are localized in the upper layer of soil, so the soil's larger, deeper portion is less available to plant roots. Therefore, it is essential to place P and K fertilizers in root zone for higher availability and its use efficiencies. Thakur and Mandal (2010) reported greater nutrient uptake and higher sugarcane yield under sub-soiling, with deep and differential rate placement of fertilizers in the root zone of the crop. Besides demonstrating such great importance of deep and differential place of fertilizers, very little research work has been conducted so far on commercial crops including sweet sorghum. Considering the above facts, the present study was carried out to study the effect of subsoiling tillage and nitrogen levels on fodder productivity and ethanol production of sorghum *(Sorghum bicolar* L.) in the Northern Himalayas.

Methods

The field experiment was conducted during the *Kharif* crop season (June to October)-2011 and 2012 at the Instructional Dairy Farm, Nagla, G.B. Pant University of Agriculture and Technology, Pantnagar, U. S. Nagar (Uttarakhand), India. The climate of the experimental site was humid sub-tropical with hot summers and cold winter. The mean annual rainfall is 1554.1mm of which 80 to 90 per cent is received from June to October. The total rainfall received during the crop period in 2011 and 2012 was 2007.8mm and 752.8mm, respectively. The soil of the experimental field was well drained with a slight silty clay loam texture and pH 7.21. The available organic carbon was 0.72% and available nitrogen and phosphorus and potash were 272.3, 29.0 and 236.1kg/ha, respectively. The experiment consisted of four tillage levels in main plot i.e. conventional tillage (CT), subsoiling (20cm) followed by (fb) rotavator x1(SS fb R), subsoiling-cum-deep placement (40cm) fb rotavator x1(DP fb R) and subsoiling-cum-differential rate fertilizer placement (25 & 50 cm) fb rotavator x1(DRF fb R) and four N levels in sub plot i.e. control (zero nitrogen), 40, 80 and 120 kg N/ha, was laid out in split plot design with four replications. The recommended dose of phosphorus (60 kg/ha) and potash (40 kg/ha) was deep placed as per the subsoiling treatments, while in conventional tillage it was applied at last tillage. The nitrogen was applied manually as per treatments in two equal splits i.e. 50 % basal and 50% at 30 days after sowing in all treatments. Sweet sorghum variety SPSSV-6 was planted on 27 May 2011 and 4 May 2012. The crop was harvest at pre heading stage and green, dry fodder yield were recorded. The ethanol yield was estimated with the help of sugar yield (Spencer and Meade, 1955) as given below;

Sugar yield (t/ha) = Available sugar (%) x Juice yield (kl/ha) /100

Ethanol yield (l/ha) = Sugar yield (t/ha) x 3.78 x1000 x 0.8

Results and Discussion

a. Effect of tillage options

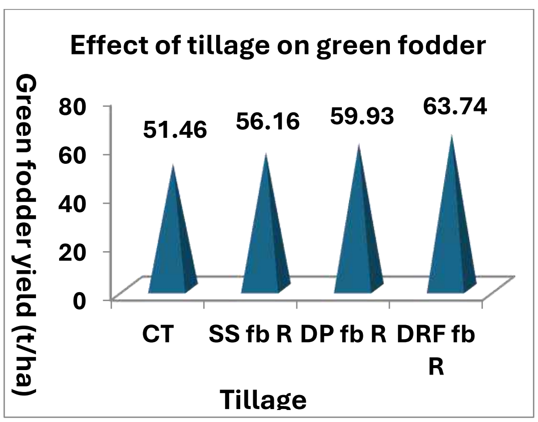
Tillage options had significant impact on the green and dry fodder yields (Table.1). The pooled values of two years of field experimentation indicated that DRF *fb* R produced significantly highest green fodder yield (Fig.1). The DRF *fb* R had 6.3, 13.5 and 23.8% greater green fodder yield than DP *fb* R, SS *fb* R and CT respectively. Similarly DP *fb* R gave 6.6, while SS *fb* R gave 9.1% more green fodder yield than SS *fb* R and CT, respectively. The dry fodder yield was also recorded significantly higher under DRF *fb* R, while DP *fb* R produced 6.7% higher dry fodder yield than SS *fb* R which also had 1.9% higher dry fodder yield than CT. DP fb R and DRF *fb* R also had 8.6% and 19.3% higher dry fodder yield than CT, respectively. Further, it was also noted that DP *fb* R and DRF *fb* R also produced 6.7% and 17.1% more dry fodder yield than SS fb R, respectively (Fig.3). The higher values of green and dry fodder yield under differential rate fertilizer placement favoured better utilization of nutrient and moisture resulting into higher growth attributes. Kumar *et al.* (2022) also reported significantly higher green and dry fodder yields than CT and SS fb R.

The ethanol yield varied significantly among tillage options during both the years (Table.1. Significantly highest ethanol yield was obtained under DRF *fb* R followed by DP *fb* R, SS *fb* R and the lowest under CT, during both the years. Based on pooled values, the DRF *fb* R yielded 23.2, 41.7 and 45.1% higher ethanol than DP *fb* R, SS *fb* R and CT, respectively (Fig.5). The higher ethanol yield was ascribed to higher stalk juice yield. Singh (2008) supported these findings.

b. Effect of nitrogen levels

The green and dry fodder yield increased with increasing nitrogen levels with highest values at 120 kg nitrogen/ha (Table.1). The pooled values showed that application of 120 kg N/ha produced 6.9 and 14.7% higher green fodder yield than 80 and 40 kg N/ha, respectively, while it was 8.2% higher at 80 kg than 40 kg N/ha. Similarly at 40 kg nitrogen, the green fodder yield was 4.7% higher than the control (Fig.2). A similar trend was also observed in dry fodder yield which was 7.1% higher at 120 kg than 80 kg N/ha (Fig.4). The higher values of fodder yields were attributed to taller plants, higher leaf area index and dry matter accumulation. The results of Moghimi and Emam (2015) and Kumar *et al.* (2022) support these findings, however they had different field ecologies and crop varieties. The ethanol yield was increased with increasing level of nitrogen and the highest values were recorded at 120 kg N/ha during both the years (Table.1). The pooled values showed 29.3, 57.8 and 62.8% higher ethanol yield at 120 kg N/ha, respectively (Fig.6). The higher ethanol yield was the result of higher green stalk yield and juice percentage. Shehab and Guo (2020) also recorded similar results.

An interaction was found between subsoiling and nitrogen levels (Table.2). The ethanol yield was increased with increasing level of nitrogen with significant highest values at 120 kg N/ha except under DP fb R, SS fb R and CT that had non-significant values between 0 to 40 and 40 to 80 kg N/ha. The conventional tillage gave the lowest ethanol yield at all the nitrogen levels and the values were non- significant between 0 and 40 as well as 40 and 80 kg N/ha and a similar trend was observed an SS *fb R* and DP *fb R* produced higher yield at 40 kg N than CT, Similarly the ethanol yield was noted significantly highest under DRF *fb R* at all the nitrogen levels but DP *fb R* and DRF *fb R* were non-significant at 80 kg N/ha. In general the ethanol yield was recorded as non-significant under CT, SS *fb R* and DP *fb R* at both control and 40 kg N/ha, whereas DP *fb R* gave significantly higher ethanol yield at both 80 and 120 kg N/ha.



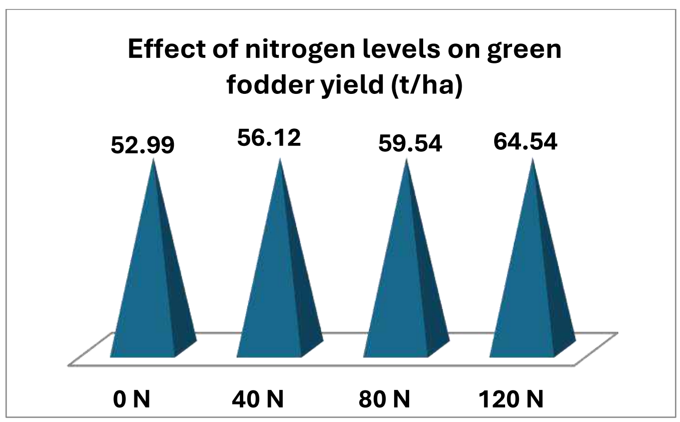


Fig.1. Effect of tillage on green fodder yield (pooled values of two years)

Fig.2. Effect of tillage on green fodder yield (pooled values of two years)

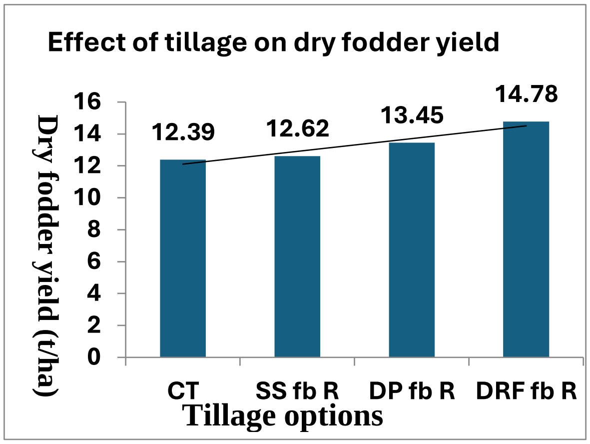


Fig.3. Effect of tillage on dry fodder yield (Pooled values of two years)

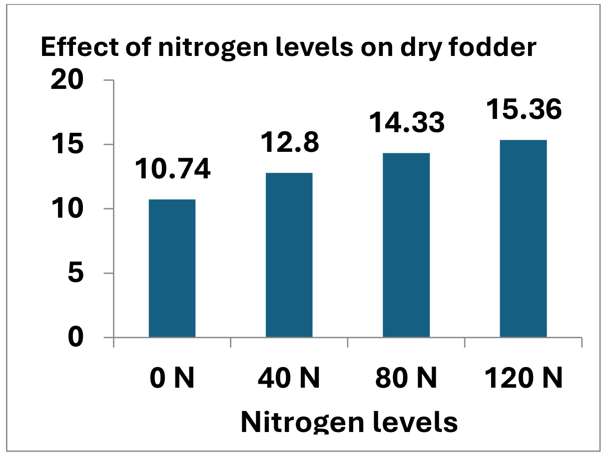


Fig.4. Effect of nitrogen level on dry fodder yield (Pooled values of two years)

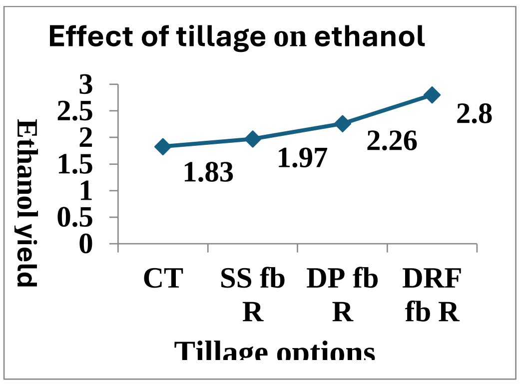


Fig.5. Effect of tillage on ethanol yield (Pooled values of two years)

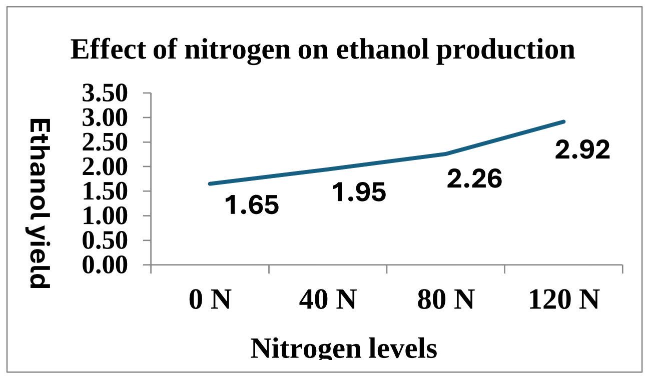


Fig.6. Effect of nitrogen level on ethanol yield (Pooled values of two years)

Table 1. Effect of tillage and nitrogen levels on fodder productivity and ethanol production of sorghum (Sorghum bicolor L.) during Kharif season 2011 and 2012

Treatment	Green fodder yield (t/ha)		Dry fodder yield (t/ha)		Ethanol production (kilo litre/ha)	
	2011	2012	2011	2012	2011	2012
A. Tillage options						
CT	52.68	50.24	13.01	11.78	1.85	1.81
SS *fb* R	56.44	55.88	13.27	11.97	2.02	1.92
DP *fb* R	60.22	59.65	14.18	12.80	2.38	2.14
DRF *fb* R	63.82	63.63	15.67	13.91	2.98	2.61
SEm±	0.35	0.90	0.18	0.20	0.80	0.80
CD at 5%	1.11	2.88	0.57	0.64	0.25	0.25
B. Nitrogen levels (kg/ha)						
0	52.99	52.87	11.27	10.20	1.70	1.60
40	56.12	54.68	13.48	12.13	1.90	1.99
80	59.54	59.33	15.32	13.55	2.26	2.25
120	64.54	62.53	16.15	14.52	2.96	2.87
SEm±	0.50	1.13	0.17	0.18	0.11	0.12
CD at 5%	1.45	2.21	0.48	0.53	0.31	0.33
Interaction	NS	NS	NS	NS	S	S

Table 2. Interaction between tillage and nitrogen level on Ethanol yield at harvest based on pooled data

Tillage	Ethanol yield (kilo litre/ha)			
	Nitrogen levels (kg/ha)			
	0	40	80	120
CT	1.3	1.6	1.9	2.4
SS fb R	1.4	1.7	2.0	2.7
DP fb R	1.8	1.9	2.4	2.8
DRF fb R	2.1	2.6	2.8	3.8
			S Em±	CD at 5%
For Comparing tillage at constant N level			0.13	0.40
For comparing N level at constant tillage			0.11	0.40

Conclusion and Implications

Based on pooled values of 2011 and 2012 field experimentation, it may be concluded that sweet sorghum may be grown under differential rate placements of P and K at 25 and 50 cm depth with application of a recommended 120 kg N/ha for higher fodder yield and ethanol production in Northern Himalayan regions of India. This may be able to be replicated in similar ecologies of the world.

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Drylands research in KALRO: addressing feed availability, livestock performance, climate smartness and business orientation challenges

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Key words: Certified Range Grass Seeds, Quality Low Methane Feed, Beef Finishing, Business Models

Introduction

The drylands in Kenya represents about 84% of land mass, hosts a ¼ of human population and >70% of livestock herd. Drylands experience below optimal livestock productivity, constrained by unavailability of quantity and quality feeds. Low availability of feeds is attributed to poor management of grazing resources in the natural systems leading to degradation and, limited adoption of improved pasture and fodder technologies leading to limited restoration and establishment of new pasture fields. Livestock in the drylands produce methane from enteric fermentation of low quality feed in the rumen. Manure also produce methane but to a lesser extent (Gerber *et al*. 2013). Enteric methane emission also represents a 2-10% loss of the dietary energy (Moraes *et al*. 2014). In the last couple of years, KALRO has been undertaking research aimed at enhancing feed availability, livestock performance, climate smartness of the production systems and profitability.

Methodology

To address the feed availability challenge, KALRO adopted the innovative approach of developing and commercializing forage varieties, working closely with Kenya Plant Health Inspectorate Service (KEPHIS). Variety development entails germplasm collection, molecular and phenotypic characterization, selection and on station evaluation of promising candidates, the National Performance Trials (NPTs) in different agro-ecological settings and Distinctness, Uniformity and Stability (DUS). The trials culminate in registration and release of varieties by KEPHIS. To realize commercialization of the varieties, the certification process was done. Certification is about building the quantity of seeds available to marketable volumes. The process starts with planting of the nucleus seed to produce breeder seed, later planted to produce pre-basic while pre-basic is planted to produce basic and so on to the certified seed generation 2. The pre-basic and basic classes are commercially produced by registered seed merchants. The basic, certified seed generation 1 and 2 goes to farmers for feed production.

To enhance livestock performance, existing forage technologies (crops) were transferred to farmers and the latter's capacity to use the technologies innovatively build using the Training of Trainers (ToT) – Demo plots methodology. About 20 forage technologies (crops) were transferred where trainer of trainees drawn from county governments of Taita Taveta, Kajiado, Narok and producer organizations were recruited and trained by KALRO research team. The trained trainers (TTs) were each assigned a demo plot or 2 where they worked with farmers to establish the forage crops which included grasses and legumes. The TTs used a training curriculum to train 30 to 50 farmers at each demo plot on forage establishment, weeding, harvesting, conservation and utilization including feed ration formulation. The farmers did own evaluation of the different forages including biomass yield, tolerance to low moisture, attack by diseases and pests, palatability and acceptability by livestock using the Secret Ballot method and, effect on the milk yield of livestock. Chemical composition of the forages was determined and the results shared back with farmers. The training enabled farmers to select forage crops to adopt and grow on scale for their livestock. Feed rations were innovatively formulated using different combinations of grasses and legumes exposed to farmers through the demo plots in order to attain the energy-protein balance required for good livestock performance.The feed rations were also tested for capacity to finish beef. Sheep were used in the trials where 6 different rations were tested against control (pure grass diets) for 90 days where the trial animals were individually stall fed. During the trials, growth performance, nutritive value and cost data were collected.

To enhance climate smartness, KALRO introduced inclusion of legume in livestock feed. During the feeding trials, data on proximate composition of the feed rations (wet chemistry) and growth performance was collected and used to estimate enteric methane emission per kg of meat produced following Intergovernmental Panel on Climate Change (IPCC), 2019 equation shown below.

(1)

$$DMP\ (g\ /\ d) = \frac{(GE\ (MJ) \times Y_m(\%)/100)}{0.05565}$$

Where;
DMP is daily methane production; Ym is the methane emission factor of 6.7 %
GE is the gross energy of the rations, computed from the equation below;
(2)

$$GE = 0.0226CP + 0.0407EE + 0.0192CF + 0.0177NFE$$

Where; CP =Crude protein; EE= Ether extract; CF= Crude fibre; NFE = Nitrogen free extract

Cost data also collected during the feeding trials was used to determine average variable cost and profitability of each ration. Business cases were formulated based on the feed rations and promoted.

Results and Discussion

The varieties: Cenchrus ciliaris (CECI) Var. MGD KBK, Cenchrus ciliaris (CECI) Var.TVT3 KBK, Enteropogon macrostachyus (ENMA) KBK, Chloris roxburghiana (CHROX) KBK4, Brachiaria KS1 and Brachiaria BS1were registered and released in December 2021. The species including Megathysus maximus MK1, Megathysus maximus MK6 and Eragrostis superba are currently undergoing the NPTs with a view of having them registered and released by KEPHIS as well. On commercialization, about 3.2 tons of pre-basic class seed have so far been bulked and are in the process of being distributed to investors for commercial multiplication.

Forage technologies transferred to farmers are: Cenchrus ciliaris (African fox tail), Enteropogon macrostachyus (Bush rye), Chloris roxburghiana (Horse tail), Sugar graze, Nutrifeed, Brachiaria cayman, Brachiaria cobra, Brachiaria camello, Panicum maximum, cowpea M66, Dolichos lab lab, Lucerne, Desmodium, Mucuna, Purple vetch, among others. A 40% adoption of the forages was registered with the farmers. In the low rainfall areas, the grasses Sugar graze, Brachiaria camello and Masaai love grass were the most adopted while the same was true for Boma Rhodes in the high rainfall areas. The legumes, Dolichos lablab, Cowpea M66 and Sweet Potato vines, Greenleaf desmodium (Desmodium intortum). Adoption of the forage technologies by farmers was informed by; biomass yield, drought tolerance, acceptability and palatability by livestock and animal performance.

For the beef finishing trials, table 1 shows CP, Metabolizable Energy (ME) of the feed rations, initial live weight, Average Daily Gain (ADG), Final Weight, Net Weight, Dry Matter Intake per day (DMI/day) and DMI as a % of Live Weight (LWT).

Table 1: CP, ME, Average Initial Weight, Final Weight and Weight Gain for Goats Fed with Different Diets

Diet	CP (%)	ME (MJ/Kg DM)	Initial Weight (Kg)	ADG (g)	Final Weight (Kg)	Net Weight Gain (Kg)	DMI g/day	DMI as a % of LWT
Maiza grain+Lucerne hay+Wheat bran+Commercial ingredients	14	11	21.3	357[a]	48.8[a]	27.5	-	-
Brachiaria sp var cayman+Desmodium	8.7	8.6	15.5[a]	317.5[b]	44.1	28.6	593.2	3.29[a]
Brachiaria spp var cayman +Lucerne	10.8	9.4	16.7[a]	277.8[b]	41.7	25.0	583.3	3.0[a]
Megathysus maximus+Lucerne	7.5	7.9	16.7[a]	238.1[b]	38.1	21.4	643.1	3.3[a]
Megathysus maximus +Desmodium	7.1	8.6	17.0[a]	297.6[b]	43.8	26.8	562.6	2.8[a]
Megathysus maximus	3.1	6.6	17.0a	119.0a	27.7	10.7	686.3	
SEM	14	11	0.69	28.1	0.99	0.59		

Inclusion of legume in the diets enhanced nutritive quality, feed intake and the average daily weight gain of sheep. This was attributed to enhanced crude protein, digestibility and low fibre content in agreement with Krause *et al*. (2002).

Table 2 shows methane yield from other trialed feed rations.

Table 2: Methane Yield from Forage Based Feed Rations by Sheep over 91 Days in a Feedlot System

Parameter	C. ciliaris	C. ciliaris + Lucerne	C.ciliaris+ Desmodium	E.macrostachyus+Lucerne	E.macrostachyus+Desmodium	E.macro stachyus	SEM	P value
CP (%)	4.4[ab]	12.1[b]	7.1[a]	8.1[bc]	11.8[c]	5.5[ac]	-	-
*ME (MJ/Kg DM)	8.2[a]	8.5[b]	8.2[a]	7.8[c]	9.1[ab]	7.1[c]	-	-
DMI kg/day	0.87[c]	0.84[c]	0.68[a]	0.71[b]	0.81[bc]	0.92[c]	0.04	**
Daily Methane production (DMP g/day)	18.4[c]	17.7[c]	14.0[a]	15.15[ab]	16.94[b]	19.36[c]	0.81	**
CH_4 yield (g CH_4/kg DMI)	21.2[c]	21.2[bc]	20.8[a]	21.2[bc]	20.8[ab]	21.0[abc]	0.13	**
Methane intensity (g CH_4/kg LW	690.2[a]	470.9[b]	350.1[b]	599.6[a]	286.7[b]	645.6[a]	146.9	NS

*[a,b,c] Mean values within a row with different superscript letter differ significantly at p<0.05; C – Cenchrus; E – Enteropogon; SEM – Standard Error of the Mean; NS – Not Significant; *The asterisk indicates values obtained through computation. Column mean with different letter superscript are significantly different at p< 0.05*

A significant difference (p<0,05) was recorded on daily methane production from sheep fed on the six diets with inclusion of Desmodium in the *Megathysus maximus* diet reducing the DMP by 25%. This is tied to the fact that increased non fiber sugar content in ruminant feeds lead to a more propionate-based fermentation pattern which in turn decreased the amount of hydrogen produced (Archimède *et al*.2014) and consequently led to lower methane emissions. Methane yields obtained in the present study ranged from 20.8 -21.2 g/kg DMI which was within the range found by other studies in tropical environment with tropical low quality forages (Archimede *et al*.2018, Gera *et al.* 2022).

Table 3: Profitability Case for 100 units

Diet	**TVC**	**Revenue**	**GM**	**BCR (>1)**	**ROI**	**Viability (V) & Ranking**
Brachiaria+Desmodium	39,976.1	201,000.0	161,023.9	5.0	4.0	V-1
Brachiaria+Lucerne	55,249.8	174,000.0	118,750.2	3.1	2.1	V-3
Megathysus maximus	39,430.6	75,000.0	35,569.4	1.9	0.9	V-5
Megathysus maximus +Desmodium	39,976.1	189,000.0	149,023.9	4.7	3.7	V-2
Megathysus maximus +Lucerne	55,249.8	150,000.0	94,750.2	2.7	1.7	V-4

TVC – Total Variable Cost; GM – Gross Margin; BCR – Benefit Cost Ratio; ROI – Return on Investment

Brachiaria+Desmodium and *Megathysus maximus* +Desmodium returned the highest BCRs of 5.0 and 4.7 and ROI of 4.0 and 3.7, respectively. *Megathysus maximus* basal diet showed the least returns. The legume addition to grass-based diets returned high BCR, GM, low Break Even Quantity (BEQ) and high ROI confirming the importance of the protein rich ingredients in livestock feeds.

Conclusion and Recommendations

KALRO is on course in terms of making available, certified range grass seed varieties for restoration of degraded rangelands and establishment of new pasture fields. This will contribute to the government effort to close the 56% livestock feed supply deficit experienced at the moment. Seed companies, farmer groups or individual farmers are encouraged to engage in commercial seed multiplication using the basic seed now available in KALRO. In so doing, the companies will help the country produce and meet the demand for certified grass seed. With a 40% adoption of forage technologies by farmers, the country is on course to significantly increase feed availability and by so doing increase livestock productivity. The KALRO team recommends that counties encourage farmers to continue adopting the improved forage crops in order to make more livestock feed available. Inclusion of the legume in the diets enhanced nutritive quality, feed intake and the average daily weight gain of sheep on the feed rations. It is therefore beneficial for sheep farmers to adopt growing of grasses and legumes for use in forage-based feed ration formulation to finish the sheep. The alternative is to ensure supplementation of the free grazing goats with cultivated protein rich feed material for the livestock finishing activities to make economic sense. Finishing of the sheep should start at between 4 to 6 months old to take advantage of the naturally fast growth at this stage and in a feedlot system. Legume addition to low quality roughage reduced daily methane emission and methane yield per unit of beef produced implying, the system is a good option for achieving the emission reduction goals for sustainable sheep production. The legume addition to grass-based diets returned high BCR, GM, low BEQ and high ROI confirming the importance of the protein rich ingredients in livestock feeds. The on-farm feed production was more cost proficient than buying from the market and thus more farmer profit maximizing.

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Effect of drought on performance in continuous grazing with breaks with and without inclusion of a rotational grazing module systems.

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Keywords: grasslands; grazing systems; good practices; drought; Uruguay.

Abstract

Rangelands are the mainstay of cattle and sheep systems in Uruguay. The current demand for global results from different grazing systems puts pressure on the generation of new knowledge. In this context, spring droughts in Uruguay are one of the most relevant challenges for livestock farmers. The objective of the following work is to evaluate the impact of drought on a continuous grazing with breaks with and without inclusion of a rotational grazing module system. The study was conducted during the 2021/2022 and 2022/2023 seasons, with the former encompassing a spring drought and the latter a severe spring and summer drought, examined two grazing systems: continuous grazing with breaks (CG) and continuous grazing with breaks plus rotational grazing module (CGR). The results showed that Aboveground Net Primary Productivity (ANPP) decreased by about 12% in both groups. The Meal Plate Index (MPI), an index that relates available grazing to the grazing required for optimal animal performance, decreased by 13% in CG and 7% in CGR. Grass Availability (GA) also decreased by 15% and 4% for CG and CGR respectively. The proportion of pasture greater than 5 cm (PRG5) decreased from 19% to 12% for CG and increased from 26 to 33% for CGR for both seasons. The main differences are that CGR maintains Meat Production (MP) (105-107 Kg per hectare) and Efficiency per Stock Unit (MPES) (133-132 kg). On the other hand, CG was not able to maintain its MPES (144-128 kg), which decreased by 12%. For CG, 9 out of 12 were negatively affected, resulting in a 22% decrease of MP. Within CG, the least affected had values of PRG5=16 and MPI=0.72, while the most affected had values of PRG5=7 and MPI=0.6. The severe drought had a differential impact on systems, CGR group showed improved levels of grass indicators and reduction in the negative impact on MP and MPES.

Introduction

Rangelands are the mainstay of cattle and sheep systems in Uruguay. The current demand for information on the overall results obtained from the different grazing systems is putting pressure on the generation of new knowledge, FPTA 356 proyect (e.g. Singh, pers. comment.). In this context, spring droughts in Uruguay are one of the most relevant challenges for livestock farmers. The objective of the following work is to evaluate the impact of drought on a continuous grazing with breaks with and without inclusion of a rotational grazing module system.

Methods

The study was conducted during the 2021/2022 and 2022/2023 seasons, with the former encompassing a spring drought and the latter a severe spring and summer drought, examined two grazing systems: continuous grazing with breaks (CG) and continuous grazing with breaks plus rotational grazing module (CGR). We work with 19 cattle and sheep ranches (average 1300 hectares) that were part of the FPTA Nº 356 (Pereira Machin, 2020) pasture management project implemented by the Instituto Plan Agropecuario (IPA). The six outputs or index that were analyzed were: 1 - Aboveground net primary productivity (ANPP) expressed in kg DM. The 'Paddock Monitoring' module allow updating the status of the paddocks, as well as displaying the following outputs or global forage performance indicators of the establishment; 2 - Grass Availability (average stock in kg DM per hectare that the establishments have at a given time). 3 - Meal Plate Index (MPI), an index elaborated in the FPTA-INIA Project No. 345 (Duarte, 2020), this index is the result of comparing the forage or grass available in the establishment, with the one that should be available for an optimal performance of the livestock. The result is expressed in decimals, MPI value 1 means that the available grazing area is equal to that needed, while lower or higher values show shortages or surpluses. 4 - Proportion of area available for grazing at different height ranges (*i.e.* generated from the proportion of area at three height ranges), this variable is represented by the following three indicators: Proportion of area with forage height; 'less than 2.5 cm' (PGR-2.5), 'between 2.5 and 5 cm' (PGR2.5To5) and 'greater than 5 cm' (PGR5). In order to assess the performance of pasture management, it was necessary to develop an indicator to describe pasture management (Lombardo, 2023). 5 - Meat Production (MP) in Kg per hectare / year, and 6 - Efficiency per Stock Unit (MPES) expressed in kg of meat produced per kg of live weight maintained in the system.

Results

The results showed that Aboveground Net Primary Productivity (ANPP) decreased by about 12% in both groups. The Meal Plate Index (MPI), an index that relates available grazing to the grazing required for optimal animal performance, decreased by 13% in CG and 7% in CGR. Grass Availability (GA) also decreased by 15% and 4% for CG and CGR respectively. The proportion of pasture greater than 5 cm (PRG5) decreased from 19% to 12% for CG and increased from 26 to 33% for CGR for both seasons. The biggest differences are in this indicator, CG decreased by 7 percentage points (37 % overall) while CGR increased by 27 % overall, which shows the capacity to provide pasture in both systems. The results show that in the 2021-2022 season, the majority (14/19) of the ranches maintained PGR5 with values above 15%. In 2022-2023, only 9 of the 19 were able to maintain this condition. In the same direction, the main differences are that CGR maintains Meat Production (MP) and Efficiency per Stock Unit (MPES). For this analysis we can look at that CGR systems have the best values for grass use efficiency (MPES), linked to improved values of GA, MPI, PRG5, MP.

Table 1. Results outputs of CG and CGR in two seasons

	CG		Difference	CGR		Difference
	2021-2022	2022-2023	in %	2021-2022	2022-2023	in %
ANPP (KgMS/ha/year)	4980	4400	-12%	4690	4150	-12%
MPI [0 To 1.2]	0,77	0,67	-13%	0,74	0,69	-7%
GA (KgDM/ha)	871	736	-15%	997	959	-4%
PGR5 (%)	19	12	-37%	26	33	27%
MP (Kg/ha/year)	99	87	-12%	106	107	1%
MPES (Kg/Stock Unit)	145	128	-12%	134	133	-1%

Figure 1. Proportion of area with forage height; 'less than 2.5 cm' (PGR-2.5) in red, 'between 2.5 and 5 cm' (PGR2.5To5) in yellow, and 'greater than 5 cm' (PGR5) in green by CG in 2021/2022.

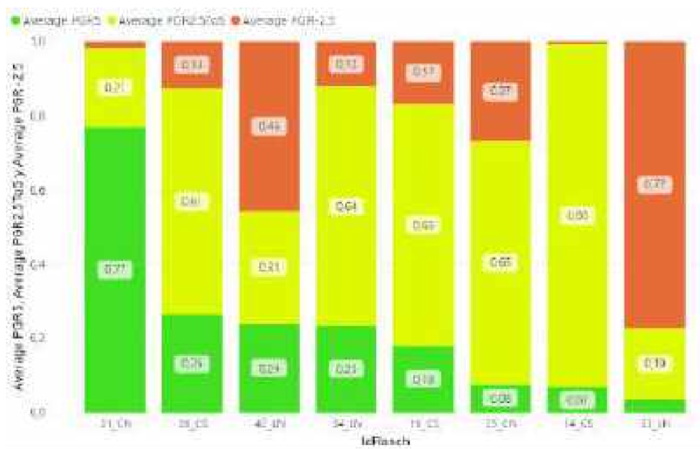

Figure 2. Proportion of area with forage height; 'less than 2.5 cm' (PGR-2.5) in red, 'between 2.5 and 5 cm' (PGR2.5To5) in yellow, and 'greater than 5 cm' (PGR5) in green by CGR in 2021/2022.

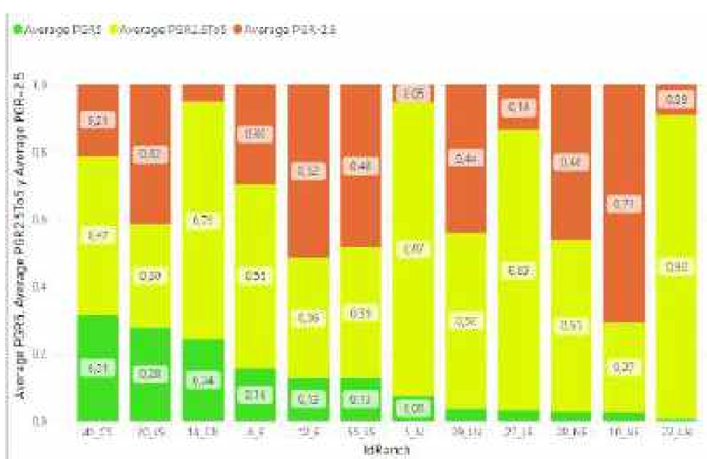

Figure 3. Proportion of area with forage height; 'less than 2.5 cm'(PGR-2.5) in red, 'between 2.5 and 5 cm'(PGR2.5To5) in yellow, and 'greater than 5 cm'(PGR5) in green by CG in 2022/2023.

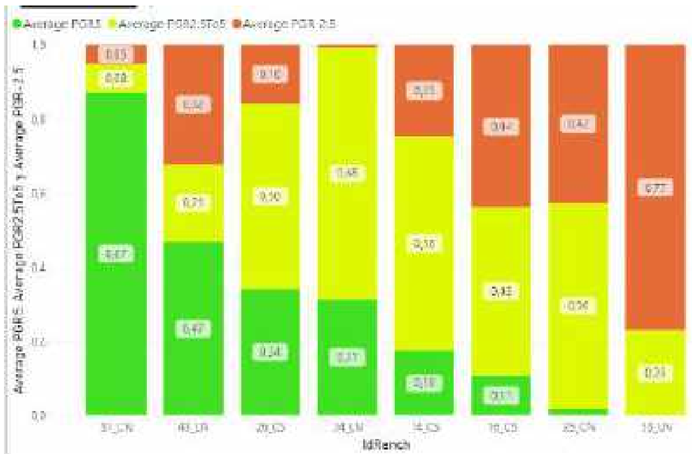

Figure 4. Proportion of area with forage height; 'less than 2.5 cm'(PGR-2.5) in red, 'between 2.5 and 5 cm'(PGR2.5To5) in yellow, and 'greater than 5 cm'(PGR5) in green by CGR in 2022/2023.

Discussion

CG was not able to maintain its MPES (144 -128 kg), which decreased by 12%. For CG, 9 out of 12 rancheswere negatively affected, resulting in a 22% decrease MP. Within CG, the least affected had values of PRG5=16 and MPI=0.72, while the most affected had values of PRG5=7 and MPI=0.6. The severe drought had a differential impact on systems, CGR group showed improved levels of grass indicators and reduction in the negative impact on MP and MPES. CGR systems had higher grazing efficiency and productive performance, they also provided higher quantities of forage. The originality of the indicators used (PRG´s) does not yet allow for comparison with local research carried out.

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Navigating fragmented landscapes: pastoralism and dependence on open natural ecosystems in western India

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Key words: land use, movement, pastoralism, deccan peninsula

Abstract
Open Natural Ecosystems (ONEs) cover about 10% of India's geographical area and are extremely fragmented. Sustainable use of ONEs for low-input livelihoods like extensive pastoralism requires an understanding of the nature of the dependence of pastoralists on these native habitats. This is especially crucial in India where such socio-ecological systems lack recognition and are classified as 'wastelands' in policy and legislation. We tracked livestock movement in different land uses of western India's ONEs for 109 days between 2022-2023. We used non-participant observations and interviews with pastoralist men and women to understand movement-related decision making. Based on simple linear models and availability vs use frameworks, we infer pastoralism's fine-scale use of the landscape. Livestock movement patterns show that pastoralist dependence on ONEs at higher elevations is highest in the monsoon (use is >2.5 times the availability of ONEs), and the availability of irrigation, household labor, and social networks determines this movement. Pastoralism in this region is heavily influenced by the availability of agricultural residues and farmer decisions contrary to the popular understanding, some households appear to benefit from irrigated agriculture. Despite rapid land transformations, however, pastoralism remains a low-input and economically lucrative livelihood that allows seasonal use of savanna ecosystems. Our findings contribute to understanding of how these ONE-based livelihoods navigate land use change and offer insights into the potential of community-led ecosystem management.

Introduction

Globally, India does not figure as a country with extensive rangelands and 'grazing-only' systems because of the wide presence of socially complex small-scale farming systems (Godde et al. 2020; Herrero et al. 2017) and hence is a data-deficient region in global analyses on rangeland management (Godde et al. 2020). However, 10% of India's geographical area is covered by Open Natural Ecosystems (ONEs) which are naturally occurring grass-dominated landscapes in semi-arid and arid regions of India (Ratnam et al. 2016). These consist of ecosystems like deserts grassy to mesic savannas, ravines, and rocky outcrops (Madhusudan & Vanak 2022). Like many other regions of the world, India has a significant population of extensive pastoralists who practice large and small livestock rearing by relying on ONEs for some parts of the year. Extensive pastoralism is a specialized method of rearing livestock in semi-arid regions that relies on movement between geographies to benefit from the fluctuation of water and biomass availability (FAO 2021). Although the contribution of this system to India's food security and economy is being formally investigated, some estimates suggest that 53% of India's milk production and 74% of India's meat production comes from extensive pastoralist systems (Kishore & Kohler-Röllefson 2020).

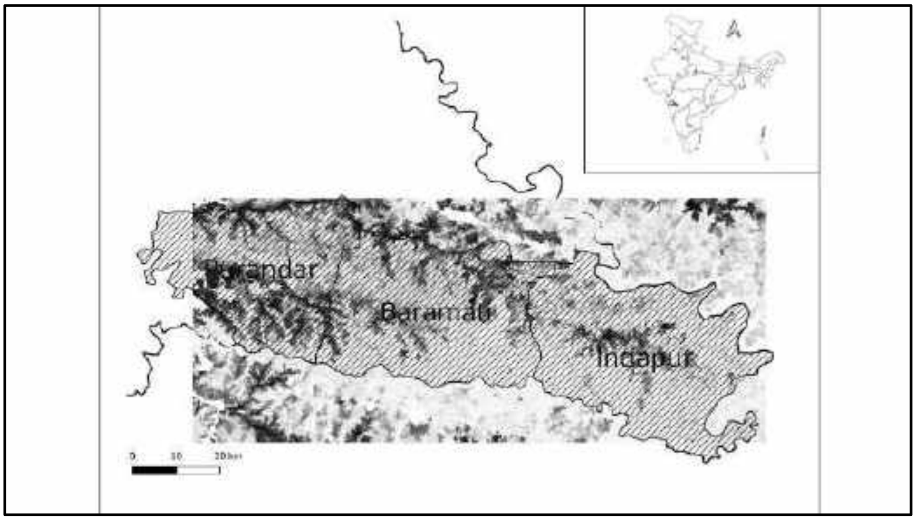
Land use diversion in ONEs, especially towards year-round agrarian production, is a well-known phenomenon. About 14.8 million ha of grasslands and shrublands have been converted to croplands in the 20th century and this conversion was especially faster post-1960s (Tian et al. 2014). Currently, ONEs are extremely fragmented, so much so that 94% of ONE patches are now only between 1-100 hectares (Madhusudan & Vanak 2022). With these high levels of fragmentation in ONEs, livestock management systems and associated institutions regulating access have further gone to the margins. Additionally, since India is not a typical extensive rangeland system (i.e. with low human population densities, dry climate & low ease of farming), livestock production systems are viewed as only supplementing agrarian livelihoods. However, at least 13 million pastoralists practice specialized forms of livestock keeping dependent on some level of mobility (Kishore & Kohler-Röllefson 2020). Hence, it becomes imperative to understand the nature of dependence and seasonal use of lands for pastoralism from the perspective of pastoralists' response to the fragmentation of ONEs.

Research on land use and pastoralist mobility from other parts of the world has shown that fragmentation causes disenfranchisement. Burnsilver et al. in Galvin et al. 2008 record how the Maasai in the Amboseli landscape, due to land fragmentation were pushed to opt for intensification of husbandry practices in smaller areas that included rearing poorly adapted hybrid cattle in arid regions. Groups of pastoralists like the Samburu, Turkana, Fulani, and Sahelian pastoralists have all been affected by some form of fragmentation (Galvin et al. 2008) bringing about changes in the way they move in the landscape and their socio-economic conditions. Butt 2014 describes a case of functional fragmentation where the creation of parks for wildlife conservation has affected how the Maasai move. He shows how new land tenure arrangements because of conservation parks has 'co-produced' the phenomenon of 'cattle incursions'. Another important form of functional fragmentation, albeit not from an arid or semi-arid savanna is the case of the Gaddi pastoralists in Himachal Pradesh. Ramprasad et al. 2020 note how afforestation activities, along with changing plant species composition, has threatened pastoral livelihoods by reducing fodder availability and forcing a change in migratory routes. However, contrary to the literature on disenfranchisement, there is also growing evidence from Africa which shows that commonages which were fragmented are also being brought back under management for pastoralism through both top-down and bottom-up tenurial arrangements (Bollig & Lesorogol 2016). However, India remains a blindspot in understanding responses of pastoralists to fragmentation.

Methods

Study site

We chose to work in the Pune district of western Maharashtra because of the presence of a considerable pastoralist population and fragmented ONEs. We specifically focused on pastoralist villages in four talukas - Purandar, Daund, Baramati & Indapur (Map 1; QGIS 3.34.13). The land cover in these 4 tehsils is a mix of ONEs (grasslands, rocky habitats, inselbergs, and scrub vegetation), irrigated and dry-land agriculture, industrial/urban areas, and rural settlements. Concerning land tenure, the ONEs in the study area are largely uncultivated private lands, followed by those managed by the Forest Department and as village commons. The region receives an annual rainfall of between 800-1200 mm.



Map 1: The above map shows the location of the study area in India. Darker the color, higher the possibility of that pixel being an ONE.

Data collection

We tracked livestock movement in different land uses of the study area for 69 days in the monsoon of 2022 and 40 days in the summer of 2023 (a total of 109 days) to understand seasonal movement patterns. We used handheld GPS devices and low-cost custom-made GPS trackers to map livestock movement where we recorded time spent in each land use by the herd (Butt et al. 2010, Wade et al. 2024). In these walk-along movement tracking surveys, we used non-participant observations of pre-herding, post-herding, and herding activities of 74 pastoralist households (both women and men) to understand movement-related decision making. We used semi-structured interviews to collect data on household socio-economic characteristics to understand dependence on pastoralism and test for relationships with movement patterns (Salamula et al. 2017; Jones et al. 2022).

Analysis

For the movement data, we used the spatial points downloaded from the GPS devices, to perform a use vs. availability analysis on land cover. Land cover information was extracted from the Dynamic World V1 10 m resolution raster available on Google Earth Engine (Brown et al. 2022). From this, we inferred whether pastoralists selected for specific land covers seasonally based on what was available for them. Since pastoralists could move, we considered the 'available' land cover as those in all 3 administrative units of our study area. We then used simple linear regressions to test for relationships between household socio-economic characteristics and movement patterns (Rstudio 2023.06.2). Lastly, using axial and open coding (Corbin & Strauss 1990), we analysed notes from our field observations on decision-making around movement and living experiences of herding livestock in ONEs and agricultural landscapes.

Results

We collected data of 75 households from 26 pastoralist settlements, out of which 70 households belonged to the Dhangar group of pastoralists and 5 were from other groups. Because we focused on herding activities, there was a gender and age bias within our pool of respondents since this demographic tended to herd livestock more often than others. Out of 75 households we interviewed or observed activities of, 64 were that of pastoralist men, 46% of whom were within 21-40 years of age. For the rest of the 10 households, 5 were women herders and 6 were pairs of men & women from the same household who were herding together.

Neither daily distance traveled seasonally nor annual migration patterns were dependent on herd sizes kept by a household (Adjusted R^2=0.006, effect size =-0.008(SE=0.006); Adjusted R^2=0.094, effect size

=0.004(SE=0.001)). However, herd sizes were strongly predicted by the number of people in the household who were engaged full-time in pastoralism and agricultural activities (Adjusted R^2=0.443; Figure 1). More specifically, with every additional member in pastoralism, 32 additional livestock heads could be reared on an average while with every additional member in farming, the herd size was reduced by 14 heads on an average.

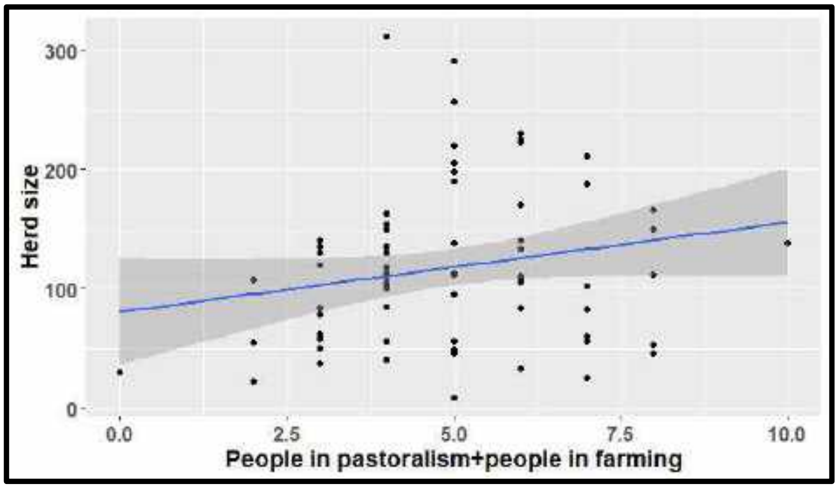


Figure 1: A linear model showing the relationship between the number of people in the household who were engaged full time in pastoralism and farming and the herd size kept by the household.

Fine-scale livestock movement patterns, when looked at from a use vs. availability analysis, show that pastoralist dependence on land covers like grass & scrub (which form ONEs) is highest in the monsoon (the frequency of their use is 2.5 times higher than their availability; Figure 2). Additionally, pastoralist households travel less in the monsoon compared to dry seasons (~ 7 km lesser on an average).

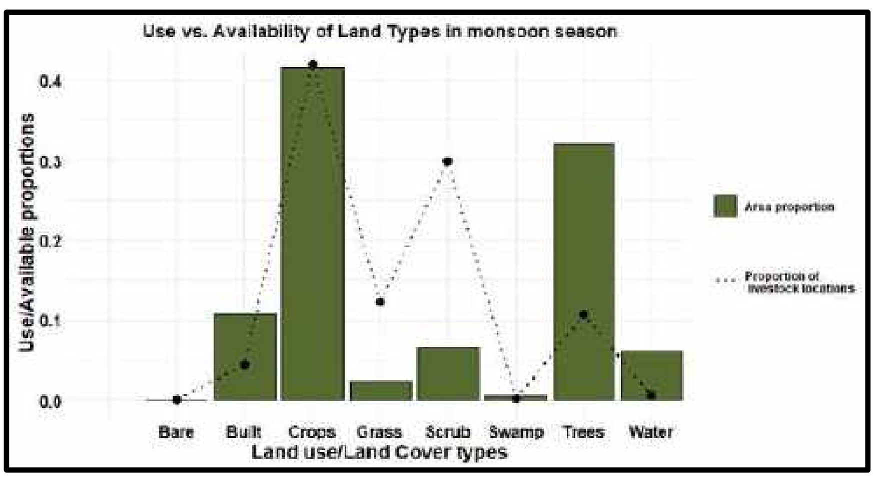


Figure 2: The bars in the above graph indicate the proportion of available land covers while the dotted lines indicate the proportion of spatial points that fell in that land cover in the monsoon season.

More than 80% of the households accessed only private fallow lands during both seasons (Figure 3).

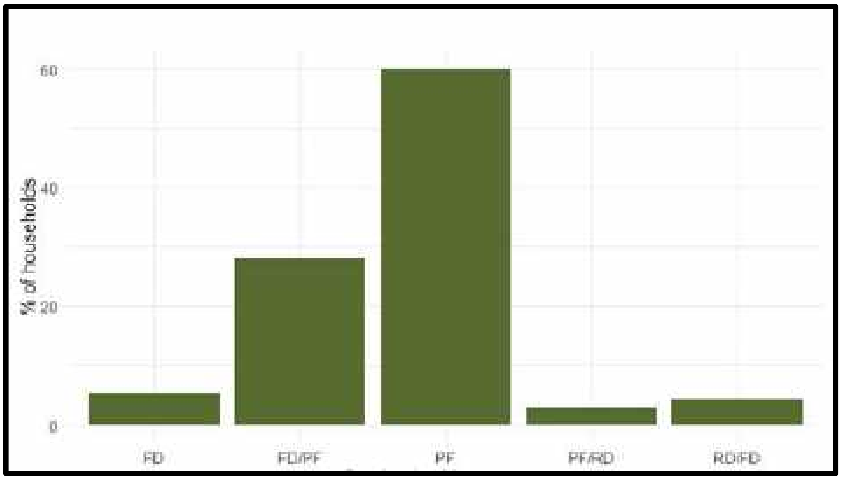


Figure 3: The bars in the above graph indicate the proportion of daily tracks in different land tenures. (FD=reserve forests, PF=private fallows, RD=Revenue department lands)

The presence of irrigation and farmer decisions determined the accessibility of lands for pastoralists. Households accessed fodder in both seasons based on interpersonal relations and social networks with farmers. Access to reserve forests was also based on informal understanding with the lower rungs of the forest bureaucracy, which often also resulted in conflicts. Because of the fragmented nature of village common lands, they were rarely sufficient for multiple pastoralist herds and thus, very few households relied on them consistently throughout a single season.

Discussion

Seasonal differences in daily distance traveled by pastoralists was expected because biomass needs are met more easily in the monsoon due to the proximity of ONEs. However, contrary to our understanding, we found poor evidence for the relationship between herd sizes and daily travel patterns as well as long distance migration patterns. Additionally, private fallow lands seemed overwhelmingly important for pastoralism in this landscape. We conclude that availability of household members and increasing social networks with farmers enabled pastoralists to navigate changing land use. This finding offers a different perspective from the more common understanding of pastoralist-farmer relations centered on conflict (Usman and Nichol, 2022; McGuirk & Nunn, 2024). We argue hence, that pastoralism needs to be viewed as a livelihood embedded in an agrarian landscape in this region of India. This is because dispersed household decisions in the landscape around the cultivation of land is determining land availability for pastoralists.

We also find that ONEs are extremely important for pastoralists in the monsoon. However, the process of 'commoning' or creation and strengthening of institutions managing commons is not adequate for livelihood security of pastoralists in this region (Bollig and Lesorogol, 2016). Instead, securing the agriculture-pastoralism nexus through institutions appears to be more beneficial for pastoralism.

Lastly, we provide evidence that ONEs in this region of India are supporting livestock production seasonally. However, land diversions in ONEs are assumed to have minimal impact on people and ecosystems. That is the reason that these lands are termed 'waste' (DoLR 2019) and demarcated for diversion. For eg. almost 60% of ONEs in Maharashtra are demarcated for potential afforestation (Madhusudan and Vanak 2022). Our findings help to develop a nuanced understanding of the nature of dependence of livestock- based livelihoods on ONEs in a rapidly modifying landscape.

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Effect of lactic acid bacteria on silage quality of sweet sorghum (*Sorghum bicolor*)

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Keywords: Fermentation quality; Identification; Isolates; lactic acid bacteria, sweet sorghum.

Abstract

The purpose of this study was to identify lactic acid bacteria (LAB) from elephant grass silage throughout the fermentation process and investigate their effect on improving quality of sweet sorghum silage. The isolates were identified based on morphological, physiological, and biochemical features, as well as 16S rRNA profiling. A total of 120 lactic acid bacteria were isolates from elephant silage seven strains were purified and idntified three strains (*Pediococcus acidilactici* (AZZ1), *Lactobacillus plantarum subsp. plantarum* (AZZ4), *L. plantarum subsp. argentoratensis* (AZZ7) and one commercial bacteria *L. plantarum, ecosyl* MTD/1(CB)) were chosen as additives at 6 log colony forming units per gram of fresh sweet sorghum grass in laboratory silos (1000 g). Silos for each treatment were opened after 30, 60, and 90 days. All isolates were Gram-positive, catalase-negative, and grew properly in 65% sodium chloride. The strains AZZ1, AZZ2, and AZZ5 were classified as the *Pediococcus genus*, while AZZ3, AZZ4, AZZ6, and AZZ7 were *Lactobacillus genus*. Compared to the control, all the isolates enhanced the silage quality of sweet sorghum silage, evidenced by significantly ($P < 005$) decreasing pH, ammonia-nitrogen contents, undesirable microbe counts, and greater lactic acid (LA) contents. During ensiling, AZZ4 performed better among all inoculants, indicated by significantly ($P < 005$) lowered pH and ammonia-N contents and increased LA contents. In conclusion, strain AZZ4 is recommended as starter culture for tropical and subtropical grasses.

Introduction

In recent years, the demand for dairy products has increased in many developing countries as well as the tropical and subtropical regions of Asia and Africa. However, the production of silage for dairy farming has been hindered in these regions because of ensiling process that is highly dependent on local environmental conditions (Sifeeldein et al., 2019). To produce high-quality silage consistently in these regions, acid-tolerant, thermophilic lactic acid bacteria (LAB) or homolactic acid fermented LAB must be identified and used as starter strains. (Sifeeldein et al., 2019). Because of the limitations of available technology, screening, selecting, and constructing starting cultures for silage production remains difficult, as is the classification of isolated strains. Closely related species, such as *Lactobacillus plantarum, Lactobacillus casei, Lactobacillus rhamnosus,* and *Lactobacillus pentosus*, which are the primary dominating strains in silage, are difficult or impossible to differentiate based on their phenotypes and genotypes (Duar et al., 2017).

In contrast, sorghum is one of the most suited plants for silage production and is becoming an increasingly significant feed crop in many regions of the world (Xie & Xu, 2019). Due to its high water soluble carbohydrates contents (WSC) and low buffer capacity, it is easy to ensile (Klevenhusen & Zebeli, 2021). It may also be an acceptable choice for silage production in marginal locations due to its high fodder output and drought tolerance. Inoculants have been proven to increase silage quality, as evidenced by lower pH and a greater number of lactic acid bacteria (LAB) (Guo et al., 2023).

Material and Methods

Sweet sorghum (*Sorghum bicolor)* grown at experimental field of Nanjing Agricultural University, Jiangsu, China. The grass was harvested at the mature stage.

Silage preparation

The chopped grasses were inoculated with three strains of LAB, *Pediococcus acidilactici* (AZZ1), *Lactobacillus plantarum subsp. plantarum* AZZ4, *L. plantarum subsp. argentoratensis* (AZZ7) and a commercial LAB *Lactobacillus Plantarum*, Ecosyl MTD/1 (CB) Ecosyl Product Inc. USA. LAB applied as additives at 6 colony forming units (cfu)/g calculated based on the fresh material weigh; Triplicate jars for each treatment were opened on days 30, 60, and 90 of ensiling.

Chemical analyses

The ammonia- N (NH_3-N) was determined according to the method of phenol-hypochlorite reaction. The pH of fresh grasses and silage were measured using a pH meter .Organic acids, including the lactic acid (LA), acetic acid (AA), propionic acid (PA) and butyric acid (BA) were analyzed by high-performance liquid chromatography according to the methods described by Mala et al.

Microbial population

A sub-sample (10 g) of wet silage from each sample was mixed with 90 mL of sterile saline solution (8.50g L^{-1}). Enumeration of LAB, aerobic bacteria, and yeast was performed using de Man, Rogosa, and Sharpe agar, nutritional agar, and potato dextrose agar, respectively. Finally, the total microbiological data were converted to log10 and presented on a fresh weight basis.

Results and Discussion

All isolates were identified as Gram-positive, catalase negative, rod-shaped bacteria. Compared to the control, all the isolates improved the silage quality of sweet sorghum silage, indicated by significantly (P < 005) lower pH and ammonia-nitrogen contents and undesirable microorganism counts, and higher lactic acid (LA) contents. During ensiling, AZZ4 performed better among all the inoculants, indicated by a significantly (P < 005) decreased pH and ammonia-N contents and a higher increase in LA contents.

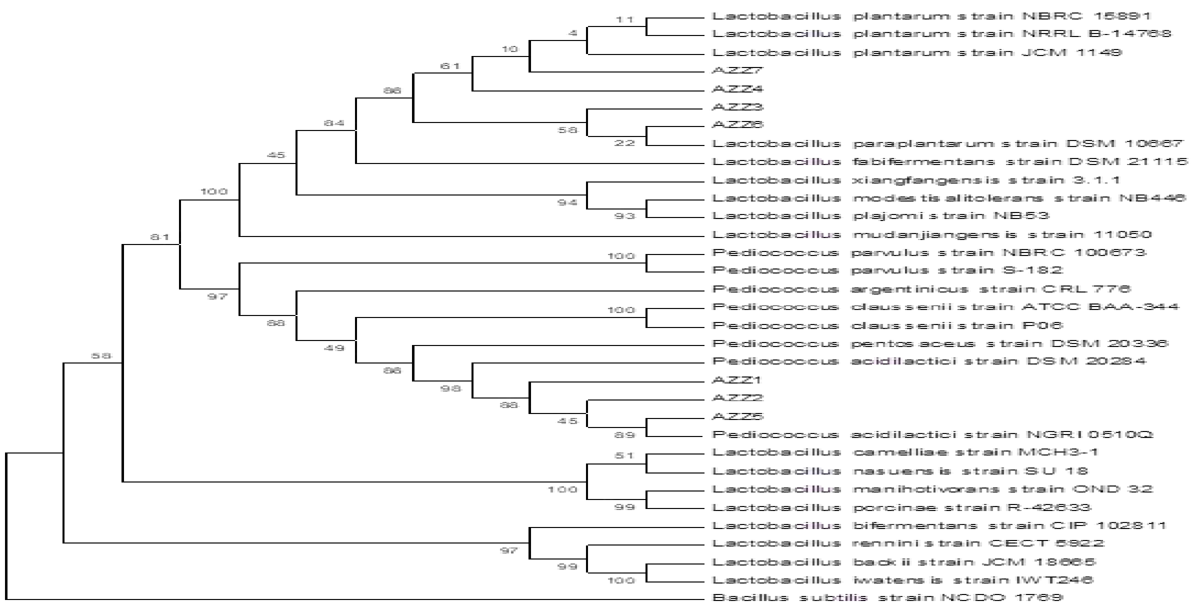

Figure 1 Phylogenetic tree of partial 16S rDNA sequences of isolated strains AZZ1, AZZ2, AZZ3, AZZ4, AZZ5, AZZ6 and AZZ7 isolate from elephant grass silage and sequences of identified bacteria in the nucleotide database of GenBank.

Effect of LAB on organic acids, pH and ammonia nitrogen of sweet sorghum silage

Effect of LAB on organic acids and ammonia nitrogen of sweet sorghum silage is shown in Fig 2. The addition of lactic acid bacteria isolates caused a higher level of LA, resulting in more decrease in pH and ammonia content than the control. The contents of acetic acid (AA) of all silages increased from 30 d to 60 days of ensiling, whereas the AA in the inoculated silages were lower (P<0.05) than the control. Propionic acid and butyric acid contents increased during ensiling and inoculated silage had lower PA and BA content than the control.

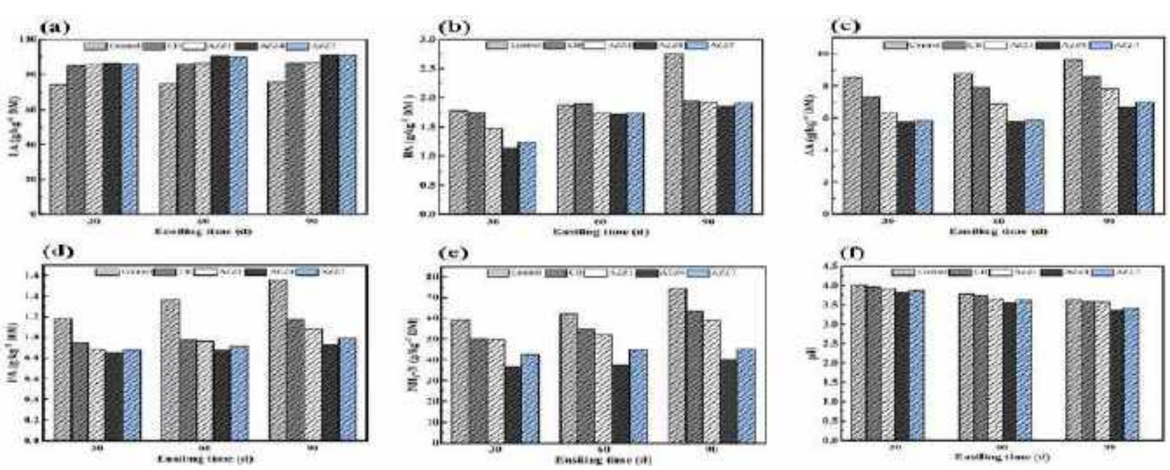

Figure 2. Effect of LAB on organic acids and ammonia nitrogen of sweet sorghum during fermentation period (a) LA: lactic acid, (b) AA: acetic acid, (c) PA: propionic acid, (d) BA: butyric acid. (e)NH_3-N: Ammonia nitrogen CB: Commercial bacteria.

Effect of lactic acid bacteria on microbiological compositions of sweet sorghum silage during ensiling

The effect of isolated strains on the microbiological compositions of the sweet sorghum silage after 30, 60 and 90d of ensiling shown in Figure 3. The population of microbial affected significantly ($P < 0.05$) by LAB addition

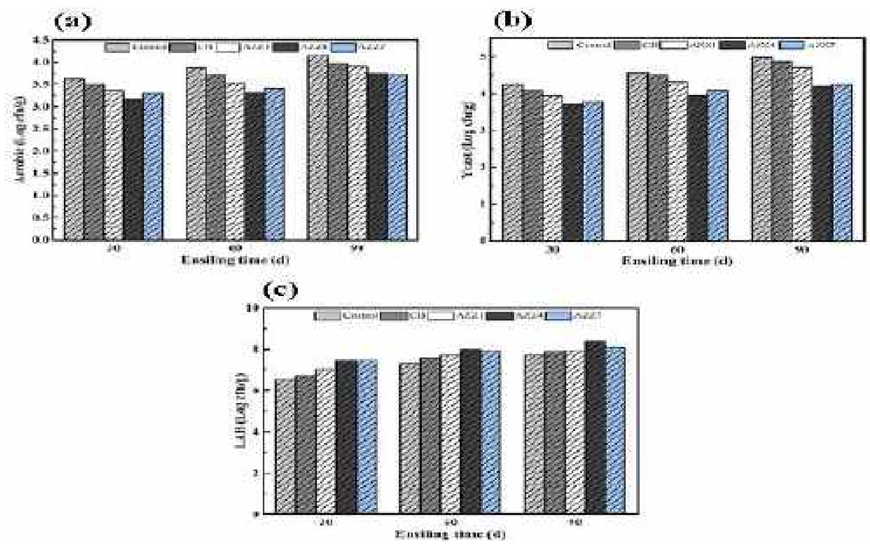

Figure 3. Effect of LAB on microbial composition of sweet sorghum silage during fermentation period, (a) LAB counts, (b) Aerobic bacteria counts, (c) Yeast counts of sweet sorghum silage. CB: Commercial bacteria, AZZ5: *Pediococcus acidilactici*, AZZ4: *Lactobacillus plantarum subsp. Plantarum*

Conclusions

In this experiment, the addition of AZZ1, AZZ4 and AZZ7 as inoculants significantly ($P < 005$) reduced the pH of the sweet sorghum silages and improved silage quality. Inoculants were efficient in improving fermentation quality, reducing NH_3-N as well as dry matter losses of sweet sorghum silage.

Acknowledgements

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Camel herder perceptions towards rangeland utilization at semi-arid areas in the Sudan

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Keywords: Camel Herders, Livestock Production System, Rangeland Utilization.

Abstract

A study was conducted in a semi-arid area in North Darfur State, Sudan, to investigate camel herders' perceptions on rangeland utilization and the main factors affecting pastoralists and pasture. Fifty individuals were interviewed using a structured questionnaire. Herders, who were either nomadic, transhumant, or sedentary, were selected randomly for interviews at home or at markets. Those who declined to cooperate were replaced. Data were analyzed using SPSS, with a T-test estimating differences between means. The results indicated that 86% of respondents were males aged 21-60 years, with 80% not attending secondary school. The study revealed that 46% of interviewees were transhumant, 46% nomads, and 8% sedentary. Sources of income were livestock (84%), agriculture (14%), and trade (2%). Animals raised were camels, sheep, cattle, and goats, using rangeland primarily during the rainy season. Camels were offered sodium chloride in the wet season at 0.45 kg three times a week and sodium bicarbonate in the dry season at 0.23 kg once a week. Sheep received 0.11 kg of sodium chloride twice a week and 0.11 kg of sodium bicarbonate once a week. Cattle were given 0.23 kg of sodium chloride three times a week and 0.23 kg of sodium bicarbonate once a week. Goats were offered 0.11 kg of sodium chloride daily. Some 92% of respondents recognized threats to rangelands namely decreased rainfall (44%), overgrazing (34%) and desert creep, and soil erosion (14%) while 8% perceived no problem. About 90% of respondents blamed nomads for damaging grazing through seasonal fires and early grazing. Shifting cultivation and climate change were also reported. Some 75% of respondents market animals when 1-3 years old increasing pressure on the range. Appropriate management of the range requires reseeding, organizing seasonal movements of pastoralist groups, and enforcing laws.

Introduction

Sudan camel herd is estimated at about 4.9 million. and play an important role in the livelihoods of pastoralists in arid and semi-arid areas of Sudan (Ali et al., 2017). Camels in the Darfur region are commonly raised under nomadic conditions. The annual migrations of nomads vary from year to year to exploit the seasonally abundant forage depending on the amount of rainfall (Abu Sin 1990). Pastoralists have invaluable Indigenous knowledge regarding the environmental changes and vegetation characteristics reflected in how they manage rangeland (Abdalla and Samat 2012). Camel pastoralists in Sudan rely on camels for food, transportation, earning cash, entertainment, and tent manufacturing. Water scarcity in these areas adversely impact camel rearing forcing them to travel for long distances to feed on the sparse desert shrubs. Long-distance walking leads to emaciation, skinniness, and reduced meat and milk production. Camels are classified as browser-grazer species. Arid and semi-arid zones are characterized by limited amounts and scant distribution of trees and shrubs which are shared with other browser animals in the range such as goats and deer (Mansoor et al. 2016). This study investigates the perceptions of pastoralists on rangeland utilization and the main factors affecting pastoralists and pastures in the study area.

Materials and methods

Data collection: A structured questionnaire which contained closed and open-ended questions was developed to enlist the responses of camel herders on their perceptions on range management and vegetation characteristics. fifty questionnaires were distributed to multiple subjects of the study sample in different localities. Because the nomads were mostly lower education level and illiterate, they were directly interviewed and all questionnaires were filled perfectly (recovery rate of 100%). The data were analyzed using (SPSS.20). A t-test was used to estimate the significance of differences between means**.**

Results and discussion

1. Personal characteristics: All herder respondents in this study were males because the management of camels needed protection and care and that entails roaming to far places, so it is a task assumed by male members of a household. The results in Table 1 indicated that 86% of the respondents were in the age range of 21-40 and 41-60 years. Differences in age groups involved in camel rearing are highly significant (P<0.000). Thus, camel rearing absorbs the most active individuals in the community since it is a tedious job. Therefore, men less than 20 or more than 60 years of age are rarely associated with camel rearing. Highly significant differences (P<0.000) in the education level of pastoralists were also found (Table 2). About 60% of interviewees had education at the Khalwa (Religious school) and primary school level, 30% had intermediate and secondary school education, 4% had a university education and 6% were illiterate. with this result in mind, perhaps it is difficult to apply pastoral extension systems because the Awareness level is an important factor concerning extension activities required to promote technologies that can contribute to improving the livelihoods of camel producers.

Table (1) Distribution of respondents according to age groups (Years)

Age group	Number	Percent
Less than 20	5	10
21– 40	23	46
41 – 60	20	40
More than 60	2	4
Total	50	100
DF	---	2.3
Sig	---	***

***Significant at 0.000 level

Table 2: Distribution of respondents according to education level

Education level	Number	Percent
Illiterate	3	6
Khalwa	17	34
Primary	13	26
Intermediate	7	14
Secondary	8	16
University	2	4
Total	50	100
DF	---	3
Sig	---	***

***Significant at 0.000 level

2. Pattern of utilization of pasture

The results indicated that 92% of the respondents belong to transhumant and nomadic systems while only 8% are sedentary. This agrees with (Abu sin, 1990) whose findings show that camels are commonly rose under a nomadic system in the study area (Darfur region). According to interviewees, the range in previous years was better than nowadays due to the better quality of plant species (42%) and an abundance of plant species (34%). In addition to the limited agricultural areas, small numbers of livestock, and insignificant harmful activities such as tree felling were reported by 12%, 8%, and 4% respectively as reasons for poorer range nowadays. Since camel herders almost completely depend on grazing as their main source of livelihood, rangeland quality is an important factor to consider. Tilahun et al. (2016) found that the traditional pastoral systems are environment-friendly compared to interventions to improve rangeland which, in turn, puts the range under severe pressure.

3. Main types of animals raised by pastoralists

A large number of pastoralists keep sheep and camels and only a few also raise goats and cattle as shown in Figure 1. Moreover, all respondents sold some of their animals to obtain money. Animals sold were mostly males between the age of 1-2 years as reported by 54% of respondents. Moreover, only 14% of respondents stated that they sell animals before they are one year old, while 20% sell at the age of 2-3 years and 12% at more than 3 years of age. This is an area for extension to convince pastoralists to sell animals at an earlier age as this reduces pressure on the range and avails markets with more tender meat.

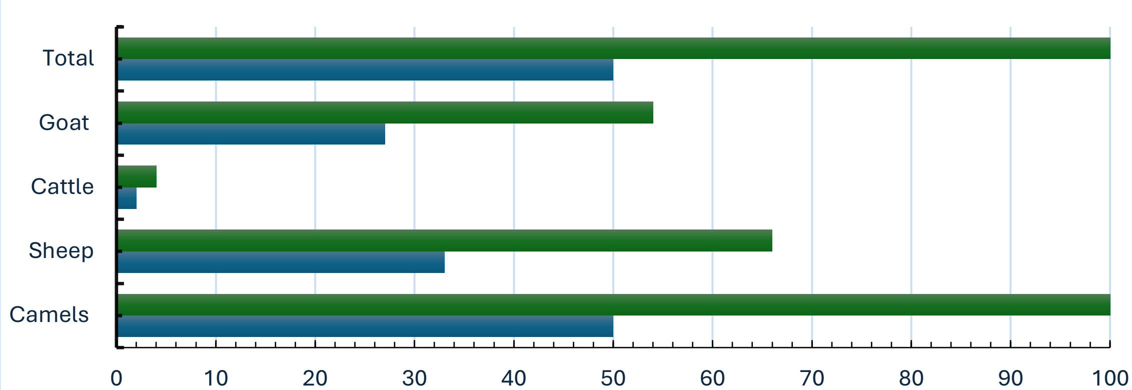

Fig 1.The Main Type of Animal Raising by Respondent in Study area

4. Common problems related to the use of pasture.

According to 92% of the respondents, there was deterioration in the pasture due to various reasons mainly a decrease in rainfall (44%), overgrazing 34% and desert creep and soil erosion (14%). Only 8% of respondents reported that there was no deterioration in the range. These results are in line with several studies that determined the factors causing rangeland deterioration. Amole et al. (2022) reported that the limited availability of forage in terms of quality and quantity in sub-Saharan Africa represented the main factor affecting livestock productivity, often rangeland deterioration is caused by the causes mentioned previously, in a study conducted by (Fenetahun & Yong-dong, 2018) which reported that absence of grazing management, extensive removing the plants for fuel wood, and unclear ownership authority of the rangeland, affect plant abundance, biomass productivity.

Conclusion

Camel herders possess considerable indigenous knowledge of their pastoral systems and they are good range managers. Besides its contribution in rangeland degradation, there are some advantages to the nomadic system such as providing higher quality forage through the seasonal movement and allowing rest periods for the plants to complete their growth cycle. However, the nomadic lifestyle has undesirable effects on pastoralists' education as seen in their education levels.

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The Paddock Challenge: comparing business as usual with recommended stocking rates

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Key words: stocking rate; carrying capacity; rangeland management; research adoption

Abstract

Cattle producers love a challenge. Will getting their stocking rates right provide production stability and allow for land condition improvement on a commercial property in Central Australia? The Paddock Challenge is a component of the Rain Ready Rangelands Project funded by the Australian Government Future Drought Fund, with the philosophy that learning through doing is the key to adoption. It aims to work with commercial producers to adopt, demonstrate and test the learnings from the Quality Graze project under their unique circumstances, and to use data to drive stocking rate and development decisions. Two pastoral stations, 400km southwest and 300km northwest of Alice Springs, Australia (Fig. 1), are collaborating with the Northern Territory Department of Agriculture and Fisheries to test the Quality Graze recommendations and compare their grazing management to a 'Challenge' paddock where a strategy adapted from Quality Graze is being applied. Comparisons and benchmarking are at the whole paddock or water-point scale, depending on station infrastructure. The first year of the challenge involved working with producers to explore their current management, collecting baseline data on pastures, animal performance, landscape use, nutrition, and health. Station data were used to inform bioeconomic modelling of the economic impacts of different stocking and management strategies. The project collaborated with producers to develop strategies aimed at enhancing the rain responsiveness of their landscapes, thereby reducing the impact of climate variability on land condition and animal production and build the climate resilience of their businesses.

Introduction

The north Australian beef cattle industry has historically been slow to adopt new research and tools (Bell and Sangster 2023). With a "learning-by-doing" and "seeing-is-believing" philosophies mind set, and with producers and researchers learning together and from each other, the Paddock Challenge project was developed as a platform for the commercial adoption of the stocking rate management recommendations from the Quality Graze project at Old Man Plains Research Station (OMP) located near Alice Springs, Australia. The Quality Graze project, a long-term grazing trial on OMP, has shown that applying stocking rates based on the long-term carrying capacity (LTCC) led to land condition improvement while producing consistently high animal performance and production stability (Materne *et al.* 2021). Furthermore, improvements in land condition increased the carrying capacity of the station.

Paddock Challenge aimed to help the participating producers develop and adopt alternatives to their existing grazing strategies that would maintain or enhance land condition while improving herd performance and business profitability. It involved exploring factors linking stocking rate, pasture utilisation, individual animal performance, total production, and profitability.

The stations' motivation for involvement was to build business resilience and stability, with the challenges of the recent dry period between 2018 and 2020 still fresh in their minds. While they can't prevent such events, the properties involved aimed to be better equipped to manage them and strengthen their operations.

Methods

The Paddock Challenge involved two properties (Mulga Park and Mt Denison) each providing two paddocks for comparing baseline pasture condition, and production and herd performance against an alternative grazing strategy developed during the project. The "**Business-as-usual**" paddock was unmodified and represented standard station practices; while the "**Challenge**" paddock was stocked based on a recommended strategy using LTCC, informed by GRASP modelling (McKeon et al. 1990), forage budgeting, and seasonal analysis, and adjusted collaboratively by producers and researchers.

Figure 1. Location of the Paddock Challenge stations and Old Man Plains Research Station (OMP)

Pasture and herd performance were monitored using a BACI design (before, after, control, impact) with spatial gradient analyses (distance-to-water as a proxy for stocking intensity). Representative pasture monitoring sites were strategically located along a transect with distance (500m, 1km, 2km, 4km and 6km) from a watering point in each paddock. Quantitative (quadrat based-BOTANAL (Tothill et al. 1992) and drone footage) and subjective (visual point-based assessment/photo point) data was gathered from each site on pasture yield and species composition, ground cover, grass basal area, defoliation, cattle activity and biocrust samples. Paddock pasture growth and utilisation were modelled following Cowley and Walsh (2023). Animal equivalents (AE) were calculated from paddock stock records and animal performance where possible (McLean and Blakeley 2014, McLennan et al. 2020). Watered area was determined using site infrastructure data, including natural and semi-permanent sources.

Pasture utilisation was modelled assuming cattle spent all their time within a 4 km radius of waters to identify potential stocking rate effects on herd performance and grazing distribution. Diet quality was assessed monthly via NIRS analysis of dung samples. Animal health monitoring focused on five common production diseases to identify discrepancies in performance. Cattle landscape use was tracked with Global Navigation Satellite System (GNSS) collars.

Baseline pasture data informed the pasture modelling for LTCC estimates while baseline individual animal performance data identified non-performing animals to inform the culling program to improve herd efficiency and match stock numbers to the LTCC.

Economic analysis, following the methodology of Holmes et al. (2017), assessed each property production system. Baseline data and animal performance were reviewed, and tailored scenarios were explored with station owners. Comparisons included results from the Quality Graze trials at OMP. Economic modelling and the stations' baseline data were used to model the financial impact of adopting change, and to provide options to navigate the transition to the new grazing system. The central modelling question was: Can we get more (land condition improvement, animal performance, kilograms of beef, profit) from less (fewer cattle)?

Results

Both stations have highlighted the value of data collection and benchmarking of their herds and business performance. Data collection enabled a snapshot of where their business currently stands and the gaps in which they can invest their efforts for the greatest return. The importance of robust, high-quality data cannot be overstated. Reliable data are the foundation for building accurate models, generating meaningful insights, and delivering outcomes that truly reflect the complexities of the systems we study.

Mulga Park plans to collect and collate additional past and present data, making it easily accessible through farm management software, to support management decisions. These include planning and matching stocking rates to LTCC to prepare for inevitable dry periods, implementing a structured weaner and heifer management program, developing targeted work plans to create a more efficient herd, and investigating strategies for managing water points with high fluoride levels.

Mt Denison is interested in adapting their stock numbers to improve herd performance and develop resilience to climate variability. They anticipate building a more efficient herd through genetics allowed by infrastructure developments, identifying indicator grass species for land condition, and continuing with some components of the project data collection such as weights and pregnancy testing.

Discussion

The Paddock Challenge project aimed to collect a variety of on-station data to identify the effect of stocking rate on land condition and herd performance, and ultimately better understand the logistic and economic complexity of adopting science based grazing land management recommendations.

Economic modelling provided the producers with a pathway to adopt new management and the benefits forward and highlighted the long-term production and financial benefits of matching stocking rates to LTCC.

Figure 2. "Paddock Walk" with producer group

Figure 3. Development of a 10-year plan

Establishing trust through long-term engagement is crucial when working with pastoralists. By presenting them with ideas and tangible results they can observe and relate to, we fostered an environment where new concepts were more readily understood and adopted. Two-way communication facilitated knowledge transfer between producers and researchers and was critical in the development of the strategy trialled in the Challenge paddock and developing plans for the next decade (Fig. 3). This subsequently encourages the uptake of recommended changes.

Continual re-enforcement of animal nutritional needs and its relation to pasture utilisation and the safe LTCC through the participants attending various courses and events helped them to gain an understanding of the science behind the 'Paddock Challenge'. This knowledge along with the baseline data collection highlighted the importance of good land condition and how the utilisation rate of these pastures through stocking rate management can improve herd performance and business stability and profitability in an extremely variable climate.

Results were extended to the wider industry through "Paddock Walks" (Fig. 2) that provide a group learning platform that was made up of personally invited neighbouring producers. Although one-on-one extension activities are resource-demanding, the findings from the Paddock Challenge are transferable to the wider industry. The benefits to the industry include an improved understanding of LTCC and safe utilisation rates of various land types, potential animal performance and landscape use, as well as enhanced and tested carrying capacity methodology. There is also a better understanding of the link between utilisation and animal performance. Additionally, the findings provide insights into other factors that affect individual animal performance, such as water quality, production diseases, and seasonal dietary needs that require supplementation.

Conclusion

Sustainable stocking rate is not necessarily about reducing total production, but about reducing the number of animals to get the same or more production from fewer animals. Economic modelling reinforced this concept and helped allay pastoralists' concerns that reducing animal numbers would reduce profit. Establishing trust through long-term engagement is crucial when working with pastoralists. By presenting them with ideas and tangible results they can observe and relate to, we foster an environment where new concepts are more readily understood and adopted.

Change is not easy, nor the ability to implement infrastructure change, particularly with the perceived business risks and worries about reduced herd production from reduced stock numbers. The difficulty in implementing and adopting science-based recommendations on a commercial property proved challenging and faced significant unforeseen challenges such as extensive wildfires that required flexibility. However, the Paddock Challenge project highlighted the advantages of 'learning-by-doing', which will ultimately lead to adoption. Change in station management and the adoption of a new grazing strategy requires a holistic approach that encompasses the entire station's LTCC, infrastructure, production system and business circumstances.

Acknowledgements

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Cattle performance does not differ between patch and broadcast burning

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Key words: Prescribed fire; grazing; animal performance; long-term study

Abstract

Over the past few decades, patch burning has become a recommended practice in the Southern Plains of the USA rather than burning an entire pasture at one time. Patch burn plans follow a burn sequence where several patches with different times-since-last-burn occur within the pastures, whereas for the broadcast burn plans entire pastures are burned at one time every several years so that each year the time-since-last burned is uniform across the pastures. The objective of our study was to determine whether animal performance, per hectare or per head, differed between the two treatments. In our long-term experiment, in three replicate blocks, the blocks were divided into two pastures that were randomly assigned the patch-burn treatment, where ¼ of the pasture was burned in a 4-yr rotation, or the broadcast burn treatment, where the entire pasture was burned every 4 years. The pastures were grazed each year with weaned growing cattle (BW = 242±16 kg) to harvest a targeted 25% of the expected annual forage production over an approximately 180 d period (45% of the use was in the dormant, DS, and 55% of the use was in the growing season, GS). Cattle received a range cube protein supplement during the dormant season. The annual gains per hectare were 60.0 kg/ha for both the broadcast and patch burn treatments. The effect of grazing season on gain per hectare and average daily gain was significant with GS gain of 49.4 kg/ha and DS gain of 10.6 kg/ha. Average daily gains were more than three times greater in the GS (0.78 kg/d) than in the DS (0.21 kg/d). These data show that whatever benefits exist for patch burning over broadcast burning, animal performance cannot be counted among them, nor can animal performance be used to justify one over the other.

Introduction

Fire is an important part of the disturbance regime in the Great Plains of North America that helped to maintain the grassland and to suppress woody plant encroachment (Anderson et al. 1970; Limb et al. 2011; Wright and Bailey 1982). Patch burning has been proposed as conservation-based management that gets fire back on the landscape (Limb et al. 2011). One feature of patch burning is that the most recently burned patch is more highly selected than other patches with longer times-since-last-burn and utilization rates are greater in the newest burn patch than others (Scasta et al. 2015). When the pasture is moderately stocked, but the most recently burned patch can only supply a fraction of the grazing animals forage demand, then utilization of the recently burned patch is uniformly heavy and use is light in other areas. In years when production is limited, the use can increase in otherwise lightly used patches and these patches serve as a forage buffer. In subsequent years, standing dead material accumulates within the pasture and forage quality declines. If patch burning is stopped for a period of years, grazing may need to be adjusted to allow the most recently burned patch to recover from heavy use within the growing season as occurs when a new patch is burned. The continual rotation of burned patches within a pasture increases the uniformity of use on the cycle time scale, but increases heterogeneity on the annual time scale. In broadcast burn pastures that are moderately stocked, the forage is all high quality, but grazing use is only moderate and soon plants that don't get grazed early in the grazing period will become less desirable and animals may begin repeat grazing some plants and avoiding other plants or even grazing sites. The uniformity of grazing use in these broadcast burn pastures, on time scales from grazing season to fire return interval, is less than for the recently burned patches. The annual provisioning of high-quality forage that occurs in the patch burn pastures each year could contribute to better animal performance. The objective of this study was to determine whether animal performance, in terms of average daily gain or gain per hectare, differs between patch and broadcast burn treatments.

Methods

The site of this long-term burning and grazing study was the Southern Plains Range Research Station in Woodward, Oklahoma, USA. The site is located near the boundary between the Cfa Koppen-Geiger climatic zone (temperate, without a dry season, and hot summers) and Bsk zone (arid, steppe, and cold; Peel et al., 2007). The experiment was set up as a randomized complete block design with 3 blocks of two pastures. The pastures ranged in size from 6.1 to 16.1 ha. Within each block, pastures were randomly assigned to one of the two burn treatments, broadcast burning or patch burning. The broadcast burn treatment involved burning the entire pasture every 4th year and the patch burn treatment involved dividing the pasture into 4 patches and burning 1 patch each year in a 4-yr rotation. For both treatments, the prescribed burns were conducted in late winter or early spring. The pastures were grazed with growing steers for a period of 83 to 97 d in the growing season (mid April to mid July) and another 83 to 91 d in the dormant season (late November to late February). Cattle were received 45 to 35 d prior to the beginning each grazing period and weighed. The cattle were stratified by receiving weight and each strata was proportionately represented in each experimental unit. The target initial weight for the growing season steers was 227 kg and for the dormant season steers it was 249 kg. Stocking rates were adjusted based on the expected annual forage production and pasture size to achieve a target forage harvest for the year of 25% with 55% of the target harvested in the growing season and the remaining 45% harvested in the dormant season. Cattle received a protein supplement during the dormant season grazing 3 days each week to meet their protein requirement.

Forage production each year was estimated by clipping quadrats in the fall from inside exclosures that had been established the winter before. In each patch of the patch-burn pastures and quarter of the broadcast-burn pastures, 8 exclosures (~ 1m in diameter) were established and the standing dead material was removed by cutting with a string trimmer to approximately 3-cm stubble height unless the patch or pasture was burned. In the fall when the plants were mostly senesced a quadrat (0.5 m^2 square) was centred in the exclosure, clipped to a 3-cm stubble height, the standing crop was placed in labelled paper bags, and taken to the laboratory to be dried in an oven and weighed.

Results

The effect of grazing season on average daily gain (ADG) interacted with forage year ($p < 0.001$). The advantage in ADG cattle had during the growing season ranged between 0.379 kg/d more (2018) and 0.831 kg/d more (2023). Averaging across forage years, the ADG for steers was more than three times greater during the growing season (0.78 kg/d, SE = 0.020 kg/d) than during the dormant season (0.21 kg/d, SE = 0.020 kg/d, $p < 0.001$). Burn treatment had no significant effect on ADG ($p = 0.5325$) irrespective of the grazing season, forage year, or both (p = 0.7679, 0.6222, or 0.5684, respectively, Fig. 1).

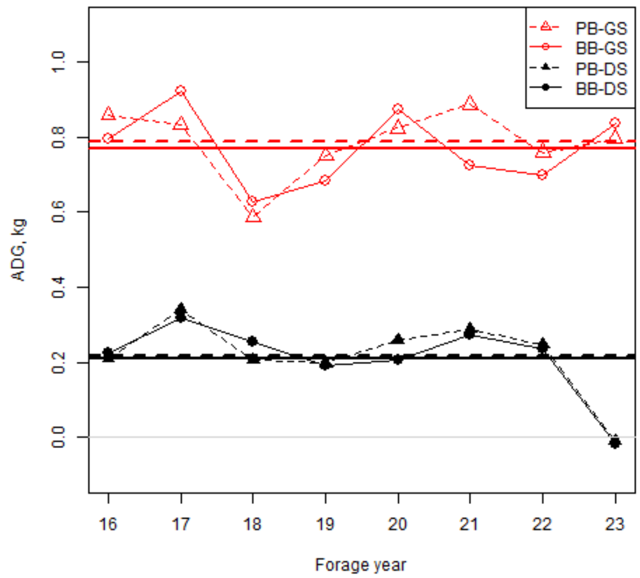

Fig. 1. Average daily gain of steers in each forage year, grazing season, and burn treatment.

Converting individual animal performance to performance per unit area for each grazing season and treatment, the significant grazing season effect on ADG translated to a significant grazing season effect on gain ($p < 0.001$) with an average growing season gain of 49.4 kg/ha (SE = 1.69 kg/ha) and dormant season gains of 10.6 kg/ha (SE = 1.69 kg/ha), irrespective of burn treatment (the p value for the season by treatment interaction was 0.8511). There was also no significant main effect of burn treatment on gain ($p = 0.9872$). Combining the two grazing season gains in each forage year and treating forage year as a fixed effect, the effect of forage year on annual gains was significant ($p < 0.001$, Fig. 2), but annual gains were not different between burn treatments ($p = 0.9853$) and burn treatment didn't interact with the effect of forage year ($p = 0.8646$). Annual gains in forage years 2017 and 2020 were each greater than in forage years 2018 and 2023 and no other forage year differences were significant. Treating forage year as a random effect, annual gains were not significantly different between the broadcast and patch burn treatments ($p = 0.9802$) and both averaged 60.0 kg/ha (SE = 2.74 kg/ha).

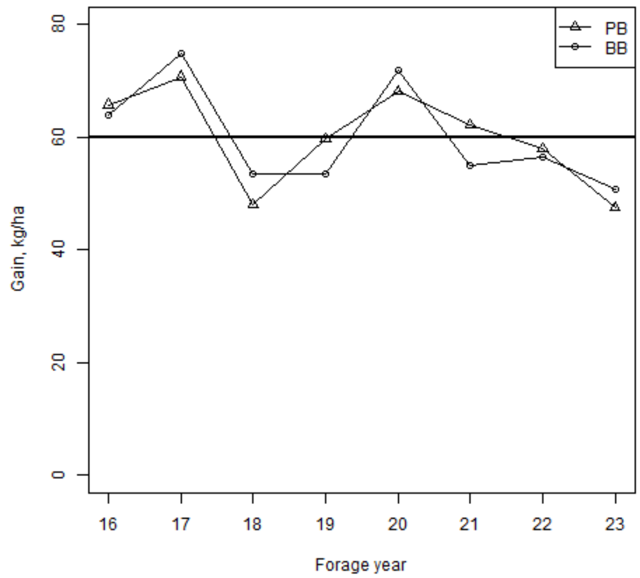

Fig. 2. Animal body weight gain (kg per hectare) for steers grazing each forage year in patch burn and broadcast burn treatments.

Conclusions

These data show that whatever benefits exist for patch burning over broadcast burning, animal performance cannot be counted among them, nor can animal performance be used to justify one over the other. Animal performance in this study varied by forage year and the season when grazing occurred, but the burn treatment was never significant and it never interacted with the other effects.

Acknowledgements

The use of animals in this experiment was reviewed by the Oklahoma and Central Plains Agricultural Research Center's Animal Care and Use Committee at Woodward and approved (AUP-002, AUP-016, and AUP-025).

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Addressing the feed deficit of the semi-arid Taita Taveta County of Kenya

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Key words: Animal source food; feed strategy; feed value chains

Abstract

Livestock production is a key economic sector in Taita Taveta County, and accounts for over 40% of agricultural earnings. The demand for animal source foods is on the rise due to increasing human population and the expanding middle class. The main livestock types kept include cattle, goats, sheep, camels, donkeys and poultry. The main feeds include roughages but climate change has adversely affected pasture and fodder production in cultivated and natural vegetation systems. According to a national feed inventory and feed balance assessment conducted in 2019, the County had a feed deficit of 23% based on livestock dry matter (DM) requirements. The deficit was further exacerbated to about 60% by a prolonged drought experienced in 2022. To promote growth of the county feed industry, a 10-year Animal Feed Strategy was developed. The strategy aimed at bridging the feed gap, and enhancing livestock numbers and livestock products by addressing challenges in the feed industry. The strategy also sought to ensure rangeland resources were managed sustainably as well as guided decisions in land use planning and investments. To meet the feed requirements by the tenth year of the strategy, USD $282.2 million was to be spent to produce 5.74 billion metric tonnes of DM feeds. The industry was to realize an annual net income of USD $133 million and create 6,000 jobs.

Introduction

The potential for livestock production in Taita Taveta County was high due to expansive rangelands covering 24% or approximately 4,100 km^2. Ranching was a major production system for beef cattle rearing. Red meat production was mainly from ruminant livestock reared under an extensive farming system while dairy cattle were reared in the hilly areas under small-holder farming systems. The estimated livestock population for 2022 and projected growth up to 2032 is shown in Table 1.

Table 1: County Livestock Statistics 2022 and Projected Growth up to 2032

Livestock		Year		
		2022	2027	2032
Dairy		32,587	34,761	37,080
Beef		149,905	191,321	244,179
Sheep		63,994	112,779	198,756
Meat goat		346,358	638,142	1,175,736
Dairy goat		6,070	6,768	7,546
Pigs		2,259	3,168	4,443
Rabbits		14,870	20,661	28,709
Chicken	Broilers	45,207	90,927	182,888
	Layers	94,643	190,361	382,884
	Indigenous chicken	647,080	1,301,509	2,617,799
Donkeys		3,704	4,010	4,341
Camels		1,319	1,428	1,546

Source; Taita Taveta County Animal Feed Strategy, 2022 – 2032 (2023)

A County animal feed inventory and feed balance analysis in 2019 indicated an overall dry matter feed deficit of 23% and crude protein and metabolisable energy deficits of 42.9% and 50.6%, respectively. To address this deficit, the County developed a 10-year animal feed strategy (AFS) for the period 2022 to 2032.

Strategy development methodology
A County Livestock Technical Working Group (TWG) was formed mainly comprising of animal production and animal health technical personnel. The group was trained through a series of facilitated workshops by a team from Kenya's State Department of Livestock (SDL) in the process of developing the strategy, including data collection and writing. The SDL had formulated a standard framework for developing animal feed strategies. The data included, human population trends, per capita consumption of animal source foods, livestock types, feed requirements, potential feed resources, cost-benefit analysis of producing feeds and potential feed business cases / investment plans in the county.

Estimating demand for animal source foods based on County per capita consumption
The county's human population in 2022 was 360,000 and its projected growth for the strategy period was 385,800 by 2027 and 407,280 by 2032 (Kenya National Bureau of Statistics census, 2019). This growth was expected to increase demand for animal source foods based on the county annual per capita consumption (Table 2). The per capita consumption were based on the following estimates of annual consumption: milk 220L, beef 9 kg, mutton 2.4 kg, chevon 2 kg, chicken 12 kg, pork 0.8 kg and 180 eggs.

Table 2: Total estimated demand and supply of animal source foods in the County

Year	Milk (Million Litres)		Meat (Million Kg)		Eggs (Millions)	
	Estimated demand	Estimated supply	Estimated demand	Estimated supply	Estimated demand	Estimated supply
2022	79.2	21.5	9.4	0.99	64.8	61.3
2027	84.8	43.1	10.1	14.5	69.4	115.7
2032	89.6	86.4	10.6	16.5	73.3	122.2

To supply the required animal source foods (Table 2), the county livestock was to be fed with sufficient feed resources to meet their nutrients requirements. These feeds were to be grown in the county by entrepreneurs developing agribusinesses. The County government was to provide an enabling policy environment.

Animal Feed Resources
Priority feed resources/value chains for the county were identified in addition to the natural pastures that supplied the bulk of livestock feed (Table 3). They were selected based on their adaptability to the local conditions and potential to increase their yield.

Table 3: Production Estimates of Animal Feed Resources in 2020 and Projected Demand by 2032

Feed Resources	2020	2027	2032
	Metric tonnes	Metric tonnes	Metric tonnes
Energy Sources			
Hay	66,285	301,385	459,916.1
Fodder grasses	19,885	52,479	80,641
Maize grain	16,609	113,434	203,671
Sorghum	567.6	1,723.5	3,449.3
Protein sources			
Sunflower seed cake*	15,427.9	36,669.9	55,919.8
Legume fodder	9,279.90	10,495.8	14,233.6
Sweet potato vines	2,651.4	7,871.8	13,720.3
Groundnuts	456.0	1,332.4	2,629.4
Animal protein Sources			
Black Soldier Fly Larvae	190.7	516.2	804.4
Natural grazing			
Field-based feed resources**	1,915,839	2,841,696	4,622,221
Total	2,047,191.5	3,367,603.6	5,457,205.9

* 95% of the sunflower seed cake was imported from outside the county.

**Acreage for field-based feed was to remain constant over the period but productivity per unit was expected to increase as a result of improved management.

Source: Taita Taveta County Animal Feed Strategy, 2022 – 2032, 2023.

Investments Plans
These plans were based on the cost-benefit analysis of developing the feed value chains to meet county demands as shown in Table 4.

Implementation of the Strategy
Implementation of the strategy was to cost approximately US$282.44 million over a period of 10 years. A detailed implementation framework with clear stakeholder roles and responsibilities and a monitoring and evaluation framework, at all levels of implementation, was developed. The County Department of Agriculture, Livestock, Fisheries, and Irrigation was to lead the implementation in collaboration with other relevant agencies and stakeholders. Upon the full implementation of the strategy, the feed value chains were expected to generate a net income of US$133 million and create 6,165 salaried jobs.

Table 4: Feed Commodity Cost-Benefit Analysis and Value Proposition to Investors

Value chains	Input Analysis		Output Analysis		Job creation[1]
	Hectares	Metric Tonnes	Total cost (Million US$)	Annual Net Income (Million US$)	
Energy Sources					
Hay	137,836.7	459,916.1	85.38	17.08	793
Maize Grain	38,781.4	203,671	29.46	5.89	274
Forage Grasses	4,869.6	80,641	9.32	1.86	87
Sorghum Grain	2,791.9	3,449	2.14	0.43	20
Protein Sources					
Sunflower Seed Cake	8,0821.3	199,714	74.90	82.39	3,825
Legume Fodder	1,367.8	6,490	1.33	2.35	109
Sweet Potato Vines	5,552.3	164,640	12.76	2.55	118
Groundnuts	1,418.4	1,647	1.08	0.22	10
Animal Protein					
Black Soldier Fly Larvae	1.8	135	0.06	0.22	10
Natural Grazing					
Field-based feed resources	599,689.5	4,622,221	66.01	19.80	919
Total	**873,130.6**	**5,742,524.1**	**282.44**	**132.79**	**6,165**

[1]It was assumed 30% of net income was used for job creation at an annual salary of US$6,462 per job created.

Acknowledgments

The Food and Agriculture Organization of the United Nations (FAO), Kenya, and SNV Netherlands Development Organization provided financial and technical support for the development of the strategy. The County Livestock technical working Group (TWG) worked diligently and owned the process of developing the feed strategy. Special thanks go to the team from the State Department of Livestock, led by Dr. Stanley Mutua, the Head of Animal Resources Division, for successfully facilitating the processes of developing the feed strategy.

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Department of Agriculture, Livestock, Fisheries and Irrigation

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Remote sensing and machine learning for monitoring carbon stocks to support sustainable grazing management

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Key words: Soil organic carbon; pasture biomass; remote sensing; machine learning; greenhouse gas

Abstract
Grasslands offer a sustainable and cost-effective resource for livestock feed while supporting carbon sequestration, thereby mitigating climate change. However, current remote sensing methods for grassland monitoring have not adequately addressed adaptive grazing management at the fine scales required for intensive grazing systems. Grazing trials conducted under La Niña conditions, with recovery periods of 3, 6, 9, 12, and 15 months, aimed to advance regenerative grazing techniques in small plots (<1 hectare). Sentinel-2 imagery combined with random forest outperformed XGBoost in estimating biomass, achieving better regression statistics ($R^2 = 0.56$, RMSE = 1,532 kg DM/ha vs. $R^2 = 0.48$, RMSE = 1,726 kg DM/ha). The model effectively captured carbon stock variability across recovery periods, with the 3-month recovery exceeding 2,000 kg C/ha. This proof-of-concept study underscores the potential of high-resolution remote sensing to enhance precision agricultural management and promote climate-resilient farming practices

Introduction
Pasture biomass, a major natural carbon sink, plays a critical role in global carbon sequestration and mitigating greenhouse gas emissions (GHG) to meet Paris Agreement targets (Harrison et al., 2016). While remote sensing and machine learning have advanced sustainable grazing management, most studies focus on regional scales, limiting their applicability at field scales (Ali et al., 2016; Ogungbuyi et al., 2023a). Regenerative grazing practices, such as short, intensive grazing periods and multi-paddock systems, promote soil health by enhancing microbial activity and organic matter incorporation (Ogungbuyi et al., 2023b). However, field biomass measurement and soil organic carbon (SOC) assessment remain capital-intensive and labourious (Mondal et al., 2017).

This study is proposing Sentinel-2 imagery, with its high spatiotemporal resolution, and machine learning to estimate carbon stocks at the field scale. Destructive sampling, combined with carbon conversion factors and root-to-shoot ratios recommended by the IPCC, provides a direct means to quantify carbon stocks (Cienciala et al., 2006; Penman et al., 2003). Previous studies show that machine learning models, such as random forest and XGBoost, effectively handle smaller datasets and manage model complexity, enabling accurate biomass estimates (Morais et al., 2021). The main objective of study is to assess pasture biomass and carbon stock variability across paddock treatments under regenerative grazing systems.

Methods
The study was conducted in Triabunna, southeastern Tasmania (S 42° 30, E 147° 59), with annual rainfall of 648 mm and temperatures ranging from 7°C to 17°C. Fertile soils and a mix of sown and native pastures support intensive rotational grazing, aided by reliable winter rainfall.

Six 0.25-ha plots—Vault 1 (V1), Vault 2 (V2), Vault 3 (V3), Vault 4 (V4), Vault 5 (V5)—and a 10-ha Vault Control (VC) plot were stocked at a rate of 2000 DSE/ha for one day. This corresponds to a stocking density of 8000 DSE/ha for the 0.25-ha plots (see Ogungbuyi et al., 2024 for details). The treatment plots were subjected to high stocking density with varying spelling and recovery periods, except for the Vault Control, which had no specific recovery period. The recovery periods were as follows: 12 months (V1), 9 months (V2), 6 months (V3), 3 months (V4), and 15 months (V5).

Aboveground biomass was destructively sampled from December 2021 to November 2022 using a battery-operated shearing handpiece in 50 x 50 m quadrats, with the average of five readings computed per paddock to minimise sampling error. Cloud-free Sentinel-2 Level 2 surface reflectance images (n=56) were downloaded from Digital Earth Australia for dates matching the biomass sampling period. Ten spectral bands (b2–b8A, b11, b12) were used to extract reflectance values after removing cloudy pixels with a detection algorithm.

A random forest model was trained using the ten spectral bands and 56 biomass samples, split into 75% training and 25% test sets. To prevent overfitting, model parameters included 50 trees, limited tree depth, and default maximum features per split. Training accuracy was assessed using out-of-bag (OOB) error estimates, and performance was evaluated with R^2, RMSE, and MAE. Similarly, an XGBoost model was trained with the same dataset and features. Hyperparameters included a learning rate of 0.05, maximum tree depth of 4, and subsample/column sampling rates of 0.8, with boosting rounds optimized using early stopping. Model performance was evaluated with R^2, RMSE, and MAE.

Aboveground carbon (AGC) and belowground carbon (BGC) were derived from field biomass and Sentinel-2 random forest (S2-RF) estimates using Equations (1) and (2):

$$Carbon = Biomass \times Carbon\ conversion\ factor \quad (1)$$

$$BGB = AGB \times root - to - shoot\ ratio \quad (2)$$

We used a carbon conversion factor of 0.47 and a root-to-shoot ratio of 0.3. Total carbon stock was calculated using Equation (3)

$$Carbon\ stock = AGC + BGC \quad (3)$$

Seasonal carbon stock variability for treatment plots was analysed using standard error of the mean. Due to the lack of SOC field data for validation, we examined NDMI, derived from Sentinel-2 as Equation (4)

$$NDMI = \frac{NIR - SWIR}{NIR + SWIR} \quad (4)$$

Results
Modelling pasture biomass with XGBoost and random forest
The random forest model outperformed the XGBoost model with better regression statistics (R^2 = 0.56, RMSE = 1,532 kg DM/ha, and MAE = 2,021 kg DM/ha) compared to XGBoost (R^2 = 0.48, RMSE = 1,726 kg DM/ha, and MAE = 2,188 kg DM/ha), demonstrating its suitability for handling complex environmental datasets, such as high biomass volumes resulting from seasonal accumulation (Figure 1).

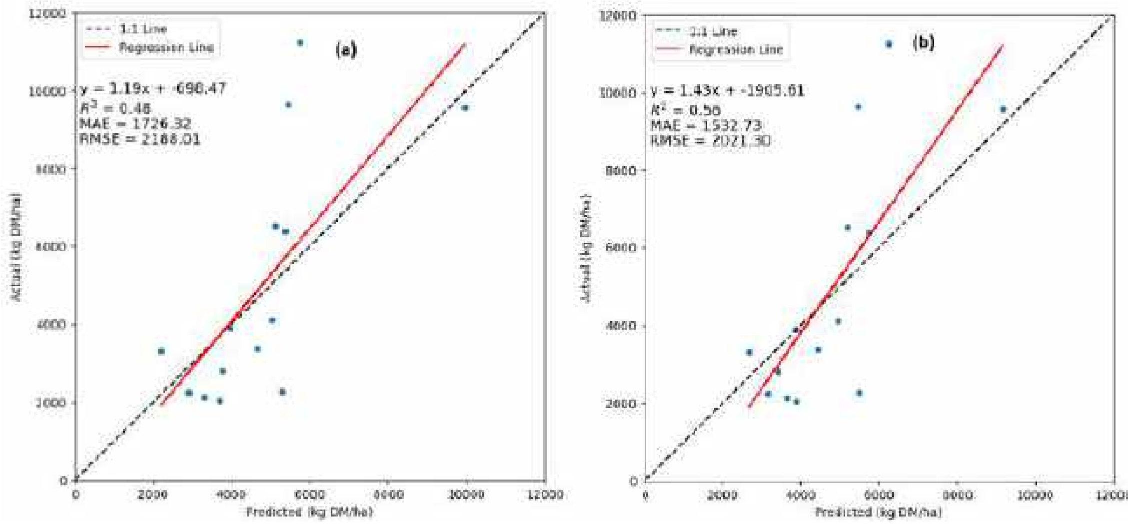

Figure 1. Comparison of Sentinel-2 estimated biomass using (a) the XGBoost model and (b) the random forest model against the actual biomass.

Carbon stock variability in the Vault Plots

The Vault plots exhibited seasonal variability in carbon stock, with Vault 4 (the three-month spelling plot) showing strong alignment between field-measured and Sentinel-2-derived carbon estimates, particularly exceeding 2,000 kg C/ha in seasonal trends (Figure 2). Additionally, the Vault 4 plot recorded the highest soil moisture index (Figure 3).

Discussion

This study highlights the capability of Sentinel-2 imagery combined with a random forest model to accurately estimate pasture biomass at the field scale, even with a limited dataset. Unlike earlier studies, this approach effectively handles high biomass volumes accumulated seasonally without saturation (Ali et al., 2016; Ogungbuyi et al., 2023a), leveraging ten spectral bands to account for environmental conditions. The random forest model outperformed XGBoost, demonstrating superior adaptability to complex data.

Vault 4, with its three-month spelling and recovery period, exhibited the highest carbon stock, benefiting from La Niña-induced rainfall and improved productivity. This aligns with prior research (Ogungbuyi et al., 2024), which found that short-term spelling under intense grazing enhances litter formation and carbon sequestration through trampling effects. Additionally, the Sentinel-2-derived soil moisture index validated this result, showing Vault 4's highest soil moisture concentration (Figure 3).

The use of a carbon conversion factor consistent with Tasmanian soil properties (50% SOC as noted by (Brady et al., 2008; Cotching, 2018) strengthens the study's methodology. This innovative approach provides a proof of concept for deriving carbon stock in the absence of direct soil sampling, offering a valuable tool for future research.

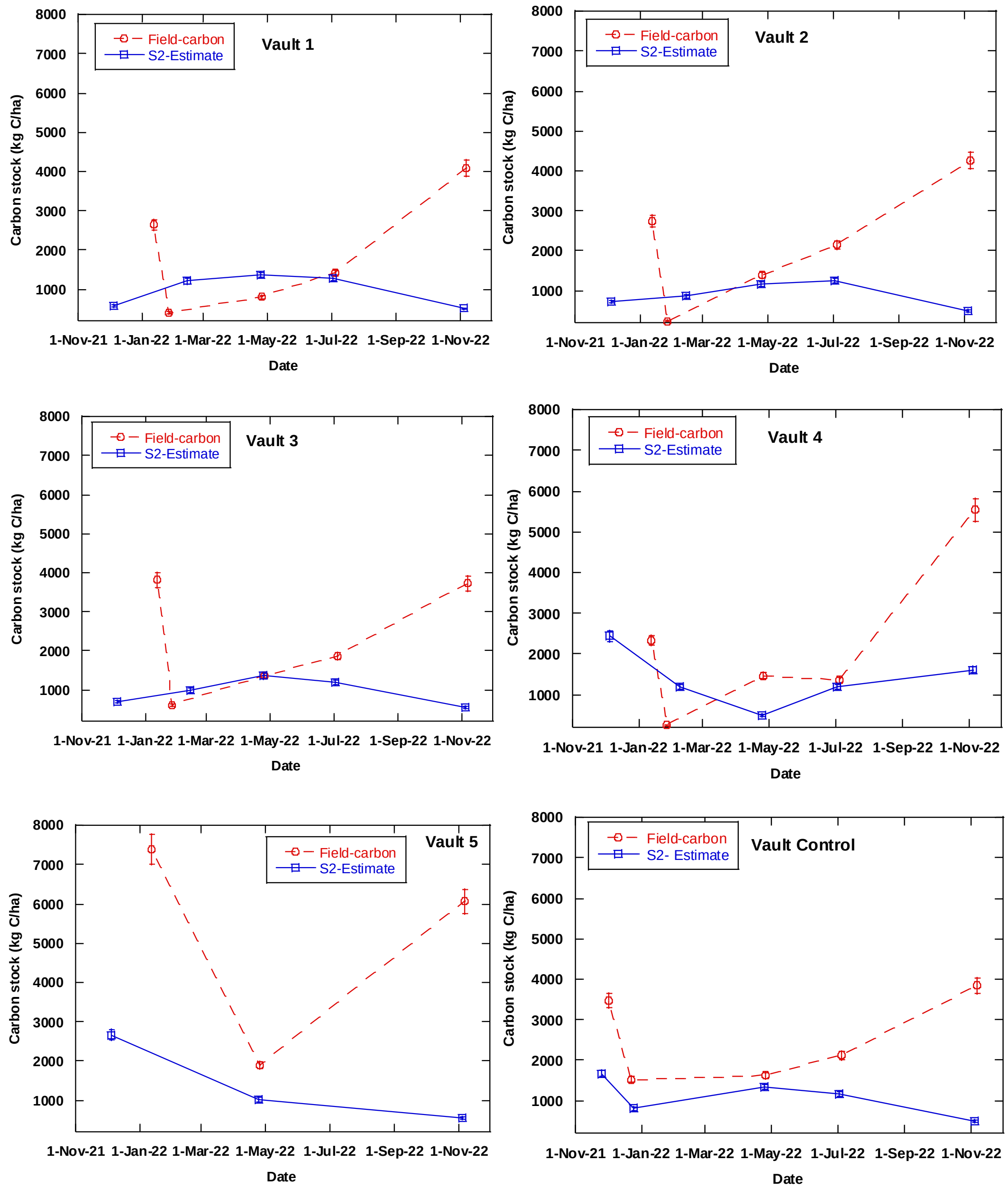

Figure 2. Seasonal variability of carbon stock in the Vault Plots.

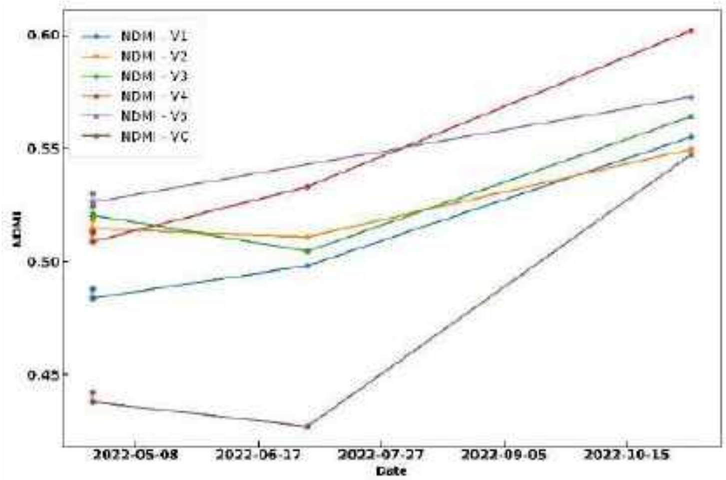

Figure 3. Seasonal soil moisture index derived from Sentinel-2 data.

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Herder-cattle-rangeland interactions: shaping grazing behaviour in the mountainous rangelands of Kunene, Namibia

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Key words: Dry season pasture, drought periods, Himba, human-animal-environment interactions, pastoral livestock production

Abstract

Livestock grazing behaviours play an important role on the health of animals and the rangelands, significantly impacting livestock production and human livelihoods. Grazing success relies on the intricate interactions between people, animals, and their rangelands. This relationship is particularly vital for pastoral communities, which often face challenges in developing environmental infrastructure. On the mountainous rangelands of Kunene in Namibia, dry seasons and drought reserves pasture areas are difficult to access. Small pockets of resources can provide essential fodder, and the ability to navigate mountainous terrain becomes vital, as pasture is often found at higher elevations. Up to now, our knowledge of the human-animal-environment relationships that shape such grazing practices is still limited. To address this gap, this study aims to investigating factors that influence cattle behaviour associated with mountain grazing. Data on cattle keeping and grazing practices were gathered with Himba pastoralists through semi-structured and narrative interviews. The findings indicate that Himba pastoralists are well aware of features of their cattle that are essential for mountain grazing. They do not only select specific traits in their cattle but also teach them new behaviours, such as foraging behaviour or navigation skills. The climbing performance of the individual animal is shaped by factors like breed, body condition, familiarity with the area, and mountain climbing experiences. Herders employ different techniques to train and assist cattle to climb, including establishing paths by removing rocks that may have caused fear due to past injuries or placing cattle dung along a track to guide the animals uphill. Himba pastoralists skilfully utilize the individual variability among their livestock, enabling cattle to learn from one another while actively shaping their grazing patterns through the instruction of new behaviours. The results specify the interrelationships between humans, animals, and environments and explain in detail how they contribute to an effective utilization of rangeland resources. The skills and knowledge of the herders, along with the skills of their cattle, enable the use of hardly accessible pasture resources, essential for the sustainability of pastoral systems in the mountainous regions of northern Kunene.

Introduction

The northern part of Kunene region is predominantly inhabited by Himba pastoralists who utilize common rangeland resources. During the critical periods, forage vegetation can still be found on rocky mountainous areas, distant from water sources (Bollig 1997). To ensure that cattle access these pastures herders adopt different practices. This human-animal-environment interaction is critical for rangelands characterized by high spatial and temporal variability in rainfall leading to high variability in the distribution of water and fodder resources (African

Union 2010). To optimize livestock grazing, herders utilize their empirical knowledge to develop grazing strategies that stimulate animals' appetite and subsequently promote increased food intake (Meuret and Provenza 2015). Understanding the behavioural patterns of individual animals facilitate livestock keepers in shaping the animals' grazing behaviours, thereby enhancing efficiency and productivity (Dimitri and Longland 2018). Due to the challenging conditions in Kunene north, accessing pastures during the dry season and drought periods depends on the relationships between herders, their herds, and their rangeland. Both the herders' practical knowledge and the cattle's adaptability are critical factors for the successful utilization of these pasture areas (Kaufmann et al. 2016). In the study region, cattle calve once a year, contributing to the sustenance of the Himba people's livelihoods for centuries. This is made possible through these interactions, which highlights the collective importance of human expertise and animal adaptability in pastoral ecosystems. However, comprehensive knowledge on how this interaction influences herding and grazing practices within these pastoral systems remains limited. The aim of this study is to understand cattle-rangeland interactions from the perspective of Himba pastoralists and to explore the factors influencing cattle behaviour associated with mountain grazing in Kunene North.

Methods

This study was conducted in the northern part of the Kunene region, which is characterized by low and erratic precipitation, with annual rainfall ranging from 50 to 400 mm over a maximum of four months. Kunene region is described as a rocky mountainous landscape (NPC, 2015).

Between March 2023 and June 2024, a total of 45 semi-structured interviews and 15 narrative interviews were conducted with Himba pastoralists in three study areas: Omuhonga, Etanga, and Etoto. Semi-structured interviews typically lasted 1 to 1.5 hours, while narrative interviews ranged from 1.5 to 2 hours. The initial participants were selected through purposive sampling, and thereafter respondents were identified through snowball method. The interviews were conducted with herders actively engaged in daily cattle management to capture first-hand experiences, knowledge, and practices. Participant observation, combined with informal discussions and prolonged engagement over 9 months, contributed to the robustness and validity of the collected data. To ensure accuracy all interviews were recorded and transcribed by a native speaker of the local language. Data analysis followed a multi-stage approach. The recorded interviews and data were organized, transcribed, and coded. Recurring themes and patterns were then identified. Respondents were grouped, and their answers to the research questions were examined. Content analysis was conducted to develop codes and categories (Creswell, 2007). Data analysis was performed with the help of MAXQDA.

Results

Cattle breeds and their characteristics

Three common cattle breeds and their respective characteristics in the study area were identified through interviews. (i) The Nguni, which is an indigenous breed (sometimes referred to as Nguni/Sanga or Sanga sub-type/eco-type), has a small body frame and low milk production (<3L/day). However, this breed is well-adapted to the region and demonstrates competence in walking long distance as well as mountainous terrain and rocky areas. Consequently, this attribute contributes to its ability to reach pastures across the seasons, enabling it to meet its nutritional needs, which in turn supports reproductive performance, by maintaining good body condition and hence go on heat few months after calving and uphold an annual calving pattern. A high calving rate not only enhances herd growth but also ensures a steady supply of milk. Although the quantity may be limited, it is often sufficient during critical periods, particularly for younger children. (ii) The Brahman which was introduced to the area from commercial farms, primarily through exchanges; it is not well-adapted to the region but can cope with extended dry season and the rocky mountainous areas to some extent. It has a big body frame that provides favourable prices when sold. (iii) The Herero (locally referred to as a breed originating from Hereroland, also referred to as composite of Brahman, Simmental, Nguni and possibly Bonsmara), demonstrates limited ability to survive drought conditions, but it is larger and produces more milk (5-7L/day) than the other two. Despite their susceptibility to drought events, about 80% of the herders maintain them, as deadly droughts occur approximately once every six to ten years. Thus, the benefits of increased milk production and meat yield, or potential financial gains from sales, are perceived to be worth the risk of losing these animals during drought periods. In terms of calving rate, both Brahman and Herero breeds are reported by the herders to likely skip one or two years of calving. Herders maintain a diverse combination of breeds and crossbreeds in their herds, as each breed offers distinct advantages.

Herders' perceptions on cattle breeds grazing behaviours

Kunene North pastoralists prefer cattle that are capable of performing grazing activities independently, such as walking to water sources, to the pasture and returning home to their calves (particularly lactating cows). This preference stems from the dominant free-ranging practices, where cattle are guided to grazing zones and left to forage on their own. This cattle-free-ranging practices is driven by labour constrains and low presence of cattle predators unlike for small ruminants that need to be herded due to the presence of jackal and leopards in the area. During the dry season, navigating mountainous and rocky terrain is crucial for the livestock to meet their nutritional requirements. Additionally, in these periods watering animals becomes one of the main activities, hand-dug wells need to be re-excavated reducing herders active herding time. Animals unable to carry out grazing activities on their own are considered by the Himba to be lazy, weak, or incapable, requiring herder's intervention. Himba pastoralists specify several cattle characteristics that resonate with their preferences.

Breed-dependent factors: The mountainous terrain poses varying levels of challenges for different cattle breeds. Nguni cattle are capable of independently ascending to mountain pastures. In contrast, Brahman cattle typically ascend partially and require herder intervention to reach grazing areas at higher elevations. Herero cattle, however, depend entirely on herders for any uphill movement.

Breed-independent factors: Individual cattle experience with mountainous environments plays a crucial role in their ability to navigate such terrain. Animals originating from non-mountainous areas lack the experience and depend on herder's support. Additionally, body condition is a critical factor; weak animals lack the strength for independent uphill ascending and thus require herders' intervention.

Herders' supportive strategies towards accessing mountain pasture

Due to the availability of pastures solely in the rocky mountainous areas during critical periods, and the inability of some cattle to access these pasture areas, it is crucial for herders to intervene to ensure continuous provision of feed resources for the animals. Herders' intervention involves different approaches, based on the individual animal's specific limitations. When livestock are unfamiliar with the area and unaware of pasture locations, the herder may employ the following strategies: *Dung application method* - herders strategically apply fresh dung along an imaginary trail. When cattle detect the scent, they assume the route is commonly used to access pasture, motivating them to ascend. *Training the lead cow* - the lead cow, typically possessing good memory and learning capabilities, is guided for about a week. Once trained, it takes the lead, and the rest of the herd follows. When animals are in poor body condition, alternative strategies are employed such as: *Creating pathways* - herders remove large, sharp rocks to facilitate cattle movement. Navigating slopes and rocky terrain can be exhausting, especially for weak animals. *Evening ascension* - to avoid daytime temperatures that can reach 35–40°C, herders move livestock during the cooler evening hours. Slow, deliberate movement also reduces exhaustion and minimizes the risk of slips, falls, and injuries. *Choosing flatter routes -* whenever possible, herders select flatter paths, as these are easier to climb, and some animals are fearful of steep slopes. *Dividing the herd* - The herd is separated into strong and weak groups and grazed on different mountains based on distance and slope gradient. Strong animals capable of efficient walking and climbing are assigned to more challenging routes, while weaker animals, including lactating cows, thin, ill, or old individuals, are grazed on less demanding terrain.

Discussion

Adaptive herding strategies: cattle breeds, environmental knowledge, and pastoral expertise

Accessing mountain pastures: Each cattle breed exhibits distinct characteristics and behaviour patterns that reflect its adaptability to the region's conditions and its value to livestock keepers. While exotic breeds perform well under optimal conditions, such as during the wet season, producing substantial amount of milk and larger framed offspring, they face challenges due to the prolonged dry seasons, drought, and the difficulty of navigating mountainous and rocky terrain. This limitation reduces their ability to access the scattered and difficult to reach pockets of fodder available on mountain pastures during the dry season/drought periods and ultimately hampers their survival under the region's peculiar conditions. In contrast, the indigenous Nguni cattle, are well-adapted to the pedo-climatic conditions. Similarly, pastoralists highlighted the strengths of local breeds, noting their resistance to drought, ability to travel long distances without water, and capacity to adapt to new or changing environments (e.g., Marshall et al. 2019; Ayantunde 2007; Tamou et al. 2018).

Herding skills: The training that herders perform to teach their animals to access to mountain pasture and to encourage them to walk on rocky paths allow continuous fodder intake of their cattle for sustenance and production. Experienced herders are known to create meal sequences for their livestock to optimise feed intake, hence improving the nutrition, health, and production of animals and landscapes (Meuret and Provenza 2015).

Calving rate: The ability of Nguni cattle to access mountain pastures enable them to meet their nutritional needs, maintaining good body condition and also enhancing annual calving rate. Adequate nutrition helps cows return to oestrus faster after calving and maintain optimal reproductive efficiency (Diskin and Kenny 2014); cows have a 70% probability of conception if they are gaining weight, compared to only 17% if they are losing weight (Pradhan & Nakagoshi, 2008). Research conducted on a Namibian research station on comparing the calving rate of different breeds over a period of 10 years under equal conditions found that, Nguni cattle have a calving rate of 89,6%, compared to the 77,4% average of four other breeds (Afrikaner, Simmental, Hereford and Santa Gertrudis) (Schoeman 1989).

Herd composition: The majority of herders, where the topographic conditions permit, prefer maintaining a mix of cattle breeds. This strategy enables them to capitalize on higher yields during favourable years while benefiting from the resilience of Nguni cattle, which ensure a consistent supply of milk and offspring with minimal input requirements. Similarly, Rendille camel herders in Kenya do not prioritize a single breed but instead maintain a diverse herd composition, recognizing that different breeds serve various roles in terms of production and self-sustenance within the herd (Kaufmann, 2007). This underscores the importance of herders' strategic herd composition, which is determined by a variety of factors beyond the simple "production" aspect often emphasized.

Conclusions

The strategic importance of herd composition enables herders to mitigate risks associated with climate variability, and ensure that immediate household requirements and long-term production objectives are met. The strategies utilized by Himba herders reflect their profound knowledge of animal behaviour and rangeland conditions, demonstrating a sophisticated understanding of the potential of the interplay between the two. The human-animal-environment interactions play significant role in utilising the hardly accessible rangeland resources, which enables livestock production, thus sustaining livelihoods of Himba pastoralists.

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Zn and Fe bio-fortification and its effect on fodder maize and sorghum for sustainable livestock production in Himalayan foothills of India

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Key words: Bio-fortification; crude protein; Fe; Leaf:Stem ratio; Zn

Abstract

A field experiment was conducted at G B Pant University of Agriculture & Technology, Pantnagar, India) in kharif (crop-growing season from June to October) 2019 and 2020 to study the effect of Zn and Fe biofortification on fodder quality of maize and sorghum in Himalayan foothills of India. The experimental site was clay loam with organic matter 0.74% and available N, P and K was 280.2, 25.2, 215 kg ha^{-1}, respectively. The initial soil Fe and Zn content was 3.582 and 0.461 ppm, respectively. The growth, yield, quality and economics of fodder crops differed significantly with higher plant height, number of plants m^{-1} row length, flowering, fodder yield, crude protein yield and economics in sorghum. Fodder sorghum produced 27.2, 18.8 and 82.5% % higher green fodder yield, dry fodder yield and net return, respectively, than maize. The green and dry fodder yields, crude protein yield and economics were significantly higher at $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$, while Zn and Fe contents in soil and plants were significantly greater at $Zn_{20b}Fe_{20b}Zn_{1f}Fe_{1f}$. Therefore, it may be concluded that both maize and sorghum, preferably sorghum, could be biofortified with application of 10 kg $ZnS0_4$ ha^{-1}+10 kg $FeS0_4$ ha^{-1} (basal)+1% $ZnS0_4$+1% $FeS0_4$ (foliar 45 DAS) for higher biofortified fodder yield and net profit for sustainable livestock production in Himalayan foothills of India and these results may be replicated in similar ecologies.

Introduction

Presently India is short of 36% green fodder, 21.9% dry fodder and 44% concentrates. Fodder maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.) are the major crops cultivated globally for green fodder, silage and hay but cereal-based diets are deficient in essential amino acids, i.e. lysine and tryptophan, vitamin A, zinc (Zn) and iron (Fe). Recently wide range deficiency of Fe and Zn in soil, food and feed has drawn attention due to nutritional health problems. Fe is the third most limiting nutrient for plant growth and its deficiency causes chlorosis, low yield and a loss in nutritional quality in many agricultural plants. Zn is also an essential micronutrient and acts as co-factor of many enzymes and regulates auxin synthesis and antioxidant production, but its deficiency decreases photosynthetic rate and induces chlorosis, sterility and fungal infection. Normally sorghum is deficient in Ca, Zn and Fe causes health problems in livestock. Most sorghum varieties contain 30 ppm Fe and 20 ppm Zn, while balanced nutrition requires 60 and 32 ppm, respectively. Agronomic manipulation is an effective tool of biofortification of micronutrients like Fe and Zn in forage crops. Mousavi et al. (2012) reported positive effect of Zn and Fe on biomass components and composition of plants. Zinc improves kernel number and weight in maize (Liu et al., 2020). Deficiency of Fe and Zn in sorghum can be altered through biofortification, which is a sustainable solution to their deficiencies (Kumar et al. 2015). Recent studies showed that foliar application of a minute concentration of nutrients, especially Ca, Zn and Fe significantly increased nutrient contents and yield in both sorghum and maize. However, research work on biofortification of Fe and Zn in forage maize and sorghum is very limited. Therefore, the present study was planned to study the effects of bio-fortification of Zn and Fe on yield and quality of maize and sorghum fodder for sustainable livestock production in Himalayan foothills of India.

Methods

Field experiment was conducted at Fodder Block, G B Pant University of Agriculture & Technology, Pantnagar, India, during *kharif (*crop season from June to October) 2019 and 2020 to study the effect of Zn and Fe biofortification on fodder maize and sorghum for sustainable livestock production in Himalayan foothills of India. The soil at the site was clay loam with pH 7.2, 0.74% organic carbon, available nitrogen 280.2, phosphorus 25.16 and potassium 215.0 kg/ha, 0.461 ppm Zn and 3.582 ppm Fe. The experiment consisted of two crops, i.e. maize and sorghum, in main plot and 07 treatments in subplot was planted in split plot design and replicated thrice.
The maize var. African Tall and sorghum var. PC-6 were planted at 30 cm x 10 cm plant geometry on 21st June in 2019 and 28th June 2020. The recommended dose of fertilizers for both crops was 100 kg N ha^{-1}, 60 kg P_2O_5 ha^{-1} and 40 kg K_2O ha^{-1}. Pendimethalin 30EC @ 1.0 kg ai ha^{-1} was sprayed as a pre-emergent herbicide to control weeds. The crop did not require irrigation due to sufficient rainfall during the crop growth period. The crop was harvested manually at 50% flowering. Crude protein content was estimated by multiplying the nitrogen content by factor 6.25, while the crude protein yield was the result of crude protein content x dry fodder yield. The Fe and Zn were determined using Atomic Absorption Spectroscopy (AAS). The economics including gross return (green fodder yield (qha^{-1}) x Sale rate ((Rs q^{-1}) and net return (Gross return (₹ ha^{-1}) – cost of cultivation (₹ ha^{-1})) were worked out on the basis of prevailing sale rate of the green fodder. The benefit:cost ratio (B:C ratio) was estimated on per hectare basis. The data were analyzed with standard procedures using OPSTAT-Online Statistical Analyzing Tools developed by **Sheoran (2021).** The treatments are abbreviated as given in Table 1.;

Table 1. Treatment details

Treatment	**Details of treatment (Trt)**	**Abbreviated treatment**
T_1	Control (no Zn or Fe application)	Zn_0Fe_0
T_2	10 kg $ZnSO_4$ ha^{-1} (basal soil application)+1% $ZnSO_4$ foliar spray at 45 DAS (days after sowing)	$Zn_{10b}Zn_{1f}$
T_3	10 kg $FeSO_4$ ha^{-1} (basal soil application) +1% $FeSO_4$ foliar spray at 45 DAS	$Fe_{10b}Fe_{1f}$
T_4	10 kg $ZnSO_4$ ha^{-1}+10 kg $FeSO_4$ ha^{-1}(basal soil application) +% $ZnSO_4$+1% $FeSO_4$ foliar spray at 45 DAS	$Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$
T_5	20 kg $ZnSO_4$ ha^{-1} (basal soil application) +1% $ZnSO_4$ foliar spray at 45 DAS,	$Zn_{20b}Zn_{1f}$
T_6	20 kg Zn SO_4 (basal soil application) + 1% $FeSO_4$ foliar spray at 45 DAS	$Zn_{20b}Fe_{1f}$
T_7	20 kg $ZnSO_4$ ha^{-1}+20 kg $FeSO_4$ ha^{-1} (basal soil application) +1% $ZnSO_4$+1% $FeSO_4$ foliar spray at 45 DAS	$Zn_{20b}Fe_{20b}Zn_{1f}Fe_{1f}$

Results and Discussion

a. Effect of Zn and Fe on fodder crops

Sorghum had significantly taller plants and more plants per unit area than maize (Table 2) mainly due to better field emergence and greater tolerance to higher soil moisture in crop seasons, similar to Adesh et al. (2021). Maize had significantly more leaves than sorghum mainly due to higher plant density in sorghum with increased internodes length. Sorghum took more days than maize to 50% flowering. The L:S ratio was significantly greater in maize than sorghum because of broader leaves in maize (Table 3). Vinita et al. (2021) also reported higher number of leaves/plant and greater L:S ratio in maize than in sorghum. Sorghum had significantly higher green fodder yield (GFY) and dry fodder yield (DFY) than maize (Table 3), ascribed to taller plants and more plants per unit area.

Table 2. Effect of Zn and Fe on growth of fodder maize and sorghum (pooled of 2019 & 2020)

Trt	Height (cm)			Plants m^{-2}			Leaves $plant^{-1}$			50% flowering (Days)		
	Maize	Sorgh.	Mean	Maize	Sorghum	Mean	Maize	Sorghum	Mean	Maize	Sorghum	Mean
T1	220	259	240	26.0	63.0	44.5	11.7	10.1	10.9	59.5	71.5	65.5
T2	235	265	250	26.0	59.0	42.5	13.0	9.5	11.2	58.2	69.3	63.8
T3	231	270	251	27.5	49.0	38.3	12.2	9.9	11.1	60.7	70.3	65.5
T4	244	262	253	26.5	56.5	41.5	12.3	9.8	11.1	57.5	70.7	64.1
T5	236	272	254	28.0	60.0	44.0	12.5	10.0	11.2	58.2	69.5	63.8
T6	233	278	256	26.0	59.0	42.5	12.9	10.1	11.5	59.5	70.5	65.0
T7	237	257	247	26.5	56.5	41.5	11.0	9.7	10.3	58.0	68.7	63.3
Mean	234	266	-	26.6	57.6	-	12.2	9.9	-	58.8	70.1	-
		SEm±	CD (5%)		SEm±	CD (5%)		SEm±	CD (5%)		SEm±	CD (5%)
Maize Factor(A)		02	05		0.8	2.4		0.1	0.4		0.2	0.5
Sub Factor (B)		03	10		1.5	NS		0.2	NS		0.3	0.8
Interaction (AXB)		05	NS		2.1	6.2		0.3	1.0		0.4	1.2

Sorghum had significantly higher crude protein content (CPC) and crude protein yield (CPY) than maize (Table 4), similar to Adesh et al. (2021). The crude fibre (CF) was significantly higher in maize than sorghum as maize has more crude protein and soluble sugar. Iron content in both soil and plant as well as Zn in plant was significantly higher in maize, but Zn content in soil was significantly higher in sorghum (Table 5). The gross and net returns as well as B:C ratio was also significantly higher in sorghum (Table 6). Sorghum gave 27.0 and 82.5% higher gross and net returns, respectively than maize, attributed to higher green and dry fodder yield. Asif et al. (2020) concluded that combined foliar application of Ca@3%, Zn@2% and Fe@ 1% improved yield and quality of forage sorghum.

Table 3. Effect of Zn and Fe on L:S ratio and yield of fodder maize and sorghum (pooled 2019 & 2020)

Treatment	L:S ratio			GFY (t ha^{-1})			DFY (t ha^{-1})		
	Maize	Sorghum	Mean	Maize	Sorghum	Mean	Maize	Sorghum	Mean
T_1	0.25	0.22	0.23	32.93	51.22	42.07	6.54	9.63	8.09
T_2	0.24	0.22	0.23	39.46	51.63	45.54	7.91	8.98	8.45
T_3	0.25	0.22	0.23	41.25	53.33	47.29	7.91	10.08	9.00
T_4	0.26	0.22	0.24	48.55	55.56	52.05	10.07	10.25	10.16
T_5	0.26	0.23	0.24	46.78	56.54	51.66	8.76	10.81	9.78
T_6	0.30	0.20	0.25	45.45	58.60	52.02	8.49	10.70	9.59
T_7	0.26	0.21	0.23	43.83	52.37	48.10	8.66	8.83	8.74
Mean	0.26	0.22	-	42.61	54.18	-	8.33	9.90	-
	SEm±	CD(5%)		SEm±	CD (5%)		SEm±	CD(5%)	
Maize Factor (A)	0.005	0.013		0.59	1.74		0.17	0.50	
Sub Factor (B)	0.009	NS		1.11	3.26		0.32	0.94	
Interaction (A X B)	0.012	NS		1.58	4.61		0.45	1.32	

b. Effect of Zn and Fe

The tallest plants of maize were measured at $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f,}$ while sorghum was found tallest under that was non-significant with $Zn_{20b}Fe_{1f}$ that was significantly equal to $Fe_{10b}Fe_{1f}$ and $Zn_{20b}Zn_{1f}$ (Table 2). The plants m^{-2} and leaves $plant^{-1}$ did not differ significantly among treatments; however, the highest values were noted at $Zn_{20b}Zn_{1f}$.

Sorghum took significantly more days to flowering than maize with highest days at $Fe_{10b}Fe_{1f}$ and Zn_0Fe_0. The L:S ratio of maize was highest under $Zn_{20b}Fe_{1f}$, while L:S ratio of sorghum did not vary statistically among treatments (Table 2). The GFY and DFY was influenced significantly by fortification of Zn and Fe with significantly higher values under sorghum (Table 2). The highest GFY of maize was recorded at $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$ that was statistically similar to $Zn_{20b}Zn_{1f}$ and $Zn_{20b}Fe_{1f}$ but the sorghum gave the highest values at $Zn_{20b}Fe_{1f}$ that was non-significant with $Zn_{20b}Zn_{1f}$ and $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$. The higher GFY and DFY was described with better growth attributes because both Fe and Zn improved enzymatic reactions, photosynthesis and finally biomass production (Cabot et al., 2019).

The Zn content in soil both fodder crops was estimated significantly higher in $Zn_{20b}Fe_{20b}Zn_{1f}Fe_{1f}$ that was non-significant with $Fe_{10b}Fe_{1f}$ (Table 4). In case of Fe content in soil, maize had significantly higher values than sorghum. The highest Fe content in both soils of maize and sorghum was recorded significantly highest in $Zn_{20b}Fe_{20b}Zn_{1f}Fe_{1f}$. The Fe content in maize was measured significantly higher at $Zn_{20b}Fe_{1f}$ which was statistically at par with $Zn_{20b}Fe_{20b}Zn_{1f}Fe_{1f}$. Similarly, the Fe content in sorghum was higher at $Zn_{20b}Fe_{20b}Zn_{1f}Fe_{1f}$ that was significantly equal to at $Zn_{20b}Fe_{1f}$. The higher dose of Zn and Fe resulted into more nutrient contents in plant and soil after crop harvest.

Table 4. Effect of Zn and Fe on Zn and Fe content in soil and plant of fodder crops (pooled 2019 & 2020)

Trt	Zn content (ppm)						Fe content (ppm)					
	Soil			Plant			Soil			Plant		
	Maize	Sorg.	Mean	Maize	Sorgh.	Mean	Maize	Sorg.	Mean	Maize	Sorg.	Mean
T_1	0.42	0.55	0.49	30.05	32.15	31.10	3.35	3.00	3.18	88.53	76.90	82.72
T_2	0.58	2.00	1.29	67.79	54.18	60.99	3.33	2.93	3.13	88.53	76.67	82.60
T_3	0.49	0.65	0.57	35.54	28.00	31.77	5.65	5.59	5.62	131.70	114.70	123.20
T_4	0.68	1.89	1.29	72.97	52.70	62.84	5.93	5.21	5.57	137.77	117.17	127.47
T_5	1.46	3.59	2.53	92.47	89.53	91.00	3.35	3.13	3.24	90.07	80.73	85.40
T_6	0.64	0.65	0.65	35.17	29.63	32.40	5.96	5.52	5.74	192.83	152.07	172.45
T_7	1.64	3.79	2.72	94.00	91.34	92.67	6.30	6.02	6.16	191.83	158.03	174.93
Mean	0.85	1.88	-	61.14	53.93	-	4.84	4.49		131.61	110.90	-
	SEm±	CD (5%)		SEm±	CD (5%)		SEm±	CD (5%)		SEm±	CD (5%)	
Main Factor (A)	0.04	0.11		0.55	1.59		0.05	0.15		1.18	3.44	
Sub Factor (B)	0.07	0.20		1.02	2.98		0.10	0.29		2.20	6.43	
Interaction (A X B)	0.10	0.29		1.44	4.22		0.14	NS		3.11	9.09	

Table 5. Effect of Zn and Fe on quality of fodder maize and sorghum (pooled of 2019 & 2020).

Trt	Crude protein content (%)			Crude protein yield (t ha^{-1})			Crude fiber (%)		
	Maize	Sorghum	Mean	Maize	Sorghum	Mean	Maize	Sorghum	Mean
T1	7.40	9.14	8.27	3.64	4.65	4.14	30.33	31.33	30.83
T2	7.72	10.53	9.13	3.84	5.39	4.61	32.62	31.03	31.83
T3	7.63	11.52	9.58	3.89	5.74	4.82	32.67	32.05	32.36
T4	7.87	11.98	9.93	3.97	5.97	4.97	33.40	30.67	32.03
T5	7.78	11.71	9.75	3.92	5.91	4.92	32.27	31.23	31.75
T6	7.88	11.58	9.73	3.97	5.79	4.88	31.90	32.72	32.31
T7	8.07	11.58	9.83	4.07	5.88	4.98	33.87	32.68	33.28
Mean	7.76	11.15	-	3.90	5.62	-	32.44	31.67	-
	SEm±	CD (5%)		SEm±	CD (5%)		SEm±	CD (5%)	
Main Factor (A)	0.10	0.30		0.06	0.18		0.15	0.43	
Sub Factor (B)	0.19	0.56		0.12	0.34		0.28	0.81	
Interaction (AX B)	0.27	0.79		0.16	NS		0.39	1.14	

The biofortification of Zn and Fe had significant effect on crude protein content and crude protein yield (Table 4). The highest crude protein content in maize fodder was recorded at $Zn_{20b}Fe_{20b}Zn_{1f}Fe_{1f}$ that was significant with only control treatment, while sorghum had significantly higher CPC at $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$ that was significant with Zn_0Fe_0 and $Zn_{20b}Fe_{20b}Zn_{1f}Fe_{1f}$. The CPY of both maize and sorghum followed almost similar pattern as CPC with highest values at $n_{20b}Fe_{20b}Zn_{1f}Fe_{1f}$ and $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$, respectively. The mean CPC and CPY was significantly higher at $Zn_{20b}Fe_{20b}Zn_{1f}Fe_{1f}$ that was significantly similar to $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$.. Chand *et al*. (2017) claimed that soil application of $ZnSO_4$ at 25kg/ha+2% its foliar spray gave maximum CPC because Zn and Fe enhanced CH_2O and protein production. The fibre content in maize and sorghum was found significantly highest at $Zn_{20b}Fe_{1f}$, and $Fe_{10b}Fe_{1f}$, respectively. The mean CF was estimated the highest at $Zn_{20b}Fe_{20b}Zn_{1f}Fe_{1f}$.. The results revealed that combined application of Zn and Fe increased the CF because Zn and Fe are essential components of various enzymes involved in plant metabolism. Qadir *et al*. (2017) noted that Zn and Fe content were greatly improved by foliar fertilization of Zn and Fe in sorghum. So, there is the direct and positive correlation between Zn and Fe. Xia et al. (2019) also described that Zn fertilization had positive impact on Fe contents of plant.

The highest gross and net return of maize was calculated at $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$ that was non-significant with $Zn_{20b}Zn_{1f}$ and $Zn_{20b}Fe_{1f}$, while sorghum gross and net return was significantly higher under $Zn_{20b}Fe_{1f}$ that was significantly similar to $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$ and $Zn_{20b}Zn_{1f}$ (Table 5). The mean gross and net returns were highest at $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$ which was non-significant with $Zn_{20b}Zn_{1f}$ and $Zn_{20b}Fe_{1f}$. The B:C ratio had similar pattern where maize and sorghum had the highest values at $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$ and $Zn_{20b}Fe_{1f}$, respectively. The mean values of B:C ratio was significantly higher at $Zn_{20b}Fe_{1f}$ that was significantly higher than $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$ and $Zn_{20b}Zn_{1f}$. These results enumerate that biofortification of Fe and Zn improved the fodder yield resulting in greater gross and net returns.

Table 6. Effect of Zn and Fe on economics of fodder maize and sorghum (pooled 2019 & 2020)

Treatment	Gross return (₹ ha^{-1})			Net return (₹ ha^{-1})			B:C ratio		
	Maize	Sorghum	Mean	Maize	Sorghum	Mean	Maize	Sorghum	Mean
T_1	65846	102432	84139	18935	61922	40429	1.41	2.53	1.97
T_2	78923	103251	91087	30217	60941	45579	1.62	2.44	2.03
T_3	82496	106655	94576	33791	64345	49068	1.70	2.52	2.11
T_4	97103	111111	104107	47243	68001	57622	1.95	2.58	2.26
T_5	93561	113087	103324	43701	69977	56839	1.88	2.63	2.25
T_6	90895	117202	104049	41035	74092	57564	1.82	2.72	2.27
T_7	87655	104735	96195	37120	60826	48972	1.73	2.39	2.06
Mean	85211	108353	-	36006	65729	-	1.73	2.54	-
	SEm±	CD (5%)			SEm±	CD (5%)		SEm±	CD(5%)
Main Factor (A)	1191	3481			1191	3481		0.03	0.08
Sub Factor (B)	2228	6513			2228	6513		0.05	0.14
Interaction (A X B)	3151	9210			3151	9210		0.07	0.20

Interaction effect

Maize green and dry fodder yield were highest at $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$, which was statically at par with $Zn_{20b}Zn_{1f}$ and $Zn_{20b}Fe_{1f}$. The sorghum fodder yields were highest at $Zn_{20b}Fe_{1f}$, which were significantly equal to $Zn_{10b}Fe_{10b}Zn_{1f}Fe_{1f}$ and $Zn_{20b}Zn_{1f}$. Similar trends were found for gross and net returns of both maize and sorghum. It indicates that maize and sorghum do best with 10kg and 20 kg Zn ha^{-1} while both crops performed better at 1% spray of $FeSO_4$. However, the higher Zn and Fe contents in fodder crops were observed at $Zn_{20b}Fe_{20b}Zn_{1f}Fe_{1f}$ which had higher cost of cultivation and lower B:C ratio.

Conclusion & Implications

Both maize and sorghum, preferably sorghum, could be biofortified with application of 10 kg $ZnS0_4$ ha^{-1}+10 kg $FeS0_4$ ha^{-1}(basal)+1% $ZnS0_4$+1% $FeS0_4$ (foliar 45 DAS) for higher fodder yield and net profit for sustainable livestock production in Himalayan foothills of India and may be replicated in similar ecologies.

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Rain water harvesting, silvipastoral and goat based integrated farming system model for livelihood resilience in drought-prone rainfed semi-arid tropics

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Keywords: Rainfed farming system; Rain water harvesting; agroforestry; intensification; Livelihood; Resilience

Abstract

Rainfed areas are the home of millions of resource poor farmers whose livelihood is under continuous threat due to frequent droughts. Assured cropping and imparting livelihood resilience to livestock keepers is a challenge. A study was planned during 2013 – 2019 for livelihood resilience of rainfed farmers through rain water harvesting and silvipasture based interventions. The one hectare rainfed farming system model comprising of rain water harvesting farm pond (25 m x 20 m x 2.5 m), less water requiring food crops (groundnut–barley and sorghum–chickpea), agrihorticulture [*Ziziphus mauritiana*+(*Sesamum indicum*–*Cicer arietinum*)], silvipasture (*Leucaena leucocephala*+Tri-species hybrid grass+*Stylosanthes hamata*) and boundary plantation (*Leucaena leucocephala* and *Opuntia ficus-indica*) was evaluated at research farm. The goat rearing potential of the above model was also estimated under intensive and semi-intensive systems. The rainfed farming system module produced 4979 kg ha^{-1} barley equivalent yield consisting of multiple products like barley, chickpea, groundnut, Indian jujube fruits, sesame, fodder (sorghum, TSH, *Stylosanthes, Leucaena* dried leaf meal and spine-less fodder cactus cladodes) and *Grewia* fruits and resulted in 655 US$ year^{-1} net returns with a benefit cost ratio of 2.1. The carrying capacity of the model was 9 and 35 goat year^{-1} under intensive and semi-intensive rearing systems, respectively. The net returns increased by 36 and 226% with the inclusion of goat under intensive (US$ 892) and semi-intensive rearing system (US$ 2136), respectively in the model. It was evident from the study that inclusion of goat, silvipasture and farm pond for rain water harvesting in the rainfed farming have resulted in higher profitability and resilience to less rainfall and its aberrations. It can be concluded from the study that water harvesting, silvipasture and goat

in rainfed farming systems could enhance the productivity and profitability and impart resilience to the livelihood of rainfed farmers in semi-arid tropics.

Introduction

Rainfed agriculture has special significance in terms of ecology, farm productivity and livelihood for millions of resource poor farmers and livestock keepers especially in arid and semi-arid tropics. Rain water harvesting cum efficient recycling and agroforestry based intensification offer a great opportunity for enhancing productivity, natural resource conservation, risk proofing and sustaining livelihood of farmers practicing rainfed agriculture (Palsaniya et al. 2021). Inclusion of animal components, especially small ruminants like goat, in such farming systems may further improve the profitability and resilience of the production system. However, the systematic information on water harvesting – crop – agroforestry – animal integration under rainfed situation is scanty and therefore, need to be researched upon. There is also a need of exploring and calculating the carrying capacity potential and possible economic benefits of such rainfed models under stall feeding and semi-intensive animal rearing systems. Therefore, the present investigation was carried out to establish the impact of rain water harvesting, agroforestry and goat based intensification on livelihood resilience of rainfed smallholder farming systems of India.

Materials and methods

The field experiment was carried out at the Central Research Farm of ICAR-Indian Grassland and Fodder Research Institute, Jhansi (Uttar Pradesh), India during 2014–2018. The soil of the site was sandy loam in texture, low in available N and K and medium in available P and soil organic carbon (0.58%). The components of one hectare rainfed farming system model are shown in table 1. Boundary plantation of *Leucaena leucocephala* and *Opuntia ficus-indica* was also there. The goat rearing potential of the above model was also estimated under intensive and semi-intensive rearing systems. The animals were stall-fed under the intensive system while they were allowed to graze in community and fallow lands and partially supplemented with farm forages, under the semi-intensive system. The life cycle assessment and process analysis approach was used in the present study (Jianbo 2006; Palsaniya et al. 2023). A detailed inventory of inputs and outputs of all the components of the rainfed farming module was compiled. The production cost and returns from individual components were calculated using prevailing market prices of their respective inputs and outputs. The gross return from each component was calculated by multiplying the quantity of produce by its prevailing market price. The total cost was deducted from the gross return to calculate the net return while the benefit cost ratio (BCR) was calculated by dividing gross returns by total cost.

Table 1 Components of the rainfed farming system model

Enterprise	Area (ha)	Component (ha)	
		Rainy season	Winter season
Food crops	0.55	Groundnut (0.3)	Barley (0.3)
		Sorghum (0.25)	Chickpea (0.25)
Silvipasture	0.2	*Leucaena* + Tri-species hybrid grass + *Stylosanthes*	
Agrihorticulture	0.2	Indian jujube + (Sesame – Chickpea)	
Boundary plantation	-	*Leucaena* and spineless fodder cactus	
Rain water harvesting pond	0.05 (20 m × 25 m × 2.5 m)	*Grewia asiatica* on pond dykes	
Total	1.0		

Results and discussion

The component yield, productivity and economics in rain water harvesting and agroforestry based improved rainfed farming system model are presented in Table 2. The food crops in the model consisted of groundnut, barley and chickpea, which on an average, produced 240, 1021 and 311 kg grain yield, respectively. Among the food crop components, the highest barley equivalent yield (BEY) was observed in barley (1021 kg) followed by chickpea (925 kg) and groundnut (718 kg). On an average of 4 years, 200 kg Indian jujube fruits, 81 kg sesame and 179 kg chickpea grain yield was produced from the agrihorticulture component in the model. The equivalent yield in terms of barley was the highest for chickpea (532 kg) followed by sesame (283 kg) and Indian jujube (144 kg) in the agrihorticulture block. Fodder sorghum produced 2314 kg green fodder which was equivalent to 581 kg BEY. The silvipastoral module recorded 2051 kg green fodder (BEY, 129 kg) from TSH, 2233 kg green fodder (BEY, 180 kg) from *Stylosanthes* and 203 kg *Leucaena* dried leaf meal (BEY, 204 kg). The boundary plantation produced 1600 kg fresh spine-less fodder cactus cladodes (BEY, 115 kg), 110 kg *Leucaena* leaf meal (BEY, 111 kg) and 5 kg *Grewia* fruits. Apart from this, the various food crops in the model produced a total of 2741 kg dry fodder year^{-1} comprising of barley straw (1496 kg), groundnut stover (325 kg), sesame stover (207 kg) and chickpea stover (405 kg from food crop component and 308 kg from agrihorticulture). In total, the rainfed farming system module produced 4979 kg ha^{-1} barley equivalent yield consisting of the multiple products above reported. The total cost of cultivation, gross returns, net returns and benefit cost ratio of the one ha rainfed farming system model were 589 US$, 1244 US$, 655 US$ and 2.1, respectively. The contribution of food crop components (446 US$) was the highest (62.9%) in the total net returns of the model, followed by agrihorticulture (137 US$, 19.3%), silvipasture (75 US$, 10.6%) and boundary plantation (51 US $, 7.2%).

The carrying capacity of the rainfed farming system model was found to be 9 and 35 goats year^{-1} under intensive and semi-intensive rearing systems, respectively (Table 3). Nearly 294 and 459 US$ initial investment was needed for animal shed, fencing, equipment and electric and water tank installations under intensive and semi-intensive rearing systems, respectively. The yearly fixed cost due to the initial investment was found to be 41 and 65 US$ under intensive and semi-intensive rearing systems, respectively. The variable cost under intensive and semi-intensive small ruminant rearing system was 1293 and 3026 US$ year^{-1}, respectively and consisted of animal cost, feed and fodder cost, labour cost, veterinary expenses and other miscellaneous cost. The feed and fodder cost was found to be the major cost (46%) followed by animal cost (30%), labour cost (21%) and others in intensive rearing system while animal cost, labour and feed and fodder constituted 50, 28 and 19% of the total variable cost in semi-intensive rearing system.

The gross return from the intensive rearing system was US$ 2226 and consisted of returns from meat (US$ 1740, 78%), skin (US$ 35, 2%), manure (US$ 75, 3%) and sale of non-edible produce (US$ 377, 17%). On the other hand, the semi-intensive rearing system yielded US$ 5226 gross returns out of which, 87% (US$ 4560) was from animal meat, 3% (US$ 135) from skin, 3% (US$ 179) from manure and 7% (US$ 352) from sale of non-edible produce from the model. The intensive and semi intensive small ruminant rearing system produced US$ 892 and 2136 net returns, respectively with almost similar benefit cost ratio. It is evident from the study that inclusions of small ruminants in rainfed farming model both as intensive and semi-intensive systems can enhance the profitability of the family farm. The net return from the rainfed farming system was US$ 655 which can increase to US$ 892 and 2136 if small ruminants are included under intensive and semi-intensive systems, respectively. The net returns increased by 36 and 226% on inclusion of goat under intensive and semi-intensive rearing system, respectively in the water harvesting and agroforestry based rainfed farming system model.

The inclusion of goat, agroforestry (tree) and farm pond for rain water harvesting in the rainfed farming resulted in higher profitability and resilience to reduced rainfall and its aberrations. In the rainfed farming system model, no crop failure was observed due to the presence of the farm pond, where rain water was harvested and efficiently utilized, when needed, through a sprinkler system for irrigation of crops. Further, the resilience in net income was the highest (2136 US$ ha^{-1}) when goat rearing was included under semi-intensive system followed by intensive system.

The increased and assured production and profitability of the IFS model might be due to the positive interactions and synergies among its components. The proper resources and by-product recycling among various components under the IFS resulted in higher productivity and income. The components in IFS interact synergistically and the by-product or output of one component is used as input in another, which minimizes the external dependence and leads to higher productivity, income and resilience (Palsaniya et al. 2017). Panwar et al. (2018) reported that the perennial components and livestock provide risk proofing to the farmer as they are more stable and less prone to aberrant weather conditions than annual food crops. Other researchers also observed that greater synergies, positive interactions and proper resource recycling among the components of IFS were mainly responsible for enhanced productivity, income and resilience (Kumar et al. 2018; Palsaniya et al. 2022).

It can be concluded from the present study that intervention of water harvesting, agroforestry and goats in the rainfed farming systems could enhance farm productivity and profitability and impart resilience to the livelihood of farmers.

Table 2 Yield, barley equivalent yield (BEY) and economics under rain water harvesting and agroforestry based rainfed farming system (mean of 4 years)

Particulars	Component*	Yield (kg $plot^{-1}$)**	BEY (kg $plot^{-1}$)	Cost of production (US$)***	Gross returns (US$)	Net returns (US$)	B:C ratio
Food crops	Groundnut	240 ± 41 (325 ± 55)	718 ± 72	103	165	62	1.6
	Barley	1021 ± 47 (1496 ± 105)	1021 ± 91	114	298	184	2.6
	Sorghum	2314 ± 170	581 ± 59	55	123	68	2.2
	Chickpea	311 ± 30 (405 ± 67)	925 ± 86	86	218	132	2.5
Agrihorticulture	Indian jujube	200 ± 50	144 ± 36	22	15	-7	0.7
	Sesame	81 ± 6 (207 ± 33)	283 ± 45	35	66	32	1.9
	Chickpea	179 ± 29 (308 ± 74)	532 ± 53	66	178	112	2.7
Silvipasture	TSH grass (GFY)	2051 ± 402	129 ± 27	13	32	19	2.5
	Leucaena (LM)	203 ± 51	204 ± 48	12	39	27	3.3
	Stylosanthes (GFY)	2233 ± 126	180 ± 31	10	39	29	3.9
Boundary plantation	Cactus +	1600 ± 300	115 ± 20	6	25	19	4.2
	Leucaena +	110 ± 17	111 ± 17	10	30	20	2.9
	Grewia	5 ± 1	38 ± 4	4	16	12	4.1
Farm pond	-	-	-	53	-	-	-
Total (1 ha)	-	-	4979	589	1244	655	2.1

*Where TSH, GFY and LM are tri-species hybrid, green fodder yield and leaf meal, respectively.
**Figures in the parenthesis are by-product of the crop and the value after ± is SE.
***The currency mean exchange value: 1 US $ = 65 Indian Rupee (₹)

Table 3 Goat carrying capacity and economic potential of the rainfed farming system model under intensive and semi-intensive rearing systems

Particulars	Goat rearing system	
	Intensive	Semi-intensive
Carrying capacity		
DM availability from model (kg ha^{-1})	3150	3150
DM required for 1 growing goat (15-38 kg body weight) (kg year^{-1})	350	90
Carrying capacity of model (goat ha^{-1})	9	35
Initial investment (US $)		
Animal shed	218	341
Fencing	49	58
Equipment	16	40
Electricity and water tank installation	10	21
Total initial investment	294	459
Interest on investment (@ 7%/annum) – A	21	32
Junk value	77	108
Length of useful life (years)	25	25
Yearly depreciation – B	9	14
Amortization cost – C	12	18
Yearly fixed cost due to initial investment (A+B+C) – D	41	65
Variable cost (US $)		
Animal cost	388	1508
Feed and fodder (from model)	589	589
Labour	267	842
Veterinary care	21	32
Miscellaneous expenses	29	55
Total variable cost – E	1293	3026
Total cost (D + E)	1334	3090
Returns (US $)		
Meat	1740	4560
Skin	35	135

Manure	75	179
Return from sale of non-edible produce from model	377	352
Gross returns	2226	5226
Net returns	892	2136
B:C ratio	1.66	1.69
Net return $goat^{-1}$	99	61

Decimal values are rounded to its nearer value; 1 US $ = 65 Indian Rupee

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Pasture Monitoring in the Southern Rangelands of NSW

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Key words: pasture; monitoring; grazing management; livestock production.

Abstract

The Producer Demonstration Site: Pasture Monitoring in the Rangelands, initiated in 2022, showcases the productivity benefits of routine monitoring and targeted management of key pastures species in the southern rangelands of NSW. Utilising a combination of on-ground monitoring and remote sensing data, the project tracks pasture production and groundcover percentages at four producer sites across 237,747 hectares in the Oxley and Booligal areas.

Critical decision points in February and August align with pasture supply and demand for these regions, influencing management decisions such as feed supplementation, destocking determinations, and weaning. Therefore, biannual observations and pasture samples of four key pasture species are taken in late summer and late winter at each site. Pasture samples are collected to analyse the crude protein, digestibility and metabolisable energy through feed test data results. Remote sensing tools, Geoglam RaPP Map and Cibo Labs, are used to measure groundcover and green cover at each observation point. Core producers meet twice each year to discuss their sites and share management learnings.

In the project's second year, notable findings include consistent composition of nutritional plants during autumn and winter across two monitoring sites. On other sites, shifts in plant quality were attributed to seasonal availability rather than nutritional changes. The key contributing plants of higher quality in August 2023 included Burr Medic (*Medicago polymorpha*), Barley Grass (*Hordeum leporinum*) and Bladder Saltbush (*Atriplex vesicaria*). Noting that although these species may represent the greatest nutritional value and availability within a paddock, grazing preferences of sheep/cattle (Graetz and Wilson 1980) mean these species might not contribute the largest portion of the livestock's diet in all cases.

The project will continue to track feed quality and its impact on livestock production in western NSW, further demonstrating the efficacy of proactive monitoring and tactical management practices in enhancing rangeland productivity.

Introduction

Managing productive and palatable plants in the pastoral system in alignment with livestock production requirements and sustainable land management is a constant undertaking for rangeland producers. Rainfall has been noted as one of the largest contributors to pasture and soil health in the Western Riverina district (Eldridge and Stafford 1999; Eldridge and Grant 2004). Considerable biomass and vegetation cover declines were recorded between 1990 – 2003 in the Saltbush range-type where seasonality was a larger driver of pasture growth than annual rainfall totals (Eldridge and Grant 2004). Declines in effective rainfall and the deterioration of pasture were linked to a reduction in pastoral productivity through reduced stocking rates (Eldridge and Stafford 1999; Eldridge and Grant 2004). This is reflective of a reduction in the perennial feedbase composition (Eldridge and Grant 2004) and a greater reliance on annual species and opportunistic rainfall to provide short term productivity benefits. As seasonal rainfall irregularity increases, managing a productive livestock enterprise conducive to maintaining and recruiting supporting perennial species will prove more difficult for producers.

The Pasture Monitoring in the Rangelands project seeks to demonstrate that livestock businesses in the southern rangelands of NSW can enhance productivity by implementing routine pasture monitoring and targeted management of key pasture species. Seasonal monitoring is conducted across four producer sites to collect locally relevant data, which permits producers to make informed and timely production decisions aligned to grazing strategies, supplementary feeding, and stocking rates. The project also facilitates peer-to-peer knowledge exchange within the producer group, where participants collaborate and share insights to improve their grazing management practices. This enables producers to combine personal experience with new tools and information to make more informed choices. The project aims to enhance producers' ability to track pasture health, species composition, and feed quality by integrating monitoring tools, including remote sensing, feed testing, and on ground assessments. Participation in the project is designed to deliver long-term improvements in pasture resilience, boost productivity in rangeland livestock businesses, and promote sustainable grazing practices that can adapt to the challenges of the region's variable climate.

Methods

Pasture Monitoring in the Rangelands commenced in 2022 as an approach to continue the site monitoring, pasture sampling and producer engagement established in the initial intakes of the Improving Tactical Decision Making (ITDM) program. The ITDM program is based on tactical management principles (Campbell and Hacker 2000) which continue to be utilised in this project to guide the methodology.

The project emphasises data-driven decision-making by combining on-ground and remote sensor monitoring. Pasture metrics, including species present, groundcover, and grazing strategies, are tracked with seasonal observations. Utilising property trigger points (Hacker et al. 2006) alongside participant producer consultation, two monitoring periods were identified for February and August, aligned to significant decision-making stages in producer management cycles. Site observations, including photo and step point assessments (Campbell and Hacker 2000), and pasture samples of four contributing pasture species are conducted biannually at each monitoring site. Feed quality is assessed primarily through crude protein (CP %), dry matter digestibility (DMD %) and metabolisable energy (MJ/kg DM) laboratory analyses. Scanning percentages, weaning rates and stock sale numbers will be incorporated into the decision-making process. Remote sensing tools, Geoglam RaPP Map and Cibo Labs, are used to collect complementary biomass, green cover and groundcover data for each monitoring period.

Following each data collection, the producer group is brought together to discuss the monitoring results, seasonal conditions, reflections on production system changes and to review concepts of the ITDM. Group meetings are held online and on-property enabling producers to share ideas, experience and practices with neighbouring businesses guided by data collected directly from their paddocks.

Data collection and producer engagement is still on-going with completion projected for early 2027, therefore, only preliminary results will be presented in this paper.

Results

Step Points

Shifts in groundcover were observed at all sites over the monitoring period to date; Sites A and D declined in groundcover in summer contrasting Sites B and C that increased in cover (Figure 1). Notably, three of the four sites have a greater level of groundcover than at the first measurement.

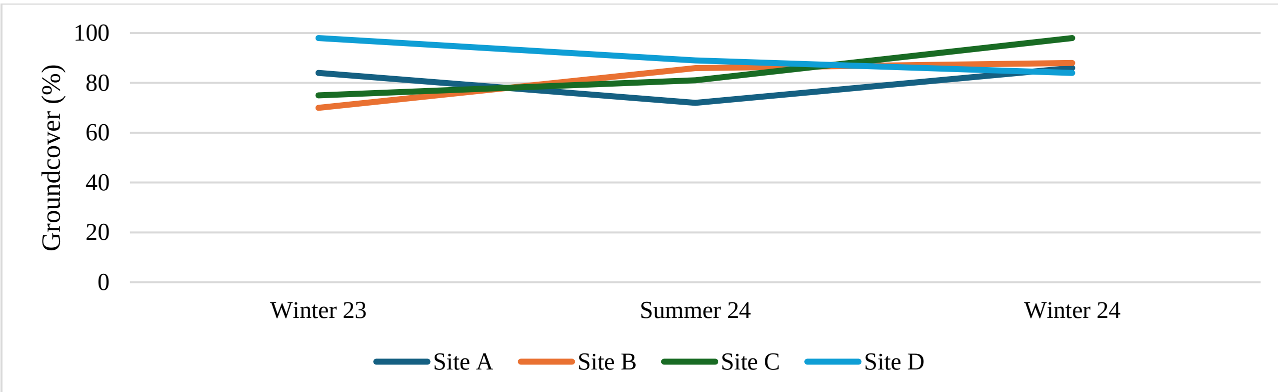

Figure 1. Percentage (%) of groundcover recorded via step point assessment at each monitoring site in Winter 2023, Summer 2024 and Winter 2023. Step point groundcover assessments were undertaken biannually at each monitoring site apart from winter 2022 and summer 2023.

Pasture Sampling

Since the inception of the project, feed testing has occurred biannually with the exception of autumn 2022 at two sites and summer 2023. Demonstrated in the site D results, species availability has changed in all sites across the course of sampling (Figure 2). *Atriplex vesicaria* and *Sclerolaena brachyptera* have consistently been available at site D. Notably at this site, *Atriplex vesicaria* is relatively stable in nutritional value, especially from winter 2023 to winter 2024 (14.6-16.3 CP%, 57-57.5 DMD %, 8.2-8.3 MJ/kg DM) but is nutritionally surpassed by more productive annual plants in winter such as *Sporobolus caroli* (8.9 CP%, 61 DMD%, 8.6 MJ/kg DM) and *Medicago polymorpha* (32.2 CP%, 84.8 DMD%, 12.6 MJ/kg DM)

Photo Points

Permanent photo points have been established at all sites to record the site condition during observational periods. Photographs were taken biannually at each monitoring site with exception of summer 2023. These images provide valuable visual comparison between seasonal conditions and corresponding feed quality data. Comparing site condition through photographs taken in this manner, as demonstrated in the site D photo point, further assists producers in understanding the changes in the timing of effective rainfall, grazing effects and progress of the site towards the grazing management objective (Figure 3).

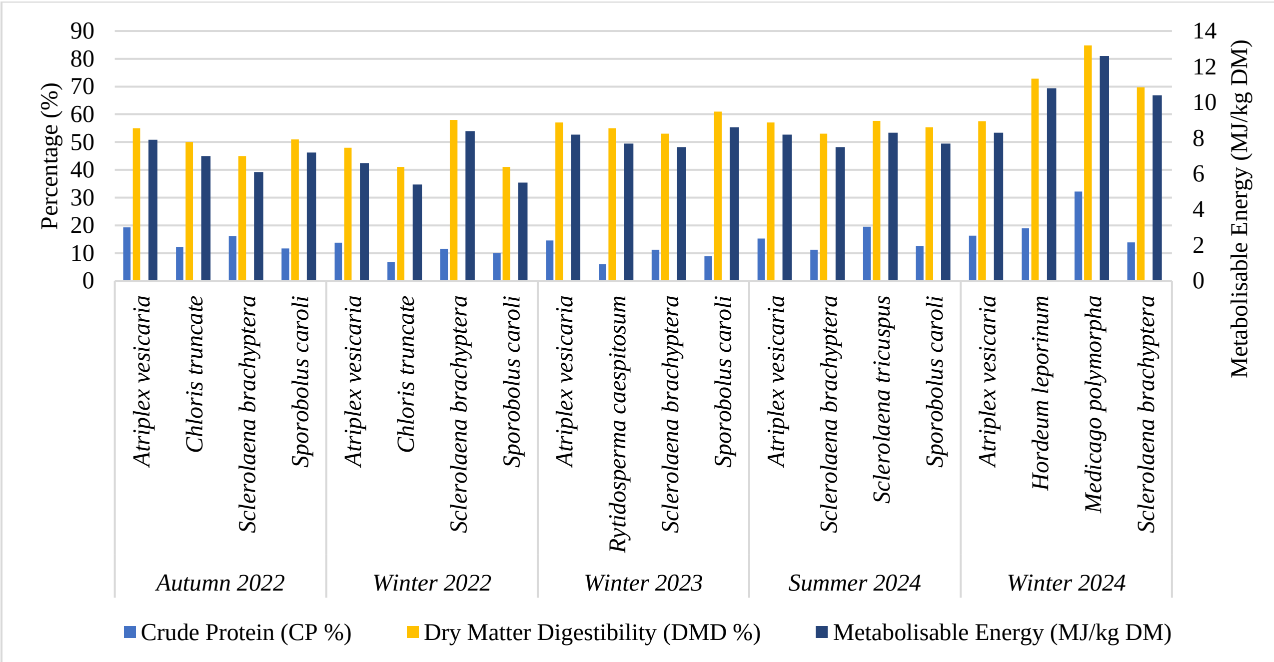

Figure 2. Feed test results summary of monitoring site D (Booligal, NSW) key pasture species at five different sampling periods throughout the project.

Figure 3. Photographs demonstrating the difference in site condition in the same season in different years. The photographs were taken at a permanent photo point at monitoring site D (Booligal, NSW) in August 2023 (left) and August 2024 (right).

Discussion

The pasture sampling process has been impacted by several factors. Sampling where sites were actively utilised by livestock or had recently been destocked resulted in preferred key species unable to be sampled on occasion due to risk of plant defoliation, biomass/height restrictions and lack of individual plants. Furthermore, staff changes early in the project, regional flooding in late 2022 to mid 2023, and shifting producer involvement have all impacted data collection, though these factors are not anticipated to significantly altered the overall findings.

Significant rainfall variability has occurred during the project. Dry winter conditions in 2023, followed by a wet summer did not directly affect the nutritional value of pasture or the feedbase composition. The largest changes were arguably when composition shifted prior to the August 2024 observation period, initiating the growth of annual grasses and forbs, a noted characteristic of effective cool season rainfall in the southern rangelands (Hacker and McDonald 2021). This is consistent with previous findings in the Western Riverina, where seasonal variability played a large role in vegetation growth and rangeland productivity (Eldridge and Grant 2004).

While the pasture species sampled generally offer high nutritional value, the selective grazing habits of sheep and cattle make it challenging to accurately assess diet composition. For instance, *Atriplex vesicaria*, although typically of high quality, was not observed to have been consistently chosen by sheep grazing at the monitoring sites. This aligns with previous findings in the district where shrub species, despite their potential nutritional value, are not commonly preferentially grazed by livestock initially (Graetz and Wilson 1980). Notably, perennial saltbushes appeared to be relatively unaffected by grazing pressure during monitoring, in contrast to annual forbs and grasses, which were more heavily utilised.

Group meetings provide producers an opportunity to discuss their own experience in relation to local literature and the alignment with the monitoring results of this project. Incorporating tools, such as Geoglam Rapp Map and Cibo Labs, into the meetings assists producers to correlate on-ground measurements with previous events and seasonal conditions. Therefore, several knowledge sources and tools are brought together to enable data-driven decisions to be undertaken for rangeland businesses.

Conclusion

Fluctuations in effective rainfall and pasture health have direct implications for pastoral productivity (Eldridge and Stafford 1999). As such, maintaining a sustainable feedbase amidst increasing seasonal variability requires tactical management strategies that account for short-term climatic changes and long-term ecological shifts. The Pasture Monitoring in the Rangelands project aims to demonstrate the role of data-driven decision-making and producer engagement in enhancing the resilience and productivity of livestock enterprises in the southern rangelands of NSW.

Acknowledgements

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The dynamic of Montado ecosystem

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Key words: Pastures; forages; multi-species; biodiversity; management.

Abstract
Agro-Silvo-Pastoralism integrates the knowledge and research of Agronomy, Forest and Extensive Animal Production systems where the soil is the common main factor and looks for application of new technologies on farming systems integrated as a multifunctional way. To improve soil capacity in Mediterranean environments the most efficient process is the improvement of Mediterranean Permanent Pastures and how higher the quantitative and qualitative production of pasture increase the level of Organic Matter in soil and the stocking rate. Also the increase of stock of water in the soil allows the enlargement of the annual cycle in pasture self reseeding plants which means higher biomass production. At some level of soil potential capacity the existence of perennial plants with summer dormancy becomes possible. This means the anticipation of the autumnal start of annual cycle of growth in pasture and decrease of forage supplementation according to the Feeding Scheme of Extensive Animal Production systems. The increase of stocking rates delay the regrowth of shrubs which means the enlargement of Montado Crop Rotation by the increase in variable n (years of pasture). This has positive effect on natural regrowth of tree component because of lower animal pressure and in the balance on vegetal stratus (*arboreus*, *arbustive* and *herbaceous*) with high levels of general biodiversity (animal, vegetal and microbioma). So, increasing the level of bioma in soil which has positive impact on the availability of nutrients and water for plants making easier the sanitary control of vegetal component and increase the general productivity of the whole system. The model of management and multifunctionality can be found in the project of conversion of Mediterranean forest in agro-silvo-pastoral system Montado by Potes et al (2021).

Introduction
Since the VI IRC in Townsville, Queensland, Australia 1999, the Montado ecosystem has been presented as an agro-silvo-pastoral ecosystem with a typical landscape which characterizes the Mediterranean region of Portugal in the Iberian Peninsula. It was built by Man and preserved among centuries by the control of shrubs and usage of natural resources within extensive farming systems. The extensive animal production systems evolved are based on pastures and forest by-products but need to be complemented with forage production and other supplements in order to adapt to semiarid environments to obtain high quality products.

Potes et al, (2021) presented the conversion of the Mediterranean Forest into a Montado ecosystem by the management of the Mediterranean environment focused on the recovery and preservation of the soil. As poor soils are generally dominant in these environments the increase of its potential productivity is essential for the development of distinct phases of the process that characterize the success of a working and balanced ecosystem.

The objective of this paper is to point out the correspondence of several papers submitted to International Congress's in the last twenty years concerning the different phases of implementation of the Montado ecosystem and show the dynamic of the management to achieve technical, environmental and economic sustainability.

Methods

The methodology used for the implementation and management of the Montado ecosystem it is the Agriculture of Conservation or Conservation Farming System which means the focus on the recovery or improvement of the soil. If the soil is considered the common base of any natural system of production in agronomy, animal husbandry or forestry, in the case of Mediterranean environments it is more important because of the level of degradation caused by human activity over plus the natural decrease in the potential productivity of the soil. So Conservation Farming consists in absence of mobilization of the soil, diversification of the rotational annual crops and the residues of crops remaining on the soil.

Results and Discussion

The first approach and identification of the physical and environmental characteristics of the farm is essential to establish the plan of the intervention regarding the stud of the status of the soil, the balance between vegetal stratus and infrastructures for animal and grazing management.

Looking for technical procedures Potes & Babo (2003) proposed the Montado Crop Rotation for combining operations as the mechanical control of shrubs (if necessary), forage crop and pasture improvement process. The implementation of the rotational interventions must be done in an appropriate plan of individualized parcels with easier access, water supply and surface according the level of stocking rates. This means the facility in animal and crops management and very importantly, the dilution on infrastructural investments along the cycle of the rotation. Such process of management is identified as multifunctionality.

The pasture improvement process was presented by Potes et al (2005) focusing on the importance of liming and P fertilisers to adapt the soil conditions to a balanced botanical composition of the flora which favours the increase of annual legumes of self reseeding. This botanical Family is the principal responsible for the increase of N in the soil with direct impact on the increment of levels of pasture biomass. The control and balance of the flora is highly dependent on the grazing management and is only possible with the adequate infrastructural plan of parcels or paddocks. How long the years of permanent pastures (n) decrease animal pressure and increase the regrowth of *arboreus* stratus mainly composed by *quercineas*.

The efficiency of the animal production systems adapted to the Montado ecosystem depends on the contribution of all natural resources for animal feeding and looking to minimize the outsourcing of the system. This is the base of extensive grazing systems which was presented by Potes (2008) as the Feeding Scheme of Extensive Animal Production Systems in the Montado. It shows the contribution of all vegetal stratus for the feeding supply and the irregularity of sources between each season of the year with impact on the different preferences that each animal species reveal for distinct products. The supplements of crop forage are the highest inputs of the scheme and can be reduced or decreased as the total natural biomass of the ecosystem increases and deeply adjusted to the stocking rate.

When the technical procedures are implemented and the dynamism of the process is guaranteed by the results the cycle of the Montado Rotation is closed and it can be possible to start de evaluation of environmental conditions or acquisitions. Potes (2011) discussed the effect of the proposed technical management of the ecosystem in the increase of level of Organic Mater (OM) in soil content and the positive impact of it in the structural and nutritional values. The consequence is the increment of level of water stocked in the soil which combined with more disponible nutrients for plants results in the increase of vegetal biomass. The cycle of water movement within the soil benefits from the distinct distribution of roots system of different stratus of plants (*arboreus*, *arbustive* and *herbaceous*) and the increase of OM in the soil and biomass of plants reveals the increase of sequestration of C in soil which is a relevant environmental service delivered by the ecosystem. The fire prevention becomes as a natural consequence of the control of shrubs (the combustible for fire) by the mosaic disposal of forest parcels (*arboreus* stratus) which represents the main goal for the balance of flora and it's also an important environmental service. Finally the high levels of biodiversity are an instrument for managing the ecosystem because permanent pastures in Mediterranean environments are characterized by high numbers of species from annual plants of self reseeding reproduction which can increase with the longing cycle as consequence of availability of water in the soil. The improved conditions of the soil at some level can even increase the biodiversity of herbaceous flora by the appearance of perennial plants with summer dormancy. The improvement of soil means the increase of bioma in the soil for humification process so micro biota increase of biodiversity is needed for the chemical formation of the soil exchange complex. Concerning the biodiversity of the animal kingdom the use of all domestic species is required because of their distinct characteristics in grazing behaviour and combines with the variable presence of wild animals, reptiles, birds and insects which results in a high level of general biodiversity. In fact it is recognized as a high spot in terms of the world biodiversity.

The Montado ecosystem is a farming system allocated in a low productivity region recognised as extensive system of agriculture and so the economic balance is very hard to achieve if only based in the high quality products it offers to the global market. Potes (2016) presented the environmental acquisitions of the adequate management of the ecosystem with positive impact in soil, water, air, fire and biodiversity as environmental services provided to the society. This is the justification for the High Natural Value (HNV) of the Montado ecosystem. More important is the balance or reduction in sanitary problems in the whole system and so it must be evaluated and valuing looking for a proper payment. Until this mechanism is not offered to the farmers the economic sustainability of the ecosystem was presented as a result of conversion of Mediterranean Forest in the Montado ecosystem (Potes et al. 2021) and can be improved when the HNV would be properly recognized and payee. However the dynamic in positive sense described can be easily reverted by the human abandon that means the natural return to Mediterranean Forest.

Conclusions

The Montado ecosystem is a very successful and dynamic achievement of the human management and conversion of the Mediterranean Forest into an agro-silvo-pastoral system. Its HNV is justified for the technical, environmental and economic sustainability.

The dynamism of the process reveals its own fragilities and economic resilience.

Looking for valorisation of extensively (Potes et al, 2024) and environmental services payment it will be necessary for increase economic sustainability and present Montado ecosystem as a model of modern agriculture.

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Bacterial infections in Tamil Nadu's free-range Indigenous cattle: Insight into AYUSH treatments

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Key Words: Indian system of Medicine; Siddha, AYUSH; Bacterial infections; Livestock health.

India takes pride in home a large livestock population, with Tamil Nadu alone housing approximately 9.5 million free-range cattle. These cattle are vital for rural livelihoods as they provide natural fertilizer, meat, milk, and even play a role in traditional Tamil bull fighting. However, due to climate change and polluted grazing lands, these animals are at risk of diseases like brucella, anthrax, pneumonia etc. Our study focused on 736, "**Pullikulam**", indigenous cattle breed known for their disease resistance. We found that during winter (June-February), 2.3% of the animals contracted tuberculosis and pneumonia by grazing in shrub jungle. In summer (March-May), 1.08% suffered from diseases caused by organisms such as *Clostridium*, *E. coli*, and Mastitis during grazing in post-harvest wet lands, diagnosed through immunological methods. These herd illnesses not only impact animal health but also cause financial hardship for marginal farmers, with an average daily revenue loss of $125 in our study group. Limited access to veterinary hospitals due to transportation and treatment costs is a major challenge. Indian system of medicine AYUSH (Ayurveda, Yoga, Unani, Siddha and Homeopathy) offers a promising solution. India's rich botanical diversity provides a natural wealth of resources for animal healthcare. For centuries, farmers have relied upon plant-based AYUSH remedies to treat animal diseases. In our study, five different Siddha formulations are administered orally with bananas to symptomatic animals for 21 days which subsequently relieved of infections. These treatments promise to be safe and effective. Additionally, traditional knowledge empowers farmers to develop new herbal formulations for animal health management. This research paves the way for developing eco-friendly and cost-effective veterinary medicines based on AYUSH principles. It highlights the vulnerability of free-range cattle to diseases and the potential of AYUSH treatments as a solution. Furthermore, it underscores the valuable role of indigenous knowledge in preserving traditional veterinary practices

Introduction

India boasts a substantial livestock population, with Tamil Nadu alone has about approximately 9.5 million free-range cattle. These animals are integral to rural livelihoods, providing natural fertilizer, meat, milk, and playing a significant role in traditional Tamil bullfighting. Despite the importance of livestock, many small and marginal farmers face challenges in affording modern veterinary care due to limited income and access to resources. As a result, they often turn to traditional Siddha medicine-AYUSH (Ayurveda, Yoga, Unani, Siddha and Homeopathy) a system of healing with a history spanning over 5,000 years (Shankar, 2016; Ponnulekshmi & Rabinarayan, 2024)

This study develops into the traditional Siddha medicine (AYUSH) and ethno-botanical practices employed to manage bacterial infections in free-range cattle. The primary objective is to document this valuable indigenous knowledge, particularly concerning the seasonal nature of these bacterial infections.

Methods

Area & Period of study: Tamil Nadu State is a tropical region situated at the south eastern extremity of the Indian peninsula. It lies between 8.5° and 13.35° North latitude and 76.15° and 80.20° East longitude. (fig.1) The study was conducted in the Madurai district of Tamil Nadu state, India during March 2023 to July 2023 (Summer season) and October 2023 to February 2024 (Winter season).

Fig1: Tamil Nadu State showing Madurai District

Study Analysis: A seasonal analysis was conducted for five diseases namely Mycobacterial infection, Pneumonia, Clostridial infection, Escherichia infection, and Mastitis, specifically targeting the indigenous disease-resistant Pullikulam cattle breed. Symptomatic animals were diagnosed by analyzing blood and milk samples using commercially available rapid immuno-diagnostic kits based on antigen-antibody agglutination assay for each type of infection.

Siddha (AYUSH) Formulations: Five different Siddha formulations (AYUSH) were used to treat bacterial infections. These formulations were administered orally to animals exhibiting symptoms such as fever, shivering, diarrhea, swollen udder, cough, mucus and phlegm secretion, and joint edema. (Table.1 and 2)

Monitoring and Evaluation: Animal samples were collected periodically (0, 7, 14, and 21 days) before and during treatment. Rapid immuno-diagnostic kits based on antigen-antibody agglutination assay for each type of infection were performed using the slide method and staining to assess the disease and treatment's efficacy. The provided formulations are commonly used by marginal farmers in the region from their traditional knowledge and found to be effective for reducing the symptoms. Hence our study focused for scientific validation through immunodiagnostic Tests.

Table-1: Name of the plants used in Siddha - AYUSH formulation

Botanical Name	Tamil Name	Common Name	Toxicity as per Siddha
Pergularia daemia (Forssk.) Chiov.	Uthamani	Trellis vine	Safe
Aegle marmelos (L.) Correa	Vilvam	Bael, wood apple	Safe
Delonix elata (L.) Gamble	Vathanarayanan	Peacock flower	Safe
Azadirachta indica A. Juss.	Vembu	Neem	Non toxic
Capparis zeylanica L.	Athandai	Ceylon caper	Safe
Leucas aspera (Willd.) Link.	Thumbai	Thumbai	Safe
Zingiber officinale Roscoe	Inji, sukku	Ginger	Safe
Piper nigrum L.	Milagu	Black pepper	Safe
Piper longum L.	Thippili	Long pepper	Safe
Acorus calamus L.	Vasambu	Sweet flag	Some toxicity in fresh rhizome
Ferula foetida (Bunge) Regel	Perungayam	Asafoetida	Safe
Gossypium herbaceum L.	Paruthi	Levant cotton	Safe
Taxus baccata L.	Thalisapatri	Common yew	Safe
Allium cepa L.	Venkayam	Onion	Safe

Table-2: Formulation and Administration of drugs for Bacterial infection

S.No.	Bacterial Infection	Formulation	Method of Administration
1.	Escherichia Infection	juice of Pergularia daemia	Orally given with buttermilk and salt
2.	Mastitis	powder of Aegle marmelos, Delonix elata Azadirachta indica, Capparis zeylanica, and Leucas aspera leaves	Orally given with luke warm water or with banana
3.	Mycobacterial infection	mixture of Zingiber officinale, Piper nigrum, Acorus calamus, Piper longum, Ferula foetida, Azadirachta indica leaf juice, and Gossypium herbaceum fruit juice	Orally given as juice or with banana
4.	Pneumonia	mixture of Piper nigrum, Piper longum, and Taxus baccata	Given with ghee or with banana
5.	Clostridial infection	macerate of Allium cepa, Acorus calamus	Given with castor oil vinegar and salt or with banana

Results

Upon survey through marginal farmers, we found that during the monsoon and winter seasons i.e., October to February, cattle's (2.3%) were prone to tuberculosis and pneumonia while grazing in shrub jungles. As well during the period of summer from March to July the cattle's (1.08%) suffered from diseases such as *Clostridium*, *E. coli*, and mastitis while grazing in post-harvest lands. These diseases were diagnosed through immunological methods and staining. After one week of oral administration of the formulation, there was a significant reduction in symptoms, and the specific pathogen antigen level decreased in agglutination reactions in the immunodiagnostic tests. Mycobacterium found in sputum even after 21 days treatment.

A survey of marginal farmers revealed that during the monsoon and winter seasons (October to February), 2.3% of their cattle were susceptible to tuberculosis and pneumonia while grazing in shrub jungles. During the summer months (March to July), 1.08% of cattle suffered from diseases such as *Clostridium sp, E. coli*, and mastitis while grazing on post-harvest lands. The samples were collected in the morning hours between 6.00am to 7.00am The tests were carried out immediately when there is appearance of clinical signs of the cattle inspected in all the months. These diseases were diagnosed using immunological methods. Following one week of oral administration of the herbal formulation, a significant reduction in symptoms was observed. The specific pathogen antigen levels decreased in agglutination reactions during immunodiagnostic tests. However, *Mycobacterium sp* was still detected in sputum samples after 21 days of treatment. These findings have been tabulated. (Table.3).

Marginal farmers in Madurai district practice traditional Siddha veterinary treatments, and our results demonstrate the efficacy of herbal formulations in reducing the burden of cattle diseases. These Siddha herbal treatments significantly reduced the antigen load in both the blood and milk of the cattle. Based on our study, farmers concluded that these Siddha herbal formulations can be administered prophylactically to all cattle throughout the year to prevent the aforementioned diseases. The study results emphasize the effectiveness of Siddha herbal treatment and offer hope for marginal farmers.

These findings could serve as foundational research for pharmacological studies of Siddha formulations, potentially leading to alternatives to allopathic medications in livestock management. This study focuses on the use of traditional remedies for prompt animal care, as well as the associated social aspects.

Table-3: Slide Agglutination Test Results:

S. No	Types of Infection	Sample from infected animals	Number of Animals	Test Performed	Presence of Bacterial Antigens/ organisms/cattle antibodies			
					0 day	7th day	14th day	21th day
1	Escherichia *Infection*	Serum	17	*E coli* slide agglutination test kits	Positive-	Negative	Negative	Negative
2	Mastitis infection	Milk	17	Slide agglutination test kit/ staining	Positive-	Positive	Positive	Negative
3	Mycobacterium Infection	Milk & Sputum	8	Rapid slide agglutination kit /Staining	Positive-	Positive	Positive	Positive
4	Pneumonia infection	Serum	8	Slide agglutination kit	Positive-	Negative	Negative	Negative
5	Clostridium infection	Serum & Stool	17	Toxin agglutination kit	Positive-	Positive	Positive	Negative

Discussion

The information provided discusses about complete disease recovery for all the bacterial infections listed above after 21 days with both symptoms and antibody titers, except Mycobacterial infection which persist even after treatment. This suggests that the traditional formulation reduced symptoms in a readily observable way. Improved productivity was confirmed by the local farmers using simple inexpensive measurements such as i.e., body weight, fat cover, milk and fighting ability.

Modern veterinary and chemical interventions have improved livestock health and productivity, but they raise concerns about environmental impact, consumer health, and the preservation of indigenous breeds. In contrast, traditional methods, relying on natural remedies, apart from curing the diseases can enrich soil, maintain genetic diversity, and reduce the need for chemicals. Livestock raised traditionally may produce healthier products and support sustainable livelihoods, benefiting small farmers and local economies. However, traditional methods might not prevent major disease outbreaks or match the productivity of modern farming. The solution is a balanced approach that integrates both traditional and modern practices to maximize benefits and sustainability.

Conclusion

Traditional livestock health management in India presents a promising path for sustainable and ethical farming. By combining traditional knowledge with modern scientific methods, it's possible to create holistic approaches that benefit both farmers and consumers. Future research should focus on documenting and assessing the effectiveness of traditional practices, as well as exploring ways to integrate them into contemporary livestock management systems for improved sustainability.

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Proximate and phytochemical composition of hay made from three different pasture species (*P. pedicellatum, A. gayanus and C. biflorus*) in Yobe State, Nigeria

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Key words: Nutritive value, Forage, Sahel, Indigenous, Rangeland

Abstract

This study investigated the quality and phytochemical contents of three indigenous grass species for grazing animals in Yobe State a semi-arid region in the sahel, Nigeria. The pasture species *Pennisetum pedicellatum, Andropogon gayanus and Chloris biflorus* were harvested from grazing rangelands in the study area, measured and then analysed for determination of their nutritive quality and phytochemical content. Plants were harvested at bloom stage, sundried to 40% moisture level,shade-dried for ten days, milled into 2 mm particle size and stored in airtight polythene bags until analysis. Results obtained for nutrient composition revealed that *A. gayanus* had higher mean value for crude protein (10.62 g/100g) followed by *P. pedicellatum* (8.94 g/100g) then *C. biflorus* (6.81 g/100g). Nitrogen free extract was highest in *C. biflorus* (50.53 g/100g) and lowest in *A. gayanus* (36.70 g/100g). Phytochemical analysis showed that the concentration of flavonoids in *P. pedicellatum* (0.15 g/100g) was slightly higher than the respective values of 0.07 and 0.04 g/100g obtained in *A. gayanus* and *C. biflorus*. Similarly, *P. pedicellatum* (0.26 g/100g) had higher tannin level than both *A. gayanus* (0.04 g/100g) and *C. biflorus* (0.02 g/100g). The mean concentration of saponins in the three grass species was 0.09 g/100g (*A. gayanus*), 0.10 g/100g (*P. pedicellatum*) and 0.16 g/100g (*C. biflorus*) while that of alkaloids fell within the range of 0.14g/100g in *C. biflorus* and 0.25g/100g in *A. gayanus.* Based on the nutritive value and phytochemical content of the pasture species analyzed, it was concluded that *A.gayanus* could be best used to improve rangeland and livestock productivity in Yobe state, Nigeria.

Introduction

The pastoral system of livestock husbandry is characterized by transhumance and communal grazing. In addition, sedentary livestock rearers' also depend on forage grasses and legumes from range lands in order to meet the nutritional needs of their animals. In essence, most ruminant livestock owners depend on grazed and conserved forage as basic feed resource (Ayodele, 2022).

The main advantages of forage as feed resource are its low unit cost and high availability compared to other animal feed materials. Forage grasses and legumes provide all the nutrients required for maintenance, production and reproduction. However, the low level of animal production experienced, particularly, in the savannah zones of Nigeria, is generally associated with the inability to sufficiently supply high quality forage, especially during the dry season. This has been the main cause of southward migration of herdsmen and the seemingly unending cases of farmers-herder clashes, cattle rustling and banditry that have claimed several lives (Abdena, 2013).

Some of the most available and popularly used forage grasses in ruminant feeding in Northern Nigeria include *Pennisetum pedicellatum* (kyasuwa- Hausa), *Androgogon gayanus* (Gamba - Hausa), *Cenchrus biflorus* (karangiya - Hausa), *Chloris gayana* (kanarin doki - Hausa), *Digitaria horizontalis* (harkiya - Hausa), among others (Garba *et al.,* 2022). However, available data on their chemical composition in the Sahel to assess their nutritional value for animals and possible utilization in traditional medicine is scarce. *Pennisetum pedicellatum, C. biflorus* and *A. gayanus* are some of the most available and used grass pastures for ruminants feeding in the study area. Apart from nutritive value vis a vis the nutritional requirements of livestock, assessment of chemical composition of forages is also useful in the area of phytomedicine. Phytochemicals are plant-based bioactive compounds produced by plants for their protection.

The aim of this research work was to evaluate the proximate composition and some phytochemical profile of three grass species; *P. pedicellatum*, *A. gayanus,* and *C. biflorus* in Yobe State. Results obtained in this study will help animal scientists, pasture agronomists, extension agents and livestock farmers in making informed decisions on effective and optimal utilization of these forage species. It will also help compound ruminant feed millers and livestock farmers with intensive and semi-intensive ruminant production systems properly mix concentrates/supplements with chopped forage to balance rations to meet the nutrient requirements of their animals.

Methods

The study was conducted at Federal Polytechnic, Damaturu, Yobe State. The area is located within latitude 11^0 North and longitude 13.5^0 East. The state shares common boundaries with Borno to the East and South-East, Jigawa to the Northwest and Bauchi and Gombe states to the Southwest (NPC, 2006). The rainy season in Damaturu is short, scorching and starts from the month of June to September with its peak at August. Rainfall could be erratic, epileptic and ranges between 180 - 240mm with relative humidity of 75 % during the rainy season with a mean annual temperature of 28^0C. The vegetation is savannah grassland with grasses, sparse dwarf trees and shrubs. Cattle, sheep and goat are usually the most important animals grazing in the area by Fulani pastoralists (ACReSAL, 2023).

The study area was a natural rangeland and three (3) forage species of *P. pedicelatum, C. biflorus and A. gayanus* were harvested at bloom stage, shade-dried for 10 days, milled into 2 mm particle size and stored in polythene bags ready for laboratory analysis of proximate composition and phytochemistry. Laboratory analysis was done at the Federal Polytechnic, Damaturu, Yobe State using the procedure of AOAC (2005). Crude protein (CP), Crude fibre (CF) and Ether extract (EE) were analysed while Nitrogen Free Extract (NFE) was obtained by calculation using the following formula;

$$NFE\ \% = 100\% - (\%\ CP + \%\ EE + \%\ CF + \%\ Ash + \%\ moisture)$$

Test for alkaloids, tannins, saponins and flavonoids were conducted following the procedures of Sofowara, 1993.

All data obtained from laboratory analysis was analyzed for mean and standard deviation (Descriptive Statistics) using the SPSS v. 25 (SPSS, 2005).

Results and Discussion

Proximate composition of Pennisetum pedicellatum, Androgogon gayanus and Cenchrus biflorus

The results for proximate analysis of *P. pedicellatum*, *A. gayanus* and *C. biflorus* are presented in Table 1. Values for moisture content (g/100g sample) were 7.11 g for *A. gayanus,* 4.27 g for *P. pedicellatum,* and 3.65 g for *C. s biflorus*. Ash content ranged between 11.79 and 21.03 g in *A. gayanus* and *P. pedicellatum* respectively. Crude fibre level was highest in *A. gayanus* (31.23 g) followed by *P. pedicellatum* (21.03 g), then *C. biflorus* (16.42 g). The crude fibre content for *A. gayanus* obtained in this study is lower than 40.70 g/100g reported by Salah *et al.* (2014) and 34.32g/100g (Amada *et al.,* 2020). On the contrary, Rahman *et al.* (2020) reported a lower mean value (18.00 g/100g) for crude fibre in *P. pedicellatum* than obtained in the present study. Furthermore, the mean crude fibre value for *C. biflorus* obtained in this study is slightly lower than 20.80g/100g (Hassan *et al.,* 2018). These differences are probably attributable to the stage of growth at which the grass was harvested. Usually, plants harvested late in their growth cycle contain higher amount of crude fibre than those cut at earlier stage (Reference).

Ether extract was higher in *P. pedicellatum* (3.87 g) than in *A, gayanus* and *C. biflorus* which were identical (2.54 g). Values for crude protein were 10.62, 8.95, and 6.81 g for *A. gayanus, P. pedicellatum and C. biflorus,* respectively. These values are comparable with 9.81 g/100g for *P. pedicellatum* (Salah *et al.,* 2014), 2.60 – 19.0 g/100g for *A. gayanus* (Evitayani *et al.,* 2004) and 3.70 – 22.00 g/100g for *C. biflorus* (Ahmed *et al.,* 2003). Nitrogen free extract, ranged from 36.70 g to 50.53g and. was highest in *C. biflorus* and lowest in *A. gayanus*. However, the value for *A. gayanus* is comparable with 37.84g/100g reported by Salah *et al.* (2014).

Table 1: Proximate composition of selected pasture grass species in Yobe state, Nigeria.

	Grass specie			
Parameter (g/100g)	***A. gayanus***	***P. pedicellatum***	***C. biflorus***	**SD**
Moisture	7.11	4.27	3.65	0.07
Ash	11.79	21.03	16.42	0.02
Crude fibre	31.23	18.93	20.06	0.11
Ether extract	2.54	3.87	2.54	0.19
Crude protein	10.62	8.95	6.81	0.13
Nitrogen free extract	36.70	42.96	50.53	0.15

SD = Standard deviation

Phytochemical Contents of Pennisetum pedicellatum, Androgogon gayanus and Cenchrus biflorus

The results for Phytochemical analysis of *A. gayanus, P. pedicellatum*, and *C. biflorus* are presented in Table 2. Mean values for flavonoids were; *A. gayanus* (0.07 g), 0.15 g (P. *pedicellatum*) and 0.04 g (*C. biflorus*). The widespread distribution of flavonoids, their variety and their relatively low toxicity compared to other active plant compounds (for instance alkaloids) meant that many animals, including humans, could ingest significant quantities in their diet. Tannin content was higher in *P. pedicellatum* (0.26 g), followed by *A. gayanus* (0.04 g), then *C. biflorus* (0.02 g). This is much lower than 10.25 g/100g reported by FAO (2016) and Sulaiman *et al.* (2020) for *A. gayanus* and *P. pedicellatum* respectively. [Why the big difference?] Tannins can reduce feed intake when found in high concentration in feed. They also precipitate proteins in the gut, reducing their digestibility (Mavromichalis, 2020).

Saponin values were 0.09 g (*A. gayanus*), 0.10g (*P. pedicellatum*) and 0.16 g (*C. biflorus*). These values are lower than 0.85 g/100g for *P. pedicellatum* (Clayton *et al.,* 2006), 4.01 g/100g for *A. gayanus* (FAO, 2016) and Cirade *et al.,* (1991) for *C. biflorus.* Saponins are glycosides present in plants, the low concentration of saponin obtained in this study will ensure an effective transverse tubular system and sarcoplasmic reticulum. (Desai *et al*., 2009). Mean values for alkaloids ranged from 0.14 g (*C. biflorus*), to 0.25 g for *A. gayanus*. Grinkevich and Safronich (1983) stated that alkaloids content in plants is usually very low and varies in plant, depending on the tissue. Depending on the type of plant, the maximum concentration is mostly observed in the leaves. This study provides an insight into the concentration of phytochemicals in the three indigenous pasture grasses studied. At harvest, the levels were low, indicating that that species could be selected for healthy animal nutrition without any detrimental effect on livestock fertility (Butkute *et al*. 2018)

Table 2: Phytochemical contents of three pasture grass species form Yobe state, Nigeria.

	Grass specie		
Parameter (g/100g)	***A. gayanus***	***P. pedicellatum***	***C. biflorus***
Flavonoids	0.07	0.15	0.04
Tannins	0.04	0.26	0.02
Saponins	0.09	0.10	0.16
Alkaloids	0.25	0.20	0.14

Conclusion and Recommendation

Based on the results obtained in this study it was concluded that the three grass pasture species *P. pedicellatum, A. gayanus and Cenchrus biflorus* harvested at the bloom stage of growth or life cycle contain appreciable levels of nutrients and secondary metabolites as required by ruminant animals especially during periods of forage and feed scarcity. *Andropogon gayanus* had the highest crude protein content of the three species, followed by *P. pedicellatum. Andropogon gayanus* is therefore recommended for improving rangelands for livestock production in semi-arid rangelands of Yobe state, Nigeria.

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Growth performance and fiber quality of Chyangra goats in High-altitude Rangelands of Nepal

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Key words: Chyangra; goat selection; crop-livestock system; growth; high altitude; selection

Abstract

Chyangra goat is important in the crop-livestock farming system for poverty reduction, livelihood, and nutritional security for smallholder farmers at high altitudes in Nepal. These goats are mainly raised for meat, fiber, and as pack animals. The study primarily aims to assess the effect of non-genetic factors on the growth performance and quality of fiber of Chyangra goats in different rural municipalities of the Mustang district. Kagbeni village of lower Mustang; and Lomanthang and Charang village of upper Mustang were the sampling sites. Chyangra fiber length was measured using a measuring pad and ruler and fiber diameter was analyzed using the Optical Projection Microscope Method whereas weight of different age groups was measured using a digital weighing balance. The fixed effect model was used to analyze the least square mean for fiber length, diameter, and weight from different sexes, locations, and age groups. The overall least square mean and standard error for fiber diameter and fiber length were 15.4±0.7 µm and 44.2±0.2 mm respectively. In contrast, the body weight of 530 Chyangra for one, two, three, four and more than four years were 12.4, 18.7, 23.9, 26.3 and 20.0 kg respectively. Males were heavier than females in all age groups. The results exhibited a wide variation in growth performance and fiber quality parameters indicating the potentiality to improve Chyangra growth rates and fiber quality by adopting proper management and selection methods.

Introduction

Chyangra goats (*Capra hircus*), also known as Himalayan goat, occupies an important place in crop-livestock farming system for poverty reduction, livelihood, and nutritional security for smallholder farmers across Nepal. Goats can be used for production of meat, milk, manure, fiber (*Pashmina or Cashmere*), leather, and as a means of transportation in the mountainous region of Nepal. Demand for goat meat increases during religious festivals of Nepalese people and fetches good price during these periods (Joshi et al. 2018). Four indigenous breeds of goat in the country have been identified and characterized so far: Terai, Khari, Sinhal and Chyangra (Pokharel et al. 2012; Gorkhali et al. 2022). Chyangra goats is the dominant breed across northern trans-Himalayan regions from an altitude of 2500–5000 mean above sea level (masl) from east to west. Chyangra goat population is estimated to be around 1% of the total goat population, i.e. 0.15 million heads in Nepal (MoALD 2024). Though these goats are reared primarily for their high-quality fiber, they are also sought for their meat. Only a limited number of studies have been conducted to determine fiber quality, and the small sample sizes used in these studies constrain their validity and reliability (Bhattarai 2017). Hence, the present study aims to assess the growth performance of Chyangra goats and to assess the effect of non-genetic factors on the fiber quality of Chyangra goats (diameter and length) in different locations of Mustang district.

Methods

Data on growth performance, fiber quality, and production systems were collected from different locations of Mustang district: Lomangthang-5 and Charang (upper elevation) and Kagbeni (lower elevation). Upper Mustang has a trans-Himalayan climate, while lower Mustang has a sub-alpine to alpine climate. Mustang is generally cool and semi-arid, with low rainfall (250–400 mm). A detailed questionnaire and data sheet were used to assess the Chyangra goats' production system, weight, fiber, and livestock management, including nutrition, health, breeding, and housing. Goats were weighed using a digital scale, and age and sex were recorded.

Growth performance from 530 Chyangra goats of different age groups (up to one, two, three, four, and above four years) from two altitudes were measured. Similarly, thirty-eight goats from Upper Mustang and twenty two from Lower Mustang were sampled, with 30 males and 35 females. Fiber samples were collected from each goat and stored in separate Ziploc bags, with location, age, and sex recorded. The sampled animals were assumed unrelated and aged 1-4 years. Sampling took place in early spring (mid-March to mid-April) in 2022 and 2023, before the molting season. Fiber samples were collected using a special combing device, with 5 grams taken from each goat (Figure 1).

Figure 1. Comb, Combing, and collection of fiber and sampling

Statistical analysis of the production system data was conducted using SPSS version 23. To address the issue of disproportionate subclass numbers, growth performance and fiber quality were analyzed using the Least Squares and Maximum Likelihood Method proposed by Harvey (1990), based on the Henderson (1953) model. Mean comparisons were performed using Duncan's Multiple Range Test (Duncan 1955). The fixed effect model was applied to analyze the least square means for various non-genetic factors (location, sex, and age group) in relation to the growth performance and fiber quality of Chyangra goats. The model is outlined as follows:

$$Y_{ijk} = \mu + a_i + b_j + c_k + e_{ijkl}$$

Y_{ijkl}=body weight, fiber length, diameter, wax percentage; μ=overall mean; a_i=fixed effect of i^{th} location (i=Upper and Lower); b_j=fixed effect of j^{th}sex (j=male and female); c_k=fixed effect of k^{th} age(k=<1yr,2yr,3yr,4yr,>4yr); e_{ijkl}=random error

Results

Body weight of Chyangra goat

Among the 530 observations recorded the overall mean body weight was 20.3 kg, with animals from Lower Mustang being heavier. Males weighed more than females, and the highest weights were observed in the 37–48-month age group, followed by 25–36 and 13–24 months. Weights in the 13–24 month group were similar to those over 48 months, with the lowest weights in 4–12 month old animals (Table 1). Chyangra from Lower Mustang had higher weights. Males were heavier than females, showing sexual dimorphism. Body weight increased with age but declined after 48 months (see Table 1).

Table 1. Least Square Mean and Standard Error of Mean (SEM) of body weight (kg) of Chyangra goats from different locations of Mustang district

Factors		Number of observations	LSM±SE
Overall Mean		530	20.3±2.42
Location			P<0.05
	Upper	359	19.6±3.58
	Lower	171	20.9±3.40
Sex			P= <0.001
	Male	126	22.8±3.89
	Female	404	17.7±2.86
Age(months)			P= <0.001
	Up to 1 year	78	12.4±0.497[d]
	13 to 24	52	18.7±0.615[c]
	25 to 36	56	23.9±0.596[b]
	37 to 48	58	26.3±0.578[a]
	Above 48	286	20.0±0.383[c]
CV%			23.76

Fiber quality of Chyangra goat

The overall mean fiber length was found to be 44.2±0.2 mm. Significant differences in fiber length were observed between locations and sexes, with goats from Upper Mustang having longer fibers compared to those from Lower Mustang. However, no significant difference in fiber length was found with respect to age. The overall mean fiber diameter was observed to be 15.4±0.7 µm . There were no significant variations in fiber diameter by location, age, or sex across these regions. However, samples from Lower Mustang showed lower values compared to those from Upper Mustang.

Table 2. Least Square Mean and Standard Error of Means (LSM±SEM) for fiber diameter and length in different

			Fiber length(mm)	Fiber Diameter (µm)
Factors		n	LSM±SE	
Overall		60	44.2±0.2	15.4±0.7
Location			P <.001	NS
	Upper	38	45.2±0.10[a]	15.6±0.4
	Lower	22	41.1±0.10[b]	15.1±0.5
Sex			P<0.05	NS
	Male	35	44.6±0.06[a]	15.4±0.4
	Female	25	42.5±0.08[b]	15.5±0.5
Age (yrs)			NS	NS
	1	12	44.8±0.13	14.9±0.9
	2	12	43.2±0.20	15.9±0.8
	3	12	45.9±0.09	15.7±0.5
	4	12	44.8±0.12	14.9±0.7
	>4	12	44.6±0.11	15.5±0.7
CV (%)			14.5	09.3

n=total number of goats from which samples were taken, each sample were replicated 10 times for analysis. NS=Non-Significant, p=p value, LSD=least significant difference, different alphabet in superscription signifies significance

Discussion

Bhattacharya et al. (2004) reported similar weights in Ladakh for Changthangi goats (20.0 ± 2.1 kg for males and 18.7 ± 1.9 kg for females at 300 days) as in our present study. The findings align with studies by Pokharel et al. (2012) and Gorkhali et al. (2022). Fiber diameter and length vary based on the goat's breed, age, and sex, with genetics playing the primary role and environmental factors such as feeding, housing, and management contributing to these traits. Thinner diameter fibers are often genetically linked to shorter fiber length (McGregor 2003). The present study demonstrates that Chyangra cashmere fiber is of high quality, with a diameter ranging from 14 to 18 µm (Gorkhali et al. 2023) similar to the finest cashmere produced by Chinese and Mongolian goats (14.5-16.5 µm) (Gurkan et al. 2023). The fiber diameter of Chyangra aligns closely with that of cashmere goats from China, Mongolia, and Afghanistan, which have diameters of 15.1 µm, 15.5 µm, and 15.15 µm, respectively (Kerven & Shrestha 2024; Couchman & McGregor 1983). Fiber length is vital for producers, as longer fibers have high value and directly increase market price. Gorkhali et al. (2023) observed similar findings in Chyangra goats from Mustang. The average fiber length determines its suitability for worsted (spin long, fine fibers into smooth, strong yarn – 30 to 50 mm) or woolen systems (spin shorter, coarser fibers into a bulkier, softer yarn - < 30 mm), with fibers under 30 mm being unsuitable for worsted processing (Ryder 1987). Female goats typically have shorter fibers, likely due to differences in feeding practices (Khan et al. 2012). Nutrition is a key factor in fiber quality (Summer & Bigham 1993), supporting findings by Bhattacharya et al. (2004). Although earlier studies linked fiber length to age, sex, and reproduction (Tuncer 2018), this study found no age-related effects. Seasonal reductions in fiber growth may result from nutrient competition during pregnancy and lactation (Khan et al. 2012), though increased feed intake can mitigate these effects (Oddy & Annison 2000).

Conclusions and implications

Non-genetic factors, including location, sex, and age, significantly influence the fiber quality and growth performance of Chyangra goats. These findings suggest that targeted improvements can be achieved by implementing effective management strategies and selection practices within a flock. By focusing on these factors, farmers can optimize the rearing conditions and selectively breed goats with desirable traits, ultimately enhancing both fiber production and overall growth performance in Chyangra goats.

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Carbon balance analysis of a sown pasture in inland arid area, China

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Key words: Carbon footprint; Food equivalent unit; Grazing; Greenhouse gases

Abstract

Grazing grasslands cover approximately 26% of the Earth's ice-free land surface, making them an important component in maintaining the global carbon balance. Recent research has shown significant carbon losses in soils under intensive pastures, particularly in developing countries where livestock farming is a dominant land use. This study aims to evaluate the net ecosystem carbon balance (NECB) of cultivated grassland grazing sheep pasture in the arid inland region of Northwest China. Based on life cycle analysis of carbon balance in grassland production systems, we hypothesis that grazing systems have a higher carbon sink capacity than hay harvesting systems because of the coupling between grassland and livestock. The sown pasture of wheat and alfalfa-fescue mixture rotationally grazed by sheep was the carbon sink, whilst the harvested pasture was the carbon source (four years). The carbon emissions per food equivalent unit (a food production units calculated based on protein and energy content) in the grazing pasture was 78.84% lower than that of the hay pasture. In grazing annual pasture and perennial pastures, the carbon emissions from livestock, processing and allocation of forage products accounted for 3.95%, 96.05% and 2.01%, 97.99% of the whole carbon emissions, respectively. The carbon emissions from sown pasture, where hay is harvested, mainly came from fertilization, irrigation and the processing and transportation of forage products. Therefore, strategies of carbon mitigation should focus on the greenhouse gas emissions of livestock production in grazing systems, and the processing and circulation of fertilization, irrigation inputs, and forage products in hay-harvesting pasture.

Introduction

Grazing grasslands, which account for 26% of the Earth's land surface and possess a substantial carbon (C) content in soils (Steinfeld et al., 2006), play a crucial role in the global carbon balance. The conversion of grasslands to cropland typically leads to a significant depletion of soil carbon (Davidson and Ackerman, 1993), while establishing pastures on previously cultivated land results in an increase in soil carbon (Post and Kwon, 2000). However, there is limited knowledge regarding the carbon balance of intensively cultivated grassland pastures and the impact of different patterns of grassland use and types on soil carbon. Previous studies have reported varying outcomes including increases, decreases, or no changes (Conant et al., 2001; Wang et al., 2011; Viglizzo et al., 2019; Lorenz et al., 2018). Therefore, this study aims to assess the net ecosystem carbon balance (NECB) of sheep grazing pasture within arid inland regions of Northwest China.

Methods

This study was conducted at Linze Grassland Agriculture Trial Station of Lanzhou University, Linze County, Gansu Province, China. Annual mean precipitation is 121~~.5~~ mm, and annual mean evaporation potential is 2390 mm. An integrated production system for sown pastures and sheep grazing has been established in the experimental area, consisting of two types of grassland: annual pasture (GA) and mixed perennial pasture （GP）. Sheep are rotated between these two types of grasslands, with grazing intensity controlled based on the height of the grass (GS). Grazing begins when the height reaches 20 cm and stops at 8 cm. The experiment covers a total area of 6 ha per grass type with three repetitions each. Additionally, a control group (HS) was set up in each type of grassland(HA, HP) using a 10 m x 10 m fence to harvest hay after maturity.

The carbon balance of a grassland agro-ecosystem is the cumulative sum of the carbon balances across its four production layers (pre-plant production system, PPP; plant production system, PP; animal production system, AP); post-biology production system, PBP) or three interfaces (Interface between herbage and site-interface A, IA; Interface between grassland and livestock-interface B, IB; Interface between grassland livestock system and social and economic management-interface C,IC). The carbon balance of a production layer or interface of a grassland system can be determined according to four parts. Carbon input (CI) refers to fertilizers, machinery, seeds, animal power, manure and other substances imported from outside the grassland system, CO_2 absorption and assimilation by photosynthesis, CH_4 and N fixed by microbial activities, and carbon and nitrogen accumulation by dust fall and soil and water conservation. Carbon emission (CE), human and livestock consumption of grass and livestock products, including food, energy, animal power, daily necessities, manure, is reduced to GHG within a certain period of time. Carbon fixation (CF), herbage, livestock, excrement, exists in a storable form in the grass industry system for a certain period of time. Carbon output (CO) refers to the output of grass and livestock products, seeds, animal power, manure. The carbon balance of the grassland system is CBGAE=CI+CF-CE-CO. If CBGAE > 0, that is, CI+CF > CE+CO, the grassland system is a carbon sink, and vice versa. The carbon balance of a production layer or an interface is calculated in the same way, and the sum of their initial carbon amount and carbon balance is the current carbon amount.

Results

The grazing system (GS) exhibits a positive carbon balance (> 0), indicating its role as a carbon sink. Carbon emissions primarily arise from the greenhouse gas release by sheep in AP, as well as the greenhouse gas emissions during the PPP's production process and livestock product output. Within the animal production layer, 43% of carbon is returned to the grassland through excrement, while 57% is discharged into the environment. The PBPcontributes to carbon emissions mainly through greenhouse gas emissions during its production process and from processing and outputting livestock products. Annual grazing grasslands (GA) demonstrate a higher carbon balance compared to perennial grasslands (GP).

The hay production system (HS) acts as a carbon source with a negative carbon balance. This can be attributed to higher levels of carbon emission in the plant production layer (PP) due to fertilization and irrigation practices. As there are no livestock involved, the animal production layer maintains a neutral carbon balance of zero. Carbon emissions within this system predominantly stem from greenhouse gas emissions during post-biological production processes and from processing and outputting forage products. Additionally, labor and mechanical input requirements are greater in hay production systems compared to grazing systems. Lastly, perennial mowing pasture (HA) exhibit higher carbon balances than annual pasture (HP).

Discussion

Grassland reclamation is the most violent human activity factor affecting soil carbon storage in grassland. The reclamation process will destroy the dense root layer, expose the deep organic carbon in the soil to the air, and accelerate the soil respiration process (Feng et al., 2019). When grassland is reclaimed for farmland, 30%-50% of the original soil carbon pool is lost, and most of this loss is caused by soil respiration emission (Genxu et al.,2002;

Rees et al., 2005). In this study, the emission of annual sown grassland was higher than that of perennial sown grassland, mainly because annual sown grassland needed to be tilled and sowing every year. In this process, the organic carbon in the deep soil was exposed to the air, which accelerated the soil respiration process.

Grazing has different degrees of influence on grassland plants, litter and soil (Li et al., 2024). These factors are not only important factors affecting grassland soil respiration (Kamran et al., 2023; Wang et al., 2023), but also affect the effects of water and heat factors on soil respiration to a certain extent. So far, there are many researches on the effects of grazing on soil respiration at home and abroad, but the results are not consistent. Some studies have shown that grazing can significantly reduce soil respiration intensity (Cao et al., 2004; Li et al., 2024), also found that the vegetation and soil conditions under fenced grazing were superior to those of grazing land, but the impact of grazing on soil respiration was not obvious (Zhao et al., 2016). In addition, studies have found that light grazing can promote soil respiration, while intensive grazing can reduce soil respiration rate (Koncz et al., 2015). It can be seen that grazing is still one of the uncertainties in estimating grassland carbon budget. In this study, the carbon balance of the grazing system is greater than that of the hay harvesting system, which is a comprehensive calculation based on the perspective of the whole ecosystem. The calculation result of the soil respiration part is that the soil respiration carbon emission of the grazing system is small, that is, the grazing reduces the soil respiration intensity and soil respiration emission.

According to the carbon input and output analysis methods of four production layers and three interfaces of grassland agro-ecosystem, the carbon balance of grazing system is the carbon sink, and the carbon balance of harvesting hay system is the carbon source. The contribution rates of the carbon balance of the four production layers to the carbon balance of the grazing system were 0.1% (pre-plant production system, PPP), 84.6% (plant production system, PP), -0.5% (animal production system, AP) and -17.0% (post-biology production system, PBP). The contribution rates to the carbon balance of mowing and harvesting hay system were 0.1% (PPP), 49.7% (PP), 0.0% (AP) and -51.1% (PBP). The carbon emissions of animal production layer and post-biological production layer in grazing system and harvesting hay system accounted for 3.95% (AP), 96.05% (PBP), 0% (AP) and 100% (PBP) of the system carbon emissions, respectively. The carbon balance of the three interfaces contributed 84.7% (BIA), 49.8% (BIB), -0.5% (BIC), 0.0%(BIA), -17.0%(BIB) and -51.1% (BIC) to the carbon balance of the grazing system and the harvesting hay system. The carbon emissions from mowing and harvesting hay, derived from fertilizers, irrigation inputs, and processing and circulation of forage products, are about three times that of grazing systems. The emission reduction of grazing system should pay attention to the animal production layer to reduce greenhouse gas emissions from the range-livestock interface. The hay production system should pay attention to the post-biological production layer, and reduce the carbon emission and carbon output in the process of product processing and circulation from the interface of grass and livestock systems-human activities.

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Bio-economic potential of pastoralsilviculture land use system in north-western Himalayas

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Key words: Pastures; Carbon sequestration; Himalayas; Agroforestry; Sustainability

Abstract

The present investigation was carried out to quantify carbon stock and economic potential of the pastoralsilviculture system along altitudinal gradient in Indian north-western Himalayas during 2019-2021. The area was divided into four altitudinal ranges as per agro-ecological classification of the state viz., altitudinal ranges viz., zone-I (<1000 m amsl), zone-II (1000-1500 m amsl), zone-III (1500- 2500 m amsl) and zone-IV (> 2500 m amsl). Further, farmers practicing pastoralsilviculture system were divided into three farmer categories *viz.* marginal (less than 1 ha land area), small (1-2 ha land area) and semi-medium (2-4 ha land area) as per Government of Himachal Pradesh standards. The results revealed that the total biological productivity (aboveground+belowground) of the pastoralsilviculture system ranged between 24.90-43.24 Mg ha^{-1}, showing an increasing trend along altitude with zone-III having maximum total biomass production. The bio-economic potential of the pastoralsilviculture system was not found to be significantly affected by the farmer category. Soil carbon density was maximum (31.65 Mg ha^{-1}) at zone-I which was significantly at par with soil carbon density at zone-III (30.86 Mg ha^{-1}). Total carbon stock potential, comprising vegetation carbon and soil carbon, of the system was recorded maximum (52.48 Mg ha^{-1}) for Zone-III, while minimum (42.58 Mg ha^{-1}) for zone-IV. Economic potential of the pastoralsilviculture system in terms of output:input ratio was found maximum (3.73) in zone-III which was significantly at par with output:input ratio in zone-II (3.62) and minimum was recorded in zone-IV (3.05).

Introduction

Tree, crop and livestock are the three basis components of agroforestry. Rearing of livestock is an integral part of the rural livelihood in the western Himalayan region that helps in maintaining the sustainability of the farming system. Livestock being an inseparable component of agroforestry is not only helpful in maintaining sustainability of the system but also is an enterprise itself. Livestock to a certain extent depends for fodder on the common property resources which play an important role in providing round the year fodder to livestock through grazing (Pathania and Dev 2011). In the Himalayan region, there is a dynamic relationship between the livestock and common property resources such as forests, water resources and grazing land. The 1.5 million hectare of grasslands constituting around 33 per cent of the land utilization of Himachal Pradesh is suffering from low productivity (GoHP 2020) mainly attributed to the lack of management, overgrazing and weed infestations. This ultimately affects the productivity of the livestock mainly dependent on these natural resources because of dearth of nutritious green fodder along with dry fodder and concentrates (NITI 2018) and widening gap between the demand and supply of the green fodder. Further, under the climate change scenario the low biological productivity of the grasslands also pose challenges to adapt and mitigate the adverse climatic conditions. Integrating grasses with the tree component may address the challenge of biological productivity, dearth of quality fodder along with sustainable land management. Pasture-based land use systems may be the solution to the problems faced by livestock sector and can help in mitigation of the challenges posed by the climate change. Keeping in view the importance of pastures the present study was carried out for determining the bio-economic potential of the pastoralsilviculture system along altitudinal gradient in western Himalayan region.

Methods

The present study was conducted during 2020-2021 at Nauni, Solan (HP), India in Chamba district of Himachal Pradesh located in North-Western Himalayas. The study area was divided into four altitudinal zones representing the four agro-climatic zones found in the state Himachal Pradesh viz., zone-I (<1000 m amsl) (Z1), zone-II (1000-1500 m amsl) (Z2), zone-III (1500-2500 m amsl) (Z3) and zone-IV (>2500 m amsl) (Z4). The pastoralsilviculture system being practiced by the three farmers categories viz., marginal (<1 ha) (F1), small (1-2 ha) (F2) and medium (2-4 ha) (F3), in the study area were identified for the assessment of their bio-economic potential. For herbage and shrubs, destructive method of sampling was adopted by making the plots of standard size 1×1 m^2 and 5×5 m^2 respectively, while, for trees non-destructive method based on the regional volume equations (FSI 1996) was used with sampling in 0.1 ha plot. The method of aboveground biomass (AGB) estimation of trees was as follow:

Stem biomass (Mg ha^{-1}) = VOB x WD
Where, VOB = volume over bark (from volume equations)
WD = volume weighted average wood density

The AGB of a tree was calculated by formula:

AGB (Mg ha^{-1}) = Stem biomass (Mg ha^{-1}) x BEF
Where, BEF = biomass expansion factor

Belowground biomass (BGB) of a tree was calculated by multiplying its aboveground with a standard factor of 0.26 (Cairns et al. 1997). Biomass carbon stock was calculated by multiplying the biomass with the standard factor of 0.5 given by IPCC (IPCC 2003). Soil organic carbon (SOC) stock was calculated using formula given below:

SOC (Mg ha^{-1}) = Soil bulk density (gcm^{-3}) × soil depth (cm) × OC (%) × 100

Where, C: soil organic carbon density

OC: soil organic carbon percent expressed in decimal fraction

Aggregation of vegetation carbon stock along with SOC depicted the total carbon stock (TCS) potential of the system. The economic potential of the system was assessed by dividing outputs obtained from the system with inputs to manage the system and is expressed as output:input ratio (O:I). Inputs include cost per unit area for the establishment and maintenance of system components, labour, land rent and plant protection, while, outputs include the market value per unit area of the various products harvested from the pastoralsilviculture system such as grass, green fodder, fuelwood, small timber and fruit. The data on various parameters were subjected to two way ANOVA using SPSS software for analysis.

Results

Biological productivity of the pastoralsilviculture system

The results revealed that the AGB, BGB and total biomass (TB) were significantly affected by the altitudinal zones (Table 1) and interaction of altitude with farmer category (Table 2). However, no significant effect of the farmer category (Table 1) was found on biological productivity of the system. In case of altitudinal zones, AGB ranged between 19.79-34.72 Mg ha^{-1} with maximum biomass recorded at Z3 and minimum at Z1. BGB ranged between 5.11-8.52 Mg ha^{-1} with trend similar to that followed in AGB. TB, being combination of AGB and BGB, also followed the same trend and ranged between 24.90-43.24 Mg ha^{-1}. In case of interaction, AGB (37.34 Mg ha^{-1}), BGB (9.33 Mg ha^{-1}) and TB (46.66 Mg ha^{-1}) were recorded maximum for the combination Z3F1, while, minimum AGB (15.76 Mg ha^{-1}), BGB (4.05 Mg ha^{-1}) and TB (19.81 Mg ha^{-1}) were recorded for Z1F1.

Carbon stock potential of the pastoralsilviculture system

In case of SOC, altitudinal zones and interaction between the factors have shown significant variation with farmer category not having any significant contribution towards SOC (Table1 and Table 2). Maximum SOC was recorded at Z1 (31.65 Mg ha^{-1}) which was significantly at par with SOC at Z3 while, minimum SOC was recorded at Z4 (22.20 Mg ha^{-1}). In case of interaction, SOC was recorded maximum for Z1F2 (34.41 Mg ha^{-1}) significantly at par with Z1F3 and Z3F1 while, minimum was recorded for Z4F2 (19.91 Mg ha^{-1}) significantly at par with Z4F3. The higher soil organic carbon may be because of the lesser dependence on biomass as fuel, better decomposition as well as management of the system which results in the production of more biomass and its incorporation in the soil. The TCS of the system was found to be significantly affected by altitudinal zones, while, farmer category didn't affected TCS significantly. Z3 resulted in maximum (52.48 Mg ha^{-1}) storage of the carbon stock in pastoralsilviculture system, while, Z4 was found to have least (42.58 Mg ha^{-1}) carbon storage in the pastoralsilvilculture system which was significantly at par with carbon stock at Z1 and Z2. Considering interaction, TCS was recorded maximum (55.09 Mg ha^{-1}) for the Z3F1, while, minimum (38.51 Mg ha^{-1}) was recorded for Z1F1.

Economic potential of the system

Considering economic potential of the pastoralsilviculture system, only altitudinal zone was found to have significant effect on the O:I. The O:I of the system varied between 3.05-3.73 with maximum O:I recorded at Z3 which was significantly at par with O:I in Z2 while, minimum ratio was recorded in Z4 which was at par with Z1.

Table 1: Bio-economics of different farmer categories practicing pastoralsilviculture along altitude

Parameters / Factors	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	TB (Mg ha^{-1})	SOC (Mg ha^{-1})	TCS (Mg ha^{-1})	O:I
Z1	19.79	5.11	24.90	31.65	44.10	3.24
Z2	24.26	5.81	30.07	27.87	42.91	3.62
Z3	34.72	8.52	43.24	30.86	52.48	3.73
Z4	32.36	8.41	40.77	22.20	42.58	3.05
LSD ($p<0.05$)	3.00	0.76	3.76	2.13	2.92	0.22
F1	29.05	7.30	36.35	28.17	46.34	3.42
F2	28.23	7.01	35.24	27.82	45.44	3.33
F3	26.07	6.58	32.64	28.44	44.76	3.48
LSD ($p<0.05$)	NS	NS	NS	NS	NS	NS

Table 2: Interaction effect of altitude and farmer's category on bio-economic potential of pastoralsilviculture

Parameters / Factors	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	TB (Mg ha^{-1})	SOC (Mg ha^{-1})	TCS (Mg ha^{-1})	O:I
Z1F1	15.76	4.05	19.81	28.61	38.51	3.24
Z1F2	22.21	5.44	27.64	34.41	48.23	3.12
Z1F3	21.40	5.84	27.23	31.93	45.54	3.37
Z2F1	29.14	6.99	36.12	28.49	46.55	3.93
Z2F2	21.64	5.18	26.82	26.79	40.20	3.45
Z2F3	22.02	5.25	27.26	28.33	41.96	3.49
Z3F1	37.34	9.33	46.66	31.76	55.09	3.49
Z3F2	37.21	9.13	46.34	30.17	53.35	3.80
Z3F3	29.62	7.10	36.72	30.63	48.99	3.89
Z4F1	33.97	8.83	42.80	23.82	45.22	3.04
Z4F2	31.87	8.29	40.16	19.91	39.99	2.96
Z4F3	31.24	8.12	39.36	22.85	42.53	3.17
LSD ($P<0.05$)	5.20	1.32	6.52	3.68	5.06	NS

Discussion

Biomass production may be the result of physiographical features, compositional differences, age, density of trees, interaction, farmer preferences, needs as well as ecological conditions as reported by Gupta et al. 2017 and Kumar et al. 2021, along altitude in Himalayan region. At Z3, the perennial components were dominated by the mature tree species having higher biomass production such as *Cedrus deodara*, *Pinus wallichiana*, *Salix spp* etc. which may be the reason for the increased biomass production. Marginal farmers being subjected to the dearth of the land availability make intensive use of the available resources in order to fulfill various needs, which may result in the higher biological productivity under the influence of intensive land management as can be predicted from higher biomass production in Z3F1. Carbon stock of the system is the aggregation of the carbon stored in the biomass as well as in the soil. The biomass carbon is just the fraction of the biological productivity of the system so it is obvious that it will show variations similar to that recorded for the biomass production of the system. Reduced soil carbon stock along altitude may be because of intensive utilization of the litter as well as biomass (Goswami et al. 2017) for fulfilling the fodder and fuel requirements. Further, decrease in temperature along altitude may reduce the rate of decomposition which under the influence of steep slopes may cause movement of the organic matter to the lower regions. Although soil carbon stock was higher at lower elevations yet the broad contribution of the biomass to total carbon stock of the system resulted in maximum carbon stock at Z3. The higher carbon stock at Z3F1 may be the cumulative effect of the farming intensity with the composition as well as density of the perennials in the system as reported by Singh et al. 2018; Adhikari et al. 2020. Pasture based systems are remunerative from the perspective of marginal lands where farmers may get multiple products along with the prevention of land from degradation. However, higher economic potential of the pasture based land use systems can be availed by incorporating agriculture and horticulture components as reported by Tiwari et al. 2021.

Thus, it can be concluded that pastoralsilviculture is the prominent pasture-based land use system in the study area having highest bio-economic potential at zone-III. The system can serve as an important land management option to reclaim the degraded land areas as well as a viable option for the mitigation and adaptation to climate change.

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Natural farming -government mission policy and its implementation in different states of India

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Keywords: Natural farming, Government, Policy, UP-AGREES ,Uttar Pradesh, UP-DASP

Abstract:
Natinal Mission on Natural Farming aims at creating institutional capacities for documentation and dissemination of best practices to implement self sustainable self generating natural farming systems to cut down cost of cultivation ,resource conservation, healthy soils,environment and food. Cell have been created for effective implementation at state level and distrct level. Project Co-ordinator and Technical Co-ordinator at HQ unit is an implementating Government nodal agency to implement the schemes of diversified agriculture support project in Uttar Pradesh. Namami Gange mega project launched by Honrable P.M. of India in 2022-23. The article is based on scheme implemented in different 28 districts of Western Uttar Pradesh. Corresponding author is the Technical Coordinatior in Government of Uttar Pradesh, under Co-ordination Department, Lucknow,(U.P.). Trials were conducted under natural farming in Bareilly district. It is recorded that Lentil , Gram, Mustard perfomed better in yield q / ha followed by old variety of Rice and Wheat. Andhra Pradesh 5.92 lakh, Himachal Pradesh 1.53 lakh and Gujrat 2.0 lakh number of farmers, and 3.73, 3.56, 8.50 Village Panchayat and 2.68 lakh ha, 9192 ha, and 2.5 lakh ha area has been covered respectively under natural farming. Cost and yield under natural farming in comparision to oragnic and conventional farming is lower.The trials have been conducted in different locations because of standisation of subhash palekar's model of BPKP (ICAR-Report,2017-18).Uttar Pradesh has coverd 97460 ha area and 05 lakh farmers during last two years (Niti Ayog Report,2024-25).Project: Uttar Pradesh Agriculture Growth and Rural Enterprise Ecosystem Strengthening (AGREES) has been launched in 28 district of eastern Uttar Pradesh state .The Government of India has applied for financing in the amount about US$ 350 Million equivelent from World Bank toward the cost of the IPF Project.The project has included the components are-Productivity enhancement,commodity clusters,digital and financial ecosystems and project management ,learning and partenerships.Cow dung based bio-stimulant was prepared locally by fermenting with cow urine,jaggery and pulses flour about 400 kg for an acre of land applied to fields increased the microbial count in the soil,which supplies the plants with essential nutrients (Jivamrit).

Introduction:

Natural farming offers a solution to various problems, such as food insecurity, farmers' distress, and health problems arising due to pesticide and fertilizer residue in air, food and water, global warming, climate change and natural calamities. It provides opportunity to use homemade seeds, local cattle's dung, urine, local vegetation and agriculture produce based formulations for plant nutrition, crop protection from pests and stress thus reduces the cost of cultivation and dependence of the farmer on market. It also has the potential to generate employment, thereby stemming the migration of rural youth. Natural farming, as the name suggests, is the art, practice and, increasingly, the science of working with nature to achieve much more with less. Natural farming is a chemical-free alias traditional farming method. It is considered as agro-ecology based diversified farming system which integrates crops, trees and livestock with functional biodiversity. In India, Natural farming is promoted as Bharatiya Prakritik Krishi Paddhati Programme (BPKP) under centrally sponsored scheme- Paramparagat Krishi VikasYojana (PKVY). BPKP is aimed at promoting traditional indigenous practices which reduces externally purchased inputs. It is largely based on on-farm biomass recycling with major stress on biomass mulching, use of on-farm cow dung-urine formulations; periodic soil aeration and exclusion of all synthetic chemical inputs. According to Department of Animal Husbandry, Dairying and Fishries Report (DADF, 2018-19),GOI, natural farming will reduce dependency on purchased inputs and will help to ease small holder farmers from credits burden. Natural Farming will be compared with Organic Farming and Conventional Farming where external inputs will be used as per requirement.The project envisions to trasform agri supplyand value chains to empower key stakeholders including Farmer Producer Organizations (FPOs),MSMEs,and Agribussiness players to srengthen market infrastructure and promote climate resilient agriculture practices to revive natural ecosystems and to develop climate resilience.

Materials and Methods:

Bhartiya Prakratik Krishi Padhati is a zero external input system of organic agriculturebased on farm biomass recycling,use of on farm cow dung-urine formulations(Bijamrit and Jivamrit). Selection of farmers dry lands, rainfed areas and tribal areas are to be given prefrence. The proposals under BPNP 409400 ha area and Rs 5599.32 lakh have been released for different states of the India. Keeping in view growing acceptance of BPKP has been updated as National Mission on Natural Farming.NF initiatives by GOI and States in FY 2022-23 nearly 9.40 lakh ha area initiated under natural farming in 17 states. More tnan 28 lakh farmes participating in NF. Namami Gange-total 1.48 lakh ha sanctioned to Bihar, Jharkhand, UP and Uttrakhand for 5 km on each side of River Ganga. Uttar Pradesh Diversification of Agriculture Support Project (UPDASP) has been implemented 28 districts of western uttar pradesh through Government of U.P. since 2014-15 (UPDASP, Report, 2014-15, 2022-23). The objective of crop productivity enhancement is to focuses on strengthening agricultural productivityagainst the backdropof high levels of climate risks and variability in prouctivity across the project areas.To support the integration of smallholder farmers into value chainsto select high-value commodities ,thereby increasing productivity,value additionand farmers' income.

Natural farming is a sustainable way of farming agriculture is at epicentre of the country's journey towards Atma Nirbharta (Self reliance) with farmers at its core. The efforts of the government have consistently focused upon upliftment, empowerment and stability of farmers in the technical, economic and social realm. It is in this endeavour that we continuously explore various methods to achieve ecologically sustainable and economically viable methods. Natural farming is one such method that holds potential to realise all these goals. It is backed by our rich traditional knowledge, and is a practice of agriculture based on locally available resources, which makes it a sustainable and viable practice. Tarai Region of the district comprised clay, clay loam and loam soils with high fertility, high rain fall and most suited for paddy, wheat and sugarcane cultivation. Out of 15 development blocks of Bareilly district, 5 blocks viz. Baheri, Damkhoda, Shergarh Nawabganj and Bhadpura falls in this agro climatic zone IV. Project area falls under Tarai agro-climatic zone of Bareilly District.The eastern UP and Bundelkhand are two economic regions that lag behind the rest of the state in agriculture, UP-AGREES project will focus on attention on 28 districts in these two regions.The project will target the participation of of women across all the interventions.At block level,the support organization is responsible for taking the package of information to the farmers/farmer producer groups.At district level, a district coordination coomittee,headed by the District Magitrate.

Table -1: Positive Effects of Natural Farming

Natural Farming Implementation	Significance of Natural Farming
➢ Urine based farming system that did not involve any external Chemical or Organic fertilizer. ➢ It is known by various names like; Zero Budget Natural Farming, PrakritikKrishi, Cow Based Natural Farming, Shashwat Kheti, Chemical Free Agriculture, etc. ➢ GoI is promoting Natural Farming through a scheme named Bhartiya Prkritic Krishi Paddhati (BPKP).	➢ Reduced cost of cultivation ➢ Reduced water requirement of crops ➢ Climate change resilient, reduced risks in farming ➢ Rejuvenateted of farm lands ➢ Safe and healthy food for citizens ➢ Utilizing the available cattle (Desi Cow) as valuable resources ➢ Helped in arresting growing weeds for fertilizers and reduce subsidy burden.

Results:
Government of India mission on national farming 2022-23 has been implemented in different states as depicted in table-2.This farming method also usesa host of other interventions.Seed treated withcow dung based stmulant which protected young roots from fungs and other soil and seed borne diseases (Beejamrit) improved germination counts.

Figure 1: Sowing of crops under natural farming at UPDASP farm

Table-2 : Implementation of the Scheme in different states of India

Paramparagat KrishiVikasYojna (PKVY)	Bhartiya prakritik Krishi Paddhati (BPKP)
➢ 30,934 clusters (20 ha each) formed since 2015-16, ➢ 6.19 lakh ha area and 15.47 lakh farmers were benefitted, ➢ A detailed online web portal- www.jaivikkheti.in	➢ GoI is promoting natural farming through a sub-scheme named BPKP since 1920-21 ➢ BPKP same as PKVY with focus on hand holding and capacity building ➢ Area covered – 4.09 lakh ha (980 clusters of 500 ha each
Namami Gange scheme	Large Area Certification
➢ 1657 Gram Panchayat in Uttarakhand, Uttar Pradesh, Bihar, Jharkhand and West Bengal for development of Organic Farming in the villages along the river Ganga, ➢ Under Namami Gange Programme- 6181 clusters and 1,23,620 ha area covered	➢ Large area under traditional organic farming systems with no synthetic input / chemical input use history are declared as certified organic under union territory: ➢ Car Nicobar – 14,445 ha ➢ Lakshdweep – 2,700 ha ➢ Ladhak -5,000 ha area

Figure 2 : Preparation of fermentate, stimulant and its application in weed crop

Table 3 :Status of Natural Farming in three states of India

Andhra Pradesh State	Himachal Pradesh State	Gujarat State
➢ Initiated in 2015 by Rythu Sadhi kara Samthi (RySS), ➢ Knowledge dissemination to Community Resource Persons, ➢ Started with 900 acers grew to 18,000 as best practitioner of Natural Farming	➢ 4 Mega farmers sensitisation programme for 6 days each, ➢ Farmer experience led to development of local crop wise package of practice	One day workshop for 10,000 farmers in 2019 followed by seven days training of 21,861 Master Trainers, Large scale dissemination of Natural Farming techniques and Success Stories through pamphlets and video(s) (Niti Ayog, 2022)

Discussion:-

In different states, number of farmers covered and implementated area in hectares under natural farming mission has been depicted in table 3.The fields were managed to have some green cover round the year to aid carbon captureby plants from the air and nurture the soil-carbon-sponge.This might kept the microbesand other organisms like earthworms,alive which helps the soil become porous and might retained more water (Whapsa).

Table 4 : Farmers and Area Covered under Natural Farming:-

Sl. No.	State	Farmers Covered	Gram Panchayat	Area Covered	Implementing Agency
1.	Andhra Pradessh	5.92 Lakh (12.3%)	3,730 (28%)	2.68 Lakh ha (4.6%)	RySS, State Govt. Coorporation
2.	Himachal Pradesh	1.53 Lakh (16%)	3,563 (98.2%)	9192 ha (0.96 %)	State Project Implementing Unit
3.	Gujrat	2 Lakh (3.76%)	8,500 (59.6%)	2.5 Lakh ha (2.5%)	State Govt.

Source : Neeti Ayog Report, 2022-23.

During the cultivation of main crops,crop residueswere used as mulch (Acchadana or Mulching) to retainsoil moisture and which could prevent the growth of weeds.This practice of farming is being adopted in different states of India. The results are similar to there findings.At block level support organisation will take the technologies and agronomic practices to the farmers/farmer groups. Implementation is shown in above tables.

Conclusion:

Natural farming comes under priority of the Central as well as the State Governments. . BPKP is aimed at promoting traditional indigenous practices which reduces externally purchased inputs. It is largely based on on-farm biomass recycling with major stress on biomass mulching, use of on-farm cow dung-urine formulations; periodic soil aeration and exclusion of all synthetic chemical inputs. Natural farming will reduce dependency on purchased inputs and will help to ease marginal and small holder farmers to doubling the farm income. Diversification of agriculture through natural farming practices in uttar pradesh as well in other states of India is under the policy of minimum support price. It is understood that required inputs are wholey farm based . Implementation data shows that yield and cost of natural farming is lower than conventional farming . Farmers need support price for their produces of natural farming as well as other seasonl crop produce.The project is managed and implementing by the Uttar Pradesh Diversified Agricultural Support Project (UPDASP) Society.Growing multiple crops in the same patch of land also raised soil fertility (MANAGE,2023)

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Indigenous Jaffna Local sheep production system as a mean of changing driver

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Key words: Endangered indigenous sheep; Nomadic pastoral system; Sustainability dimensions

Abstract
Jaffna Local sheep (JLS) is an endangered indigenous sheep population in Sri Lanka. They have been identified as a breed that has a negative population trend. A study was undertaken to identify the sustainability dimensions of JLS production system. Socio-economic data were collected using a pre tested questionnaire from three leading sheep farms in the Jaffna peninsula, Sri Lanka. The results show that the farmers were having more than 40 years of experience in sheep farming. The sheep were reared with minimum inputs in a nomadic pastoral system. They were reared mainly for manure purpose. On request of the crop farmers, sheep are night paddocked in farm lands such as fallow paddy fields, coconut and palmyra lands. In addition, when the stocking rates are high the excess sheep are sold for meat purpose. Only extensive management is undertaken with a low input system. The sheep are hardy and well adapted to the hot and humid climate in the Jaffna peninsula, Sri Lanka and they convert the low-quality fibrous feed (weeds and crop residues available in the feeding grounds) into nutrient-rich meat with low contamination of medications (antibiotics). The dung and urine enrich the soils with nutrients enabling the crop farmers to cut down on the use of inorganic fertilisers. The household income is stabilized via the earnings from sheep system. Overall, the system showed that the resources are shared among the farming community with less negative impact on the environment. Main drawbacks in the system were the reluctance of the younger generation to be engaged in the JLS farming and the scarcity of feed during the drought period and main paddy cultivation season.

Introduction
Most of the developing countries rear indigenous sheep on small- or large-scale, either under extensive or nomadic pastoralism systems. Indigenous species are mainly reared under low-input low-output production systems with a minimum investment. Most of these indigenous sheep breeds are reared in African, Asian and European countries. Indigenous sheep breeds have the ability to survive in harsh environments where water and grasses are scarce and also where there are arid or semi-arid environments with low-quality forages. These indigenous breeds are reserves of valuable genetical materials that have the ability to adapt to such harsh environmental conditions and be resistant to the available nutrient fluctuations at different seasons, pest and disease outbreaks (Kosgey & Okeyo 2007).

Among all sheep breeds available in Sri Lanka (Bikenary, Bannur, Red Madras, Dorset), there is a traditional indigenous sheep breed called as *Jaffna local* sheep (JLS) restricted to the Jaffna Peninsula in the Northern part of Sri Lanka. *Jaffna Local* sheep is an endangered indigenous sheep population in Sri Lanka (ICAR- NBAGR 2016;

Kurukulasuriya et al. 2022). They have been identified as a breed that has a negative population trend (Vijitha & Silva 2013). They are well adapted to the hot and humid climate in the Jaffna peninsula. Even though the origin of Jaffna local sheep is not well documented, according to Goonewerdene et al. (1984) they may have been introduced to Sri Lanka many years ago by the traders from South India. The geographical nature of the peninsula restricts the movement of JLS and may have led to an uncontrolled inbreeding within the herd resulting in the existing ecotype of JLS with its unique morphological and genotypic characteristics (Goonewerdene et al. 1984; Silva et al. 2009). Main feed available for JLS are the low-quality roughages such as grasses and shrubs in the roadsides, unused lands and other governmental lands and the dried stubbles in the fallow paddy lands (Silva et al. 2009). Thus, the present study was designed to identify the sustainability dimensions (aspects related to environment, economy and society) of JLS production system in Sri Lanka.

Methods

Study area

The study was undertaken in three *Jaffna Local* Sheep (JLS) farms each situated at Kaithady (9.6884 ^{0}N, 80.1010 ^{0} E) and Tellippalai (9.7911 ^{0}N, 80.0339 ^{0}E) at Chawakachcheri (9.6665° N, 80.1321° E) Divisional Secretariat in the Jaffna district which is located in the Northern province of Sri Lanka. The three farms were belonged to Agroecological zone of low country dry zone (LD3) and had red-yellow latosol soil type (Punniyawardhena 2008). Mean annual rainfall was 1,105mm and mean annual air temperature was 31^{0}C. The study was undertaken from July to October 2022.

Farmer Survey

Data related to *Jaffna Local* sheep (JLS) rearing farmers were collected from the Divisional Veterinary Office, Jaffna District. Many farmers were restricted to the Divisional Secretariat, Chavakachcheri. Thus, two farms at Kaithady and one farm at Tellippalai village were selected for the survey on socio-economic status related to JLS farmers.

To collect the socio-economic data, a pre tested questionnaire included with both open and close ended questions was used. The questionnaire consisted with five main sections; the first section included demographic information (age, gender, level of education, income). The second section included information related to the JLS farm (objective of rearing JLS, herd size, rearing system, feeding, vaccination, mortality rate). The third section was related to the farmers' socio-economic status (income from the JLS farm, expenditure). The fourth section was related to the potentials and drawbacks for rearing JLS and the fifth section about suggestions for popularizing the farming of JLS.

Statistical analysis

Descriptive statistics (mean, mode, frequency and percentage) were used to analyze the following data related to JLS farmers; demographic information (age, gender, level of education, income), information related to the JLS farm (objective of rearing JLS, herd size, rearing system, feeding, vaccination, mortality rate), farmers' socio-economic status (income from the JLS farm, expenditure) and the potentials and drawbacks of rearing JLS and the suggestions for popularizing the farming of JLS.

Results

The farmers belonged to Tamil community and their religion was Hinduism. They were having more than 40 years of experience in sheep farming. The sheep were reared with minimum inputs in a nomadic pastoral system. They were reared mainly for manure purpose. However, when the stocking rates are high the excess sheep are sold for meat purpose to the buyers coming from the southern part of the country as there is no demand for *Jaffna Local* sheep meat from the local population.

Only extensive rearing system is undertaken and the flock of sheep is night paddocked on farmlands such as fallow paddy fields, coconut and palmyra lands on request by the owners of the agricultural fields. The owners pay a premium price (LKR 45,000 per unit of paddy field) for night paddocking the sheep. This method provides the much-needed organic matter to the agricultural soils through dung and urine enriching them with macro and micro nutrients. This practice reduces the requirement of inorganic fertilizer input during the paddy cultivation. Overall, the resources are shared among the sheep and crop farming communities with less negative impact on the environment.

Most of the instances farmer and the flock stay at one land/field for a maximum of three days and shift to another location on request. The flock of sheep is restrained to a paddock using temporary fences made up of either thatches or metal polls. The farmer may hire one or two other helpers to take care of the flock during day and night depending on the size of the flock.

Main sources of feed were the roughages available in the fallow paddy fields, other agricultural fields, road sides and play grounds. Main sources of water were the dug wells and seasonal ponds available in the grazing pathways. Farmers used some cultural methods to treat the sheep and they were annually vaccinated against foot and mouth disease. However, restraining individual sheep for disease treatment was the most cumbersome activity as the sheep were not used to human touch and handling.

Main potentials available are the JL sheep who are well adapt to Jaffna peninsula, availability of feed and water in majority of the months and the availability of feeding land areas while the drawbacks include; unwillingness of labourers to stay with the flock and move them to feeding grounds and lack of sources of feed and water during the dry months.

Figure 1: Jaffna local sheep resting on a fallow paddy field

Conclusions

The objective of this study was to identify the sustainability dimensions (aspects related to environment, economy and society) of the *Jaffna Local* sheep production system in the Northern part of Sri Lanka. This sheep is reared in a nomadic pastoral system with minimum inputs. The main purpose of rearing *Jaffna Local* sheep is for manure and meat. The sheep is fed with feeds available in fallow paddy fields, other agricultural fields, road sides and play grounds and water which is freely available in the dug wells and seasonal ponds in the feeding grounds. The flock of sheep is night-paddocked on farmlands on request by the owners of the agricultural fields. The sheep is confined to an agricultural field with temporary fences to restrict the animal movement during the night time. This method provides the much-needed organic matter to the agricultural field through dung and urine enriching them with macro and micro nutrients. This practice reduces the requirement of inorganic fertilizer input during the crop cultivation. Overall, the resources are shared among the sheep and crop farming communities with less negative impact on the environment.

In addition, the disease incidences are also less in this production system as *Jaffna Local* sheep are well adapted to the harsh environmental conditions prevailing in the area as they were reared for generations and generations in the peninsula.

Compared to the indigenous goat breeds in Sri Lanka, *Jaffna Local* sheep breed is less exploited and popular due to their inherently lower production capacity. In contrast, to mutton from goats, there is no demand for *Jaffna Local* sheep meat from the local population and thus sold the extra animals for meat purpose to the buyers coming from the southern part of the country. Thus, only a limited number of farmers daringly invest in the management of *Jaffna Local* sheep but those farmers earn a considerable profit from this farming system.

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XII INTERNATIONAL RANGELAND CONGRESS AUSTRALIA 2025

Using biodiversity to connect rangeland forage nutritive values and methane production potential

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Key words: forage nutritive value; methane; transhumance

Abstract

In the western United States, extensive rangeland livestock grazing systems rely on the diversity of rangeland plant communities to provide vegetation structure and forage nutritive value. With an increased interest in enteric methane production from rangeland livestock across production systems, managers and policy makers need accurate and actionable information about how forage nutritive value influences enteric methane production from native rangelands. Currently, efforts to quantify and mitigate enteric methane from grazing livestock have not accounted for the spatially and temporally dynamic nature of rangeland forage resources used in extensive rangeland production systems. We clipped rangeland forage biomass at the US Sheep Experiment Station in Dubois, Idaho, USA at monthly intervals from sample points along a biodiversity gradient to quantify the nutrient value (crude protein, fiber, and organic matter). We will then estimate methane produced from each rangeland forage sample using an *in vitro* incubation system to simulate ruminant digestion. Using a combination of mixed-effect models and ordinations, we will determine the relationship between nutritive value and enteric methane potential. Understanding this relationship can help livestock managers make grazing decisions to mitigate enteric methane production when possible.

Introduction

The biodiversity of rangeland plant communities is a primary indicator for determining ecosystem integrity and the ecosystem's ability to provide goods and services that support food security, rural livelihoods, wildlife conservation, and carbon management (Ahlering et al., 2020; Pellant et al., 2020). Heterogeneity in rangeland vegetation is essential for ecosystem provisioning. As biodiversity diminishes, susceptibility to climatic variability increases, threatening short- and long-term output of important services. In the western U.S., extensive livestock production systems graze a variety of lands ranging from intact, heterogenous native plant communities to those that have been converted to more homogeneous communities. Such conversion may be intentional, e.g., introducing new plant species to enhance forage production, or unintentional, e.g., invasion of invasive species. Regardless, loss of heterogeneity reduces adaptive capacity by coupling rangeland management outcomes to just few or even a single plant species.

The nutritive value of available rangeland forage is spatially and temporally dynamic with the composition, phenology, and management driving intra-year variability (Ganskopp and Bohnert, 2009; NASEMR, 2016;

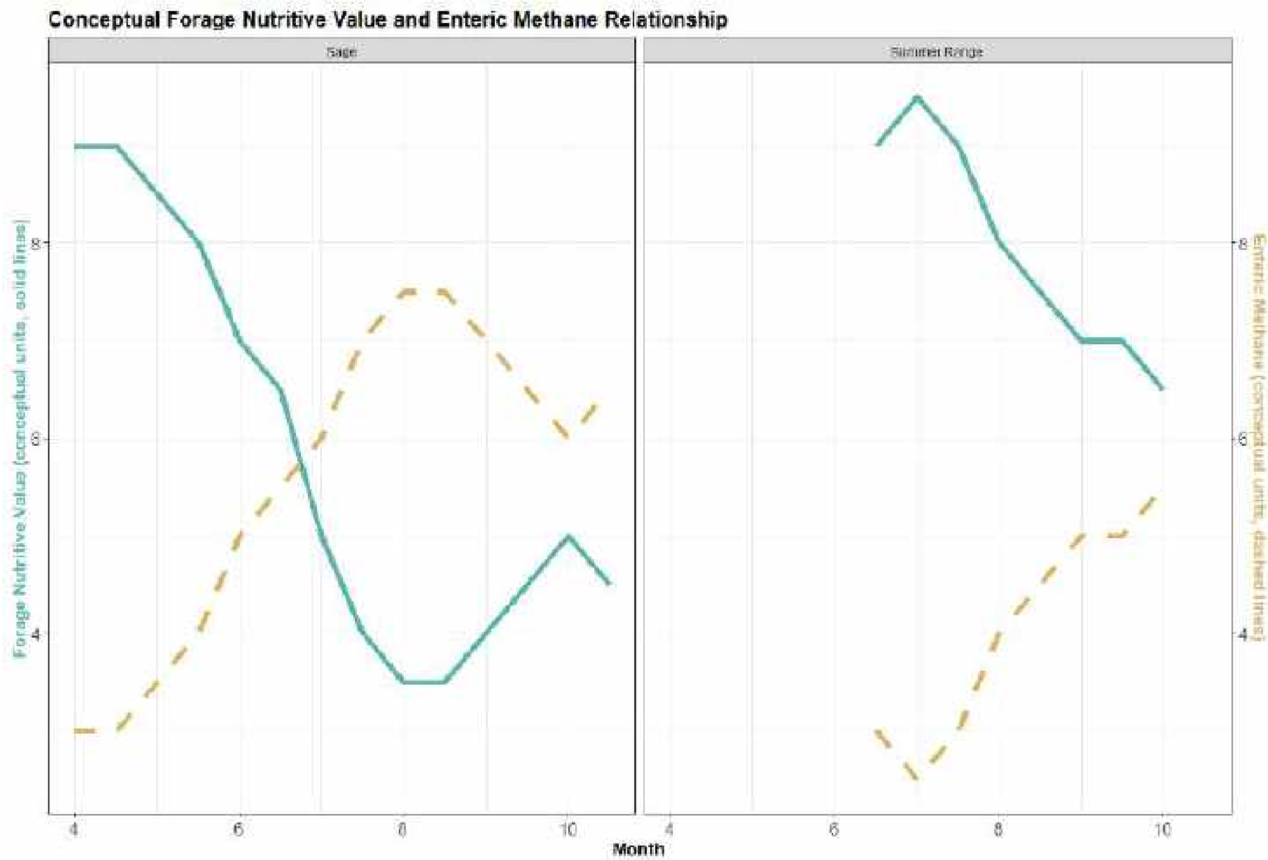
National Research Council, 2007; Spiess et al., 2024). As plant communities shift, or are altered over time, we would expect the nutritional profile of the plant community to also change. For rangeland managers, conservationists, and livestock producers, understanding how the nutritive value of a plant community shifts over the growing season within a year can inform management decisions to meet outcome expectations.

Forage nutritive value is also an indicator for enteric methane potential once digested by ruminants (Bezabih et al., 2014; Khan et al., 2021; Thompson and Rowntree, 2020), which include both domestic and native (wild) species. Of the commonly measured nutritive profile parameters, neutral detergent fiber has previously been found to have a significant, positive relationship with enteric methane production (Bezabih et al., 2014; Khan et al., 2021). With increased focus on greenhouse gas fluxes in rangelands (Recktenwald and Ehrhardt, 2024; Sanderson et al., 2020; Thompson and Rowntree, 2020; Wang et al., 2021), an understanding of intra- and inter-year variability in enteric methane potential for rangeland plant communities will facilitate long-term rangeland management towards vegetation diversity goals to minimize enteric methane potential. This research will also help expand the discussion of enteric methane production from rangelands given that the intra-season variability of rangeland forage nutritive value is currently missing from the broader discussion of enteric methane production of rangelands. As this project progresses into plant communities along the elevation gradient in the region, we will be able to compare nutritive trade-offs in grazing at different points in the growing season or losing grazing access to higher elevation communities (Wilmer et al., 2024).

For this paper, we outline our initial rangeland forage pilot project that we are currently analysing and then transition into describing the broader rangeland forage project. We are working towards documenting and quantifying the community composition, structure, and nutrition profiles of vegetation across temporal, elevation, and biodiversity gradients bedded within an extensive rangeland livestock system. We will address broader interests and issues in greenhouse gas emissions, rangeland management, animal production, and adaptive management capacity to begin filling a critical knowledge gap relevant to a variety of stakeholders that include livestock producers, land management agencies, wildlife conservationists, and policy makers. Our approach will include direct comparisons of the forage nutritive value and enteric methane potential profiles among native sagebrush steppe rangeland plant communities along biodiversity gradients. Results will provide a foundation for evaluating how losing, maintaining, or improving biodiversity affects the provisioning potential of extensive rangeland systems.

Methods

For the pilot project, we collected rangeland forage samples from two adjacent sagebrush steppe management units to compare differences in forage nutritive value and enteric methane potential between a burned and unburned area in July 2024 and then between summer (July 2024) and early fall (September 2024) for the unburned management unit. We clipped available forage in 0.25 m^2 frames at sample points distributed across each management unit after determining the species composition by cover for each frame. We then ground all samples through a 2-mm sieve using a Wiley Mill to prepare for nutrient and methane analyses. At this point in time for the project, we are transitioning to sample analysis. A subsample of each sample will be sent off for crude protein and fiber analyses and a subsample will be used to determine *in vitro* digestibility and enteric methane potential. In addition to traditional wet chemistry methods, we are also using near-infrared spectroscopy to prepare spectral calibration curves for future nutritive value analysis. We are using a Gas Endeavour *in vitro* rumen incubation system (Liu et al., 2018) to determine enteric methane potential.



Conceptual figure for the expected forage nutritive value and enteric methane potential relationship over the potential grazing seasons in eastern Idaho, USA sagebrush steppe and higher elevation rangeland plant communities. Based on existing research, we are expecting to find that forage nutritive value is inversely related to enteric methane potential. The shorter grazing season for the summer range panel is related to the shorter growing season and access logistics due to snow at higher elevations than in the sagebrush steppe panel.

Using a combination of mixed-effect models and ordinations, we will determine the overall relationships between nutritive value parameters (crude protein, acid detergent fiber, neutral detergent fiber, and acid detergent lignin), digestibility, and enteric methane potential (Spiess et al., 2024). We expect enteric methane potential to be inversely correlated with nutritive value (Khan et al., 2021; Thompson and Rowntree, 2020). For the pilot project data, we expect the available forage in the burned management unit to have a higher nutritive value (higher protein, higher digestibility, lower fiber) than the adjacent unburned management unit. We also expect the samples from the unburned management unit in July to have a higher nutritive value than samples collected from the same unit in September.

Next Steps & Discussion

Following the pilot project, we will be expanding to a manipulative experiment in summer 2025 to target the biodiversity component of this relationship between forage nutritive value and enteric methane potential in addition to temporal variability of the forage base. At the experimental study sites, we will manipulate the community within subplots through a combination of herbicide treatments to target different functional groups and investigate how removing species from the community will affect the nutritive profile. The full subplot treatment factorial at each experimental site will include: no herbicide – control, forb-targeted herbicide, shrub-targeted herbicide, forb & shrub-targeted herbicide. To capture the temporal progression of the forage, we will clip frames from each factorial subplot at monthly intervals from May through October.

We expect that the reduction in biodiversity will correspond to an overall reduction in forage nutritive value due to fewer species and functional groups contributing to the overall growth curve of the respective subplots. Similarly, we expect that samples from later in the growing season will have lower forage nutritive value and higher enteric methane potential than samples from earlier in the growing season. This will help illustrate how grazing similar plant communities at different times of the year can meet, exceed, or fail to meet an animal's nutritional needs (Wilmer et al., 2024).

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XII INTERNATIONAL RANGELAND CONGRESS AUSTRALIA 2025

Seasonal grazing distributions of livestock in the communal rangelands of Namaqualand

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Key words: Pastoralism; Indigenous Knowledge Systems; Semi-Arid; Transhumance; Spatial perceptions; Sustainability

Abstract

The role of indigenous grazing management practices in flexible and sustainable resource use has been widely identified and recognised in the literature. However, these grazing management practices in the semi-arid pastoral areas in Namaqualand in South Africa have not adequately been studied in terms of GPS-based seasonal grazing distribution. This study aimed to assess the seasonal livestock grazing distributional patterns across three communal rangelands in Namaqualand using GPS collars. The objectives were to: 1) generate grazing distributional maps to identify patterns of seasonal rangeland use, 2) compare home range and grazing intensity of livestock between seasons, 3) delineate different grazing zones at different times of day known descriptive model of daily indigenous grazing management practices of Namaqualand and 4) contrast seasonal differences within these grazing zones regarding grazing activity. Catlog GPS collars were mounted on livestock and T-LoCoH R package and Google Earth was used to generate grazing distributions maps showing areas most frequently used by livestock (grazing intensity) and daily livestock movement patterns. The results showed that Namaqualand herds grazed a small proportion of their home range regardless of season. Wet-season herds had smaller home range. The area associated with high grazing intensities in both seasons was significantly smaller than at lower grazing levels. No significant differences in mean area associated with seasonal variation within each level of grazing suggests herders are not seasonally altering areas associated with grazing intensity to prevent seasonal over-exploitation of resources. Grazing activity is lower in the herded zones than in when unherded. Grazing activity and distance travelled in the herded zones is lower in the wet season but area covered is less as resources are abundant. This suggests that indigenous herding practices in Namaqualand requires vast ecologically aware decision-making processes associated with effective sustainable resource use. We argue that due to the flexibility and adaptability of indigenous grazing managements Namaqualand, herders may increase the area covered at high grazing intensities during the wet season will improve livestock productivity without compromising rangeland condition. Furthermore, contemporary of grazing management systems should be more inclusive of indigenous management as aspects of holistic grazing management have embedded in these practices for a long time.

Introduction

Poor grazing management in arid rangelands can lead to rangeland degradation through overgrazing. In Namaqualand, and South Africa more broadly, historical management practices were shaped by perceptions such as 'The Tragedy of the Commons,' which inaccurately blamed overgrazing on ineffective indigenous grazing systems (Hardin 1968). These misconceptions disrupted the transhumance mobility patterns of subsistence livestock owners, undermining their ability to adapt to changing environmental conditions (Samuels et al. 2008). As a result, indigenous communities were significantly hindered in their efforts to manage rangeland resources effectively.

Despite these perceptions the Namakwa herders maintained their highly mobile indigenous grazing management practices. Effective grazing management of communal rangelands requires mobility from both herders and their livestock across various spatio-temporal scales (Samuels et al. 2007). Indigenous communal farmers and herders navigate the landscape with their livestock, guided by ecological knowledge refined over generations (e.g., transhumance) (Allsopp et al. 2007). This mobility enables herders to flexibly adapt resource use to fluctuating ecological and environmental conditions."

While the flexibility and sustainable resource use of indigenous grazing management practices in Namaqualand have been widely recognized in the literature (Asheenafi and Leader-Williams 2005; Samuels et al. 2007; Allsopp et al. 2007), these practices have not been sufficiently represented through GPS-based seasonal grazing distribution maps. To better assess the flexibility and adaptability of these indigenous practices, it is crucial to investigate GPS maps of grazing distribution patterns.

This study aims to assess the livestock grazing distributional patterns across three communal rangelands in Namaqualand. The objectives of this study are to:

1. Generate grazing distributional maps to identify patterns of rangeland use between wet and dry seasons.
2. Use different times of the day within grazing course to delineate different grazing zones.
3. Contrast seasonal differences within these grazing zones regarding grazing activity.
4. Compare home range and grazing intensity of livestock between seasons.

Methods

To determine seasonal livestock grazing distribution patterns in space, two data collection field trips were undertaken in the wet season (Winter and Spring) and dry season (Summer), where two CatLog GPS (Global Positioning Systems) tracking devices were attached to two random adult animals (sheep and/or goat) in every herd.

Additionally, the Catlog GPS trackers also record animal velocity which is essential for determining the specific daily livestock activity along the grazing course based on the descriptive model of indigenous grazing practices model from Debeaudoin (2001) [Unpublished Master's thesis]. The collars were left to record daytime movements for duration about three months and GPS data was retrieved.

GPS positional data from each animal was extracted and analysed using the CatLog Software and the R package Time Local Convex Hull (T-LoCoH) (Getz and Wilmers 2004) to generate isopleths which represent the varying proportions of the total grazing distributional extent used by the animals of interest. Google Earth Pro (2023) was used to map the isopleth data.

T-LoCoH is an R package that creates isopleth diagrams showing an object's range in space and time using the Minimum Convex Polygon (MCP) method. Each polygon within the isopleth represents the extent of the areas utilized and the frequency of use over time at each location (Gusha et al. 2018; Gwate 2018). These polygons, or hulls, were assigned categorical classes (iso levels) and color codes to indicate the proportion of the total area utilized and the corresponding frequency of use. Based on the iso levels and their color codes, grazing intensity was categorized into three levels: high, moderate, and low

Two-way Wilcox-Mann-Whitney t-tests or Kruskall-Wallis tests and a relevant post-hoc tests were used to analyse significant seasonal variations spatio-temporal variables.

Results

Livestock movement during the wet season and dry seasons in the study area

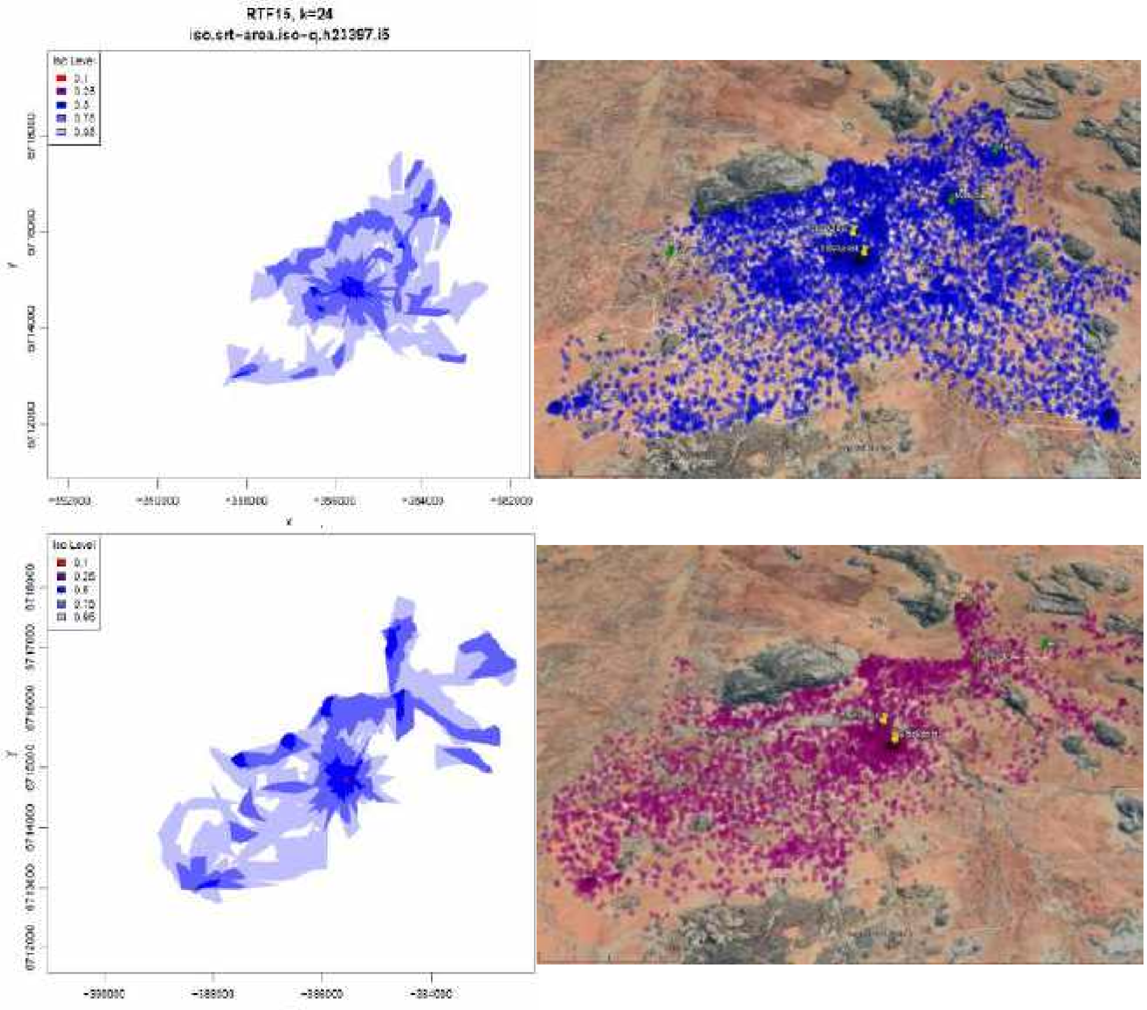

Fig. 1: Isopleth diagrams produced from hulls arranged by area denoting the frequency of occurrence and proportions of the total area occupied by an adult *Capra hircus* during the wet season (bottom left) and *Ovis aries* in the dry season (top left) in Concordia. Google Earth maps (right) depicting the grazing distribution of a *Capra hircus* (purple dots) during the wet season and *Ovis aries* (blue dots) during the dry season in Concordia. Stock post (Yellow pin) and grazing intensity levels (Green pins).

The home range appears larger in the dry season compared to the wet season in Fig. 1.

Spatial data: and grazing intensity during dry seasons of the study area

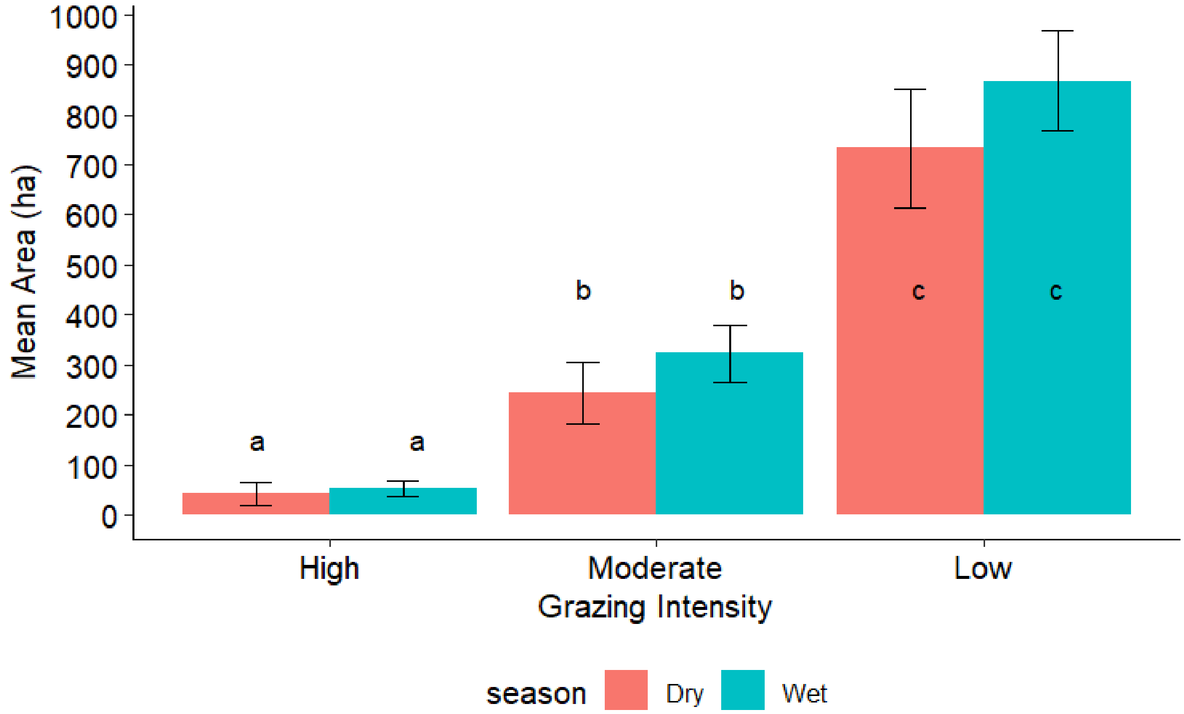

Fig. 2: Mean area grazed at every level of grazing intensity between wet and dry seasons across all three communal areas.

Fig. 2, shows there are significant differences in mean area covered at different grazing intensities ($X^2 = 46.327$, df = 2, p-value < 0.05). Mean area covered is lowest at high grazing intensity (48.1±13.5 ha) and there are no significant differences in mean area associated with seasonal variation within each level of grazing (z-value = 0.785, p-value = 0.432).

In Fig. 3, each of the grazing zones indicate particular time classes within a daily grazing course. The Excitement/appetite moderation zone (EAM) is between 07:00 – 11:00, Target Zone and waterpoint (T) is between 10:00 – 14:30 and the Late Afternoon Meal zone (LAM) is between 14:30 -17:00.

Fig. 3A, indicates the mean speeds of livestock associated with grazing zones along the daily grazing route in Namaqualand. The bar plot shows mean speed is significantly slower in LAM (0.852±0.0010 km/h) than in the other zones (both p-values < 0.05).

Fig. 3B, shows there is significant difference in mean grazing speeds between seasons only at EAM and T zones only (p-value < 0.05), where livestock move faster during the wet season (Wet: 0.945±0.006 , Dry: 0.907±0.008).

Grazing activity of livestock and speeds along daily grazing course during the wet and seasons

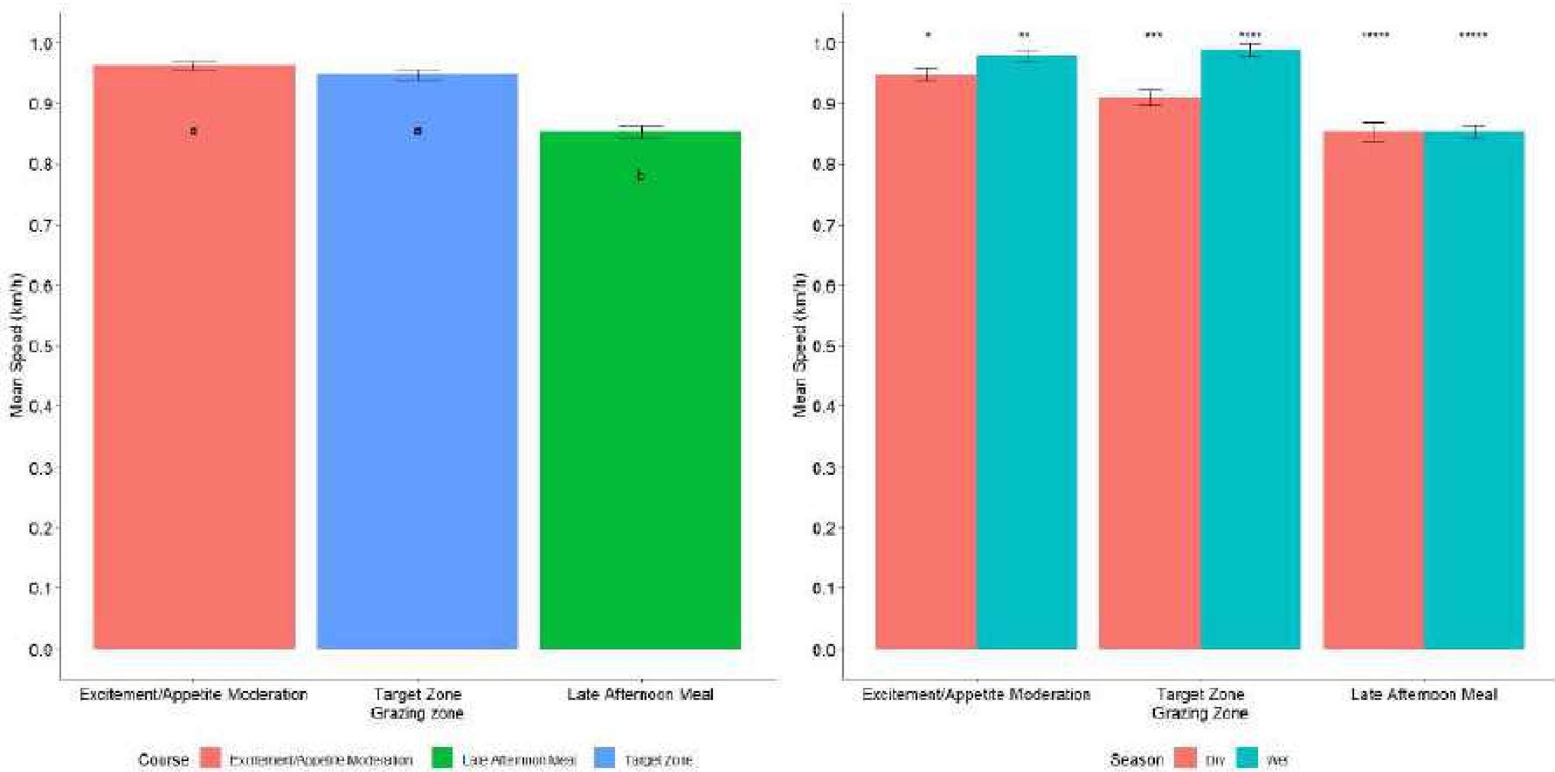

Fig. 3: Shows the differences in mean grazing speeds of livestock at different time specific zones along daily grazing route. (A) depicts the grazing speeds across all seasons. (B) indicates the grazing speeds between seasons. Letters (a, b) and (*) indicate significant differences in bar plots A and B respectively.

Discussion, Conclusions & Implications

Some of the historical perceptions indigenous herders derived from the ‘tragedy of the commons’ on indigenous herders is that they are selfish and do not have the skills to manage communal rangelands effectively.

However, the data shows that indigenous herders in Namaqualand are practicing ecologically sustainable grazing management (Fig. 3). This is because the mean area grazed differs at every level of grazing intensity such that high grazing intensities occupy the smallest areas (Fig. 3). Although this may be because palatable succulent karoo vegetation is limited to small patches, it is more likely that high intensity grazing is spatially limited by herders to allow for longer resting periods to conserve these palatable patches.

Furthermore, there is evidence (Fig. 3) that Namakwa herders are ecologically aware regarding sustainable use of resources not just in space but also in time as the mean areas grazed at all grazing intensity levels remains unchanged across seasons. This suggests that herders are preventing seasonal exploitation of resources to promote accumulation of available forage for their livestock. This allows flexibility for potential future exploitation of palatable plants.

Therefore, the spatial and temporal restrictions on grazing within the home range by Namakwa herders while maintaining livestock production improves the quality of both the livestock and rangeland condition. These are principles similar to those in holistic and adaptive grazing management (Mann and Sherron 2018) though these concepts are already embedded into the vast indigenous ecological knowledge of Namakwa herders. The success of this though requires vast ecological knowledge at various spatio-temporal scales by Namakwa herders and, contrary to historical perceptions, is an example of effective grazing management.

Furthermore, this study indicates that there are significant differences in mean speeds of livestock differs in the mid-afternoon (T) along a daily grazing route (Fig. 2A-B). This finding is similar to that found in the Richtersveld National Park by Hendricks (2004), where there was a significant difference in herd speeds between morning and afternoon. Speeds in different zones (Fig. 2) suggest variations in grazing activity, with slower speeds indicating more intense grazing activity. The reduced speed from the mid-afternoon reflects peak grazing activity during this time. This is likely because the animals are unherded during this time as studies by Debeaudion (2001) and Samuels (2006) show many Namakwa herders leave their animals once they reach the (T) in the afternoon as they have other duties to perform. This ensures animal well-being through limited free-range grazing on good quality forage and allowing for effective rumination.

Conversely, in the morning and early afternoon grazing activity is lower because animals are moving faster as they are being actively herded. This is similar high intensity short-duration grazing (Chaplot et al. 2016; Louhaichi et al. 2021), where herders take all their and are constantly moving. This permits longer resting periods and evenly distributes grazing impacts. This emphasises the flexibility and adaptability of the indigenous grazing management system in Namaqualand.

Additionally, grazing activity changes in the herded zones (EAM and T) between seasons (Fig. 2B), where grazing activity is lower in the wet season. Moreover, distance travelled may also be inferred from speed as a greater speed suggests more ground is covered in the same time. Thus, herds travelled further in the wet season but this is contrary to many studies which state livestock should instead travel further in the dry season as resources are limited (Lawrence et al. 1988; Hulbert et al. 1996; Sieff 1997; Samuels 2006; van Beest et al. 2011).

However, this finding aligns with existing literature only when seasonal resource availability and spatial perceptions are correctly interpreted (Fig. 2B). Specifically, it is essential to distinguish between the distance travelled and the area covered. For instance, during the wet season, when resources are abundant, livestock may travel further but cover a smaller area due to the concentrated availability of palatable vegetation. Conversely, in the dry season, when resources are scarce, livestock may not travel as far but cover a larger area as they forage for dispersed vegetation. The alignment of this observation with broader literature underscores that Namakwa herders have preserved their seasonally adaptive farming practices over time, despite evolving perceptions.

Effective grazing management in Namaqualand requires deep ecological knowledge across scales. As climate variability intensifies (Thornton et al. 2014), adaptive indigenous grazing practices offer valuable insights for mitigating climate change impacts. Modern management strategies should prioritize indigenous knowledge and involve local communities in shaping future approaches.

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In vitro assessment of the relationships between the digestion of different types of rice straw in the rumen.

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Key words: Clostridium; Bacteroides; PCR; DGGE; Solid-Liquid Fractions

Abstract

The aims of this study were to examine bacterial communities in relation to the rumen digestion of rice straw and to understand how concentrate supplements affect gut bacteria involving the digestion of a rice straw-based diet. The substrates were rice straw (RS) alone (experiment 1) and RS with 25% concentrates (barley and kidney beans) (experiment 2). The genomic DNA was collected to determine bacterial diversity by conducting denaturing gradient gel electrophoresis (DGGE). V6–V8 region group-specific (Clostridium and Bacteroides) primers were employed in the analyses. The DGGE band pattern was subjected to cluster analysis to demonstrate the similarity and difference between dietary treatments and solid-liquid fractions. Fiber digestibility, gas production, and volatile fatty acid (VFA) concentration were increased with incubation time. The differences between solid and liquid fractions were significant in total bacteria, Clostridium, and Bacteroides communities. These results indicate a stable community structure of Clostridium and Bacteroides groups involved in the digestion of rice straw-based diets in the rumen.

Introduction

Ruminant animals rely on forage as a primary nutritional component, but forages like rice straw are high in fiber, low in protein, and poorly digestible, which presents a challenge for Afghan farmers who primarily feed their cattle such roughage during the dry season (Van Soest 1994). Afghanistan's livestock population includes approximately 3.7 million cattle and 18 million sheep and goats, many of which are fed low-quality, high-fiber feed (Fitzherbert 2007). To improve meat and milk production, diets need higher nutritional density through increased concentrates, but this affects the gut bacterial community (Chesson 1988). This study focuses on understanding the relationship between fiber digestion, rumen bacterial communities, and the effects of concentrate supplements on the digestion of rice straw in cattle (Beever and Mould 2000).

Methods

In this study, a randomized factorial design was used with two experiments. In experiment 1, 12 rice straw samples from four locations in Afghanistan (Nangarhar and Khost provinces) were collected, and in experiment 2, one rice straw type was selected with barley (25%) and kidney beans (25%) used as supplements. All samples were analyzed in triplicates. The chemical composition was analyzed in the laboratory at Kabul University, and rumen fluid was collected from Holstein dairy cows in Japan (McManus et al. 1976). The *in vitro* gas production technique was employed using 87 glass vials, with samples incubated for various time points (Pell and Schofield 1993). Gas production and fermentation parameters like pH, VFA, and bacterial communities were measured. Microbial DNA was extracted and amplified using PCR, and microbial community profiling was done using DGGE (Yu and Morrison 2004). Scanning electron microscopy (SEM) was used to analyze rice straw morphology, and bacterial populations were monitored through nested PCR techniques (Hatfield et al. 1999).

Table.1. VFA concentration (mmol/l) of four types rice straw in different incubation of periods

Incubation period	Ingredient				
VFA	RS-1	RS-2	RS-3	RS-4	P Value
24 h Incubation period					
Acetic acid	31.38± 3.78	19.78±1.58	21.59±7.92	17.58±1.04	*
Propionic acid	12.65±1.75	8.02±1.58	11.49±4.94	6.30±0.21	*
Butyric acid	3.81±0.56	2.54±1.03	2.05±0.05	2.08±0.62	NS
Total VFA	49.075	20.6	35.12	26.62	*
48 h Incubation period					
Acetic acid	39.90±0.59	30.15±4.09	35.42±7.94	28.34±1.44	*
Propionic acid	17.64±4.65	16.73±1.42	18.55±0.13	16.44±1.65	NS
Butyric acid	3.41±0.16	1.94±0.26	3.48±1.53	2.13±0.19	*
Total VFA	60.95	48.81	57.44	48.9	*
120 h incubation period					
Acetic acid	73.24±8.00	61.40±13.29	63.44±9.21	58.14±6.56	*
Propionic acid	22.79±7.53	22.20±0.20	20.94±0.04	21.24±0.47	NS
Butyric acid	5.07±0.41	4.09±1.40	4.68±2.38	4.96±1.70	NS
Total VFA	105.34	87.92	89.17	84.49	*

The four types of rice straw from different provinces of Afghanistan, RS-1; rice straw of Ningarhar sorkhrood, RS-2; rice straw of Ningarhar behsood, RS-3; rice straw of Khost mandozai, RS-4; rice straw of Khost shamal. Data are mea1 ± SD. *P<0.05, NS; not significant.

Results

Fermentation Parameters

The fermentation parameters for rice straw alone showed that cumulative gas production increased over the incubation period, with significant differences observed at 72, 96, and 120 hours. RS-3 produced the most gas, followed by RS-1, and RS-2 produced the least. NDF digestibility increased over time, but no significant differences were found between the straw types. The total VFA concentration increased with incubation, with RS-

1 achieving the highest concentration, followed by RS-3. RS-1 and RS-3 also exhibited higher acetate concentrations throughout the incubation, while propionic acid was higher only at 24 hours. When rice straw was supplemented with concentrates (barley and kidney beans), cumulative gas production increased significantly, especially with barley (RS-BR) and kidney beans (RS-KB) after 48 hours. The pH decreased with supplementation but not significantly. RS-KB showed a significant increase in total VFA concentration, followed by RS-BR, with propionic and butyric acids significantly higher in RS-KB. Acetic acid, however, was unaffected by concentrate supplementation.

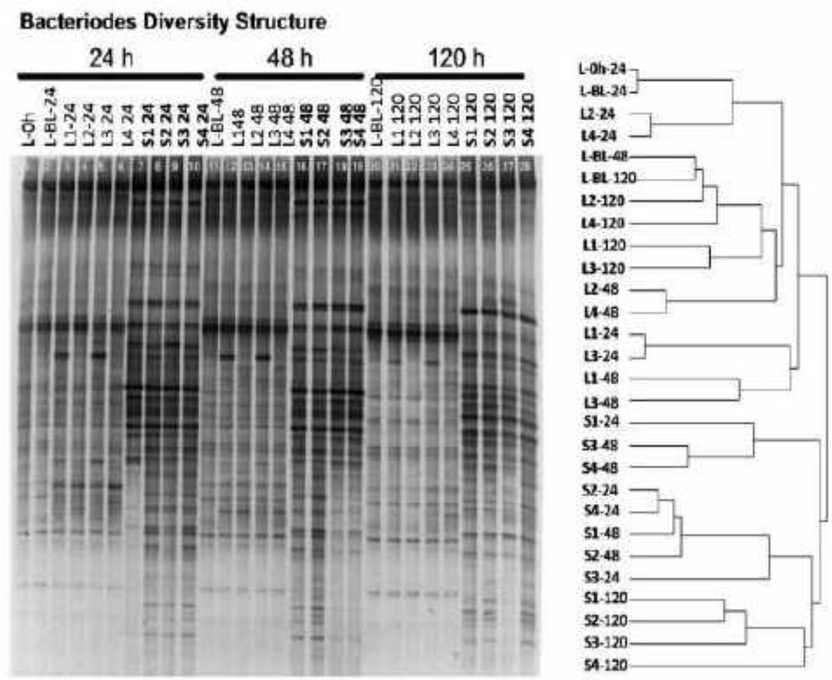

Figure 1. Liquid- and solid-associated bacterial communities determined by DGGE employing group specific primers for *Bacteroides-Prevotella*. The first letter stands for liquid (L) and solid (S)-associated bacteria, the second letter for 1,2,3,4 is the four types of rice straw, and the following description in parenthesis for 24, 48 and 120 hours of

Scanning electron microscopy (SEM) & PCR-DGGE

Scanning electron microscopy analysis revealed that rice straw had smooth hyphae at the beginning of the incubation, but over time, the hyphae became increasingly degenerated and damaged, with the damage size growing at 24, 48, and 120 hours. PCR-DGGE analysis of the bacterial communities showed that, for rice straw alone, there was no significant change in the Clostridium and Bacteroides-Prevotella groups throughout incubation. Solid-associated bacterial fractions showed a higher density of dominant bands, with RS-1 and RS-3 showing distinct band patterns in the liquid fraction compared to RS-2 and RS-4. In the rice straw and concentrate treatments, the bacterial community profiles showed clear differentiation between solid and liquid fractions, with Clostridium groups in the liquid fraction affected by both barley and kidney bean supplementation, and the Bacteroides-Prevotella group showing changes only in the liquid fraction with RS-KB. However, there was no significant impact on the solid-associated bacterial community by either concentrate.

Discussion

The cumulative gas production varied significantly between the types of rice straw, with differences linked to the chemical composition, especially fiber content (Hatfield et al. 1999). Straw with lower lignin and higher hemicellulose content (RS-3 and RS-1) showed better fermentation parameters, including higher NDF digestibility, which increased over the incubation period. This slow digestion is attributed to the complex interactions between lignin and structural carbohydrates, which are challenging for microorganisms to break down (Chesson 1988). The increased VFA concentration also reflected the improved fermentation rate, which was consistent with higher gas production (Plaizier et al. 2008). The rice straw varieties exhibited variability in chemical composition, with differences in NDF and ADF content affecting gas production and VFA concentration (Beever and Mould 2000). The degradation of rice straw cell walls increased over time, with visible differences in degradable tissue zones correlating with fermentation parameters and gas production (Van Soest 1994).

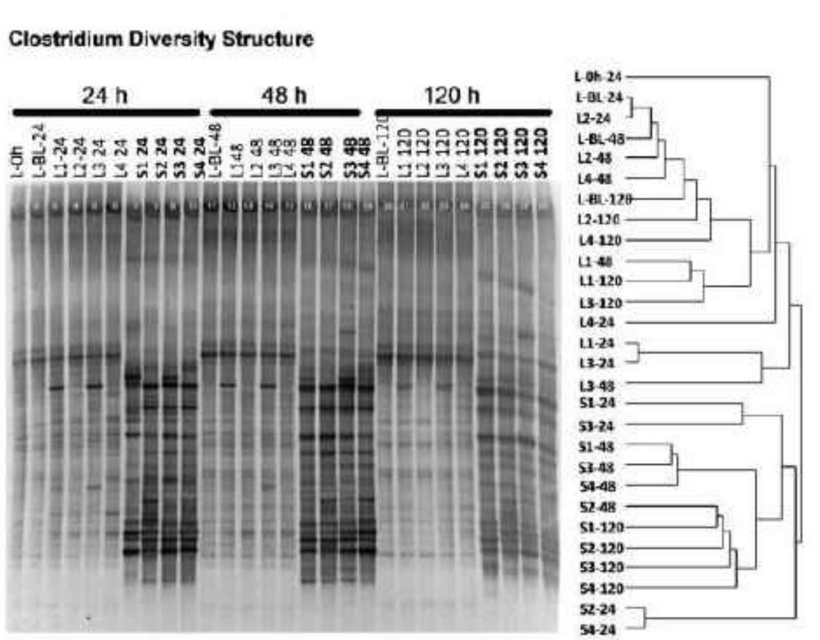

Figure 2. Liquid- and solid-associated bacterial communities determined by DGGE employing group specific primers for *Clostridium*. The first letter stands for liquid (L) and solid (S)-associated bacteria, the second letter (1,2,3,4) is the four types of rice straw, and the following description in parenthesis for 24, 48 and 120 hours of

The bacterial communities in the solid and liquid fractions showed distinct profiles, primarily due to the attachment of fibrolytic bacteria to solid particles, which are predominant in rumen fiber digestion (Silva et al. 1987). Solid-associated microbes were more abundant throughout the incubation periods, aligning with findings that fiber digestion is mainly driven by these microbes (Jung and Varel 1988). The addition of concentrates (barley and kidney beans) led to increased gas production and propionic acid concentration, while acetic acid was unaffected, suggesting that starch-enriched diets favor propionate production (Pell and Schofield 1993). The lack of significant changes in the solid-associated bacterial community may be due to the low concentrate proportion in the diet, as evidenced by the relatively stable pH (Nagaraja and Titgemeyer 2007). However, the liquid-associated bacterial communities, particularly in the Clostridium and Bacteroides-Prevotella groups, were affected by the concentrate treatments, likely due to the presence of undigested solid particles in the liquid fraction (Yu and Morrison 2004).

The results indicate that although the digestibility of rice straw was not notably improved by the concentrate supplementation, the changes in microbial communities and fermentation parameters underscore the role of microbial dynamics in fiber and starch digestion (Chen et al. 2008).

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How grazing management practices affect the livestock productivity in steppe

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Key words: Grazing activity; Energy expenditure; Feed intake; Rangeland productivity

Abstract

Understanding how grazing management practices affect the livestock productivity in steppe is a key issue to the sustainable rangeland. We conducted a grazing experiment in 2022 and 2023 at the steppe of Inner Mongolia. Five grazing managements included light (LGL, 0.38 sheep units·ha^{-1}·yr^{-1}), moderate (MGL, 0.75 sheep units·ha^{-1}·yr^{-1}), and heavy (HGL, 1.06 sheep units·ha^{-1}·yr^{-1}) grazing of lambs, moderate grazing of ewes (MGE, 0.75 sheep units·ha^{-1}·yr^{-1}), and the mixed grazing of both (MIX, 0.75 sheep units·ha^{-1}·yr^{-1}) in a randomized block group design with three replicates. Of these, LGL, MGL and HGL were the grazing intensity treatments, MIX, MGL and MGE were the flock treatments, and the MIX treatment consisted of mix-grazing lambs (MML) and mix-grazing ewes (MME). The results showed that there were significant differences ($P<0.05$) among the daily grazing time (DGT) of lambs with different grazing intensities, and the DGT of lambs under MGL treatment was the shortest. There were significant differences in DGT of sheep with different flocks, where MGL treatment was the highest while MGE was the lowest. Besides, significant differences were found in daily overall dynamic body acceleration (DODBA) of sheep with different flocks, with MME treatment being the highest and MML being the lowest. There were significant differences among daily feed intake (DFI) and average daily gain (ADG) of sheep with different flocks. Among them, DFI was significantly higher in ewes (MGE, MME) than in lambs (MGL, MML), while ADG was significantly lower. The linear mixed models showed that ADG in lambs was mainly positively influenced by DFI under various grazing intensities. Differently, ADG was mainly positively affected by DGT and negatively affected by DODBA under various flocks. In conclusion, different grazing managements had significant effects on sheep productivity and their grazing activities. And the grazing intensity regulated productivity by influencing the feed intake, whereas flock had effects by influencing the activity level. These provide new ideas to guide the grazing management practices in steppe.

Introduction

Understanding how grazing management practices affect grassland livestock productivity is a key issue in achieving sustainable rangeland development. Among these practices, grazing intensity and flock structure are two key guiding parameters that are of great concern to pastoralists in practical production. These parameters regulate grazing patterns and livestock productivity within pastures (Animut et al., 2005; Grace et al., 2019). During grazing, the livestock productivity is closely related to their behavioural characteristics (Portugal et al., 2021; Yu et al., 2024). This is because animals maintain a trade-off between energy expenditure and nutrient intake, specifically balancing their activity levels and feed intake (Charnov, 1976). With the advancement and maturation of animal kinematics and related supporting technologies, overall dynamic body acceleration (ODBA), calculated by triaxial acceleration, has been proposed as a metric to characterise animal energy expenditure (Green et al., 2009; Wilson et al., 2006). Furthermore, machine learning models built on accelerometer datasets can classify animal behaviour with accuracies exceeding 90% (Yu and Klaassen, 2021). Therefore, to determine whether there were significant differences in the productivity and grazing activity of sheep under different grazing management practices, and to explore the intrinsic relationships between these factors, we conducted the following study using triaxial accelerometers.

Methods

The study was conducted in Xilinhot City, Xilingol League, located in the Inner Mongolia Autonomous Region of China. The experimental site represents a typical steppe ecosystem, predominantly composed of *Stipa krylovii* and *Leymus chinensis*. The experiment was conducted from July to September in both 2022 and 2023, utilising crossbred *Ujimqin* and *Dorper* sheep with comparable body sizes as experimental animals. Five grazing managements included light (LGL, 0.38 sheep units·$ha^{-1}·yr^{-1}$), moderate (MGL, 0.75 sheep units·$ha^{-1}·yr^{-1}$), and heavy (HGL, 1.06 sheep units·$ha^{-1}·yr^{-1}$) grazing of lambs, moderate grazing of ewes (MGE, 0.75 sheep units·$ha^{-1}·yr^{-1}$), and the mixed grazing of both (MIX, 0.75 sheep units·$ha^{-1}·yr^{-1}$) in a randomized block group design with three replicates (FIG.1). Of these, LGL, MGL and HGL were the grazing intensity treatments, MIX, MGL and MGE were the flock treatments, and the MIX treatment consisted of mix-grazing lambs (MML) and mix-grazing ewes (MME). For each experimental treatment, six sheep were fitted with Druid NANO collars (Chengdu, China) to record real-time triaxial acceleration data. These data were subsequently used to calculate the daily overall dynamic body acceleration (DODBA) and daily grazing time (DGT) of the sheep. Additionally, five 1 m × 1 m grazing exclusion cages were randomly distributed across each experimental plot to estimate the daily feed intake (DFI) of the sheep using the exclusion cage method. And the sheep were weighed at each mid-month in order to determine their average daily gain (ADG). The experimental design was conducted in accordance with the established ethical guidelines for animal research. All statistical analyses in this study were conducted using R software (version 4.3.0).

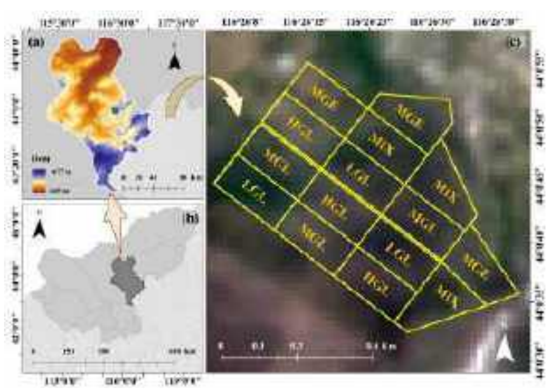

Figure 1 Study area and experimental design. Figure a showed the elevation of Xilinhot and the location of the study area, Figure b showed the location of Xilinhot in the Xilingol League, and Figure c showed the plots arrangement of the experimental design.

Results

DODBA and DGT under different grazing managements

The DODBA of lambs under different grazing intensities showed no significant differences (FIG.2-a). However, DODBA exhibited a significant decreasing trend over the months ($P<0.05$). In contrast, significant differences in DODBA were observed among sheep from different flocks (FIG.2-b; $P<0.001$), with the highest values recorded in the MME treatment and the lowest in the MML treatment. Significant differences were observed in the DGT of lambs across different grazing intensities ($P<0.05$), with the MGL treatment exhibiting the shortest DGT (FIG.2-c). And a significant decreasing trend in DGT was observed over the months ($P<0.05$). Similarly, the DGT of sheep varied significantly among different flocks (FIG.2-d; P<0.001), with the longest DGT recorded in the MGL treatment and the shortest in the MGE treatment.

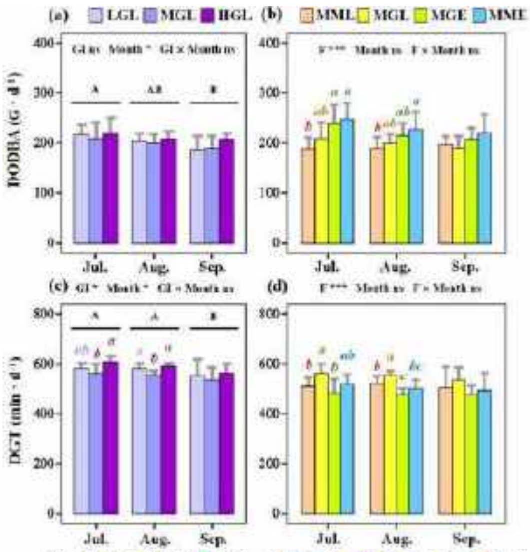

Figure 2 Differences in the sheep grazing activity among various grazing managements. Figures a,b represented the differences in daily overall dynamic body acceleration (DODBA) of sheep under different grazing intensities (GI) and different flocks (F), respectively. Figures c,d represented the differences in daily grazing time (DGT) of sheep under different grazing intensities and different flocks, respectively.

DFI and ADG under different grazing managements

There were no significant differences were detected in the DFI or ADG of lambs under different grazing intensities (FIG.3-a,c). However, both DFI and ADG exhibited a significant decreasing trend over the months (P<0.01). Conversely, significant variations in DFI and ADG were observed among sheep from different flocks (FIG.3-b; P<0.001). Specifically, ewes (MGE, MME) had significantly higher DFI compared to lambs (MGL, MML), while their ADG was significantly lower.

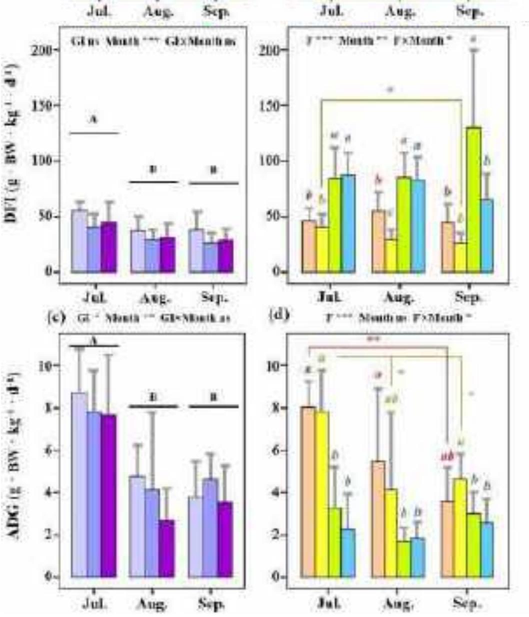

Figure 3 Differences in the sheep productivity among various grazing managements. Figures a,b represented the differences in daily feed intake (DFI) of sheep under different grazing intensities (GI) and different flocks (F), respectively. Figures c,d represented the differences in average daily gain (ADG) of sheep under different grazing intensities and different flocks, respectively.

Relationship between sheep productivity and grazing activity under grazing managements

The generalized linear mixed model revealed that, under varying grazing intensities, the ADG of lambs was predominantly influenced by the positive impact of DFI (Fig.a; P < 0.001). Conversely, within different flocks, ADG was predominantly influenced by the positive effect of DGT (FIG.4-b; P < 0.01) and negatively influenced by DODBA (P < 0.01).

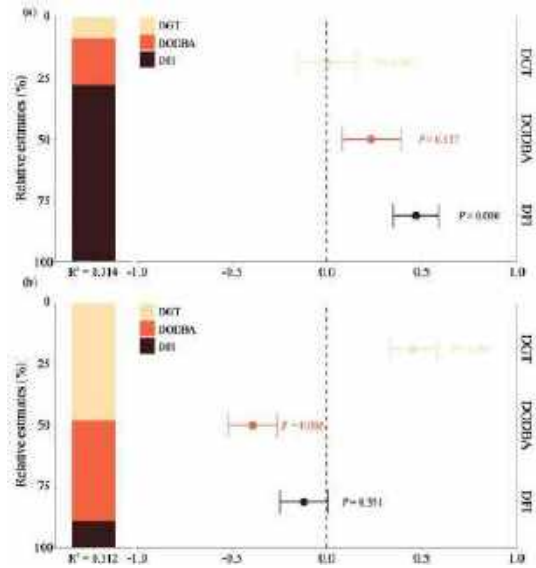

Figure 4 Effect of grazing activity of sheep on their productivity under different grazing managements (GLMM). Figure a showed the effects of grazing behaviors of sheep on their productivity under different grazing intensities, and Figure b showed the effects under different flocks.

Discussion

According to the results of the GLMM, grazing intensity influenced ADG through DFI. However, no significant differences in DFI were observed among lambs under different grazing intensities. This lack of variation could be attributed to the comparable growth stages of lambs across treatments, as factors such as body size and age–which were key determinants of feed intake and weight gain–were similar. Consequently, no significant differences in DODBA or DFI were detected among the treatments, resulting in non-significant differences in ADG (Charnov, 1976). Significant differences in ADG were observed among sheep from different flocks, with ewes displaying significantly lower ADG compared to lambs. Moreover, the DGT in the MGE treatment was significantly shorter than that in the MGL treatment, whereas the DFI of ewes was significantly higher than that of lambs. According to the GLMM, flock influenced ADG through DGT and DODBA. This could be attributed to the similar grazing intensities across treatments, which provided comparable access to pasture resources. Simultaneously, ewes, due to their greater grazing experience, exhibited higher foraging efficiency, spending less time while consuming more feed (Thórhallsdóttir et al., 1990). However, the larger body weight of ewes relative to lambs resulted in higher energy expenditure during grazing, as reflected in the higher DODBA (Mysterud and Austrheim, 2016). Additionally, the presence of ewes and lambs grazing together may have introduced lactation-related behaviors, with lambs benefiting from additional nutrition through nursing (Pullin et al., 2017). The interaction of these factors, in conjunction with the physiological stages, led to the lower ADG in ewes compared to lambs. In conclusion, grazing management significantly influenced sheep productivity and grazing behavior, with grazing intensity affecting productivity through feed intake and flock structure influencing activity levels, offering insights for optimizing steppe grazing practices.

Acknowledgements

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Effects of fermentation time of natural-pasture-based total mixed ration on slaughter performance and organ development of sheep

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Key words: Fermenting total mixed rations, spleen, production, health

Abstract

Fermenting total mixed rations (FTMR) is an important method for changing traditional extensive livestock farming practices, improving animal health, and enhancing the quality of livestock products. It offers several advantages, including a wide source of feed raw materials, a long and safe storage time, labour and time savings and providing nutritionally balanced feed for pastoralists throughout the year. However, the existing data are insufficient about how FTMR with different fermentation durations affect animal performance and health. Therefore, this study aims to evaluate the effect of natural forage silage-based FTMR with different fermentation durations on production and health of sheep. In Hulunbuir, total mixed rations were formulated with natural forage silage on a fresh weight basis, and fermented for 0 day, 10 days and 20 days respectively. Eighteen sheep were selected and randomly divided into three groups of six sheep. The three groups were fed TMR (CK), FTMR fermented for 10 days (FTMR1) and FTMR fermented for 20 days (FTMR2) over a period of 75 days, respectively. Results showed no significant differences in carcass weight, carcass yield, longissimus dorsi muscle (LDM) area and GR value among the groups (P>0.05). The FTMR2 group had a significantly higher spleen weight and proportions to carcass weight than the other groups, with no significantly differences between CK and FTMR1. Other organ weights and proportions to carcass weight showed no significant differences (P>0.05). In conclusion, FTMR provides similar effects to TMR without harming organs. FTMR fermented for 20 days promotes spleen development and immune function, benefiting livestock health.

Introduction

In the Mongolian Plateau, native grass serves as the primary fodder source for livestock production. Apart from making hay, ensiling native grass is seen as an emerging new trend (Hou et al., 2023; Y. Li et al., 2022). Total mixed ration is an ideal method for meeting the growth requirements of livestock by combining native grass silage with other roughage, concentrates, vitamins, and minerals. It can reduce selective feeding, increase dry matter intake, and stabilize the rumen internal environment, compared with the traditional feeding model (Beigh et al., 2016; Bharanidharan et al., 2021). However, TMR is susceptible to aerobic spoilage (Seppälä et al., 2013), and requires a high level of mechanization in the production process (Bueno et al., 2020). These factors limit the circulation and promotion of TMR, especially in some Asian countries. Currently, in Asian countries, livestock farming operates at a household or small-scale farm basis is typical. Due to constraints in funds, technical knowledge, and production equipment, farmers find it is challenging to adopt TMR for livestock feeding.

Nevertheless, fermented total mixed ration (FTMR) can save labour in the TMR preparation process, enabling long-term storage and distant distribution of TMR (Weinberg et al., 2011). Compared with TMR, FTMR improves the aerobic stability (Wang et al., 2016) and nutrient digestibility of the diet (Miyaji et al., 2017), while reducing methane emissions (Cao et al., 2010).

Throughout the FTMR distribution process, farmers often purchase and store large quantities of FTMR at once. In this process, the nutritional composition of FTMR could be influenced by factors such as raw material composition, storage time, and storage conditions. Studies indicate obvious changes in the soluble protein and soluble sugar fractions in FTMR; solubilization of the protein fraction in FTMR is enhanced with prolonged storage and higher storage temperatures, while most soluble sugars are lost during the fermentation process (Weinberg et al., 2011). However, the existing data are insufficient about how FTMR with different fermentation durations affect animal performance and health. Therefore, this study aims to evaluates the effects of natural forage silage-based FTMR with different fermentation durations on production and health of sheep.

Methods

Animals, diets, and experimental design

Eighteen sheep of similar weight (33.55 ± 0.86 kg) were randomly divided into three groups of six head. The groups were fed either a total mixed ration (CK), a short term fermented total mixed ration (FTMR1, fermentation time for 10 days), or a long-term fermented total mixed ration (FTMR2, fermentation time is 20 days). Total mixed rations were formulated according to the nutrient requirement of a meat-type sheep (NY/T816-2021). The main components of the native pasture species are *Leymus chinensis*, *Bromus inermis*, *Potentilla bifurca*, *Astragalus laxmannii*, and *Artemisia argy*i. The experiment lasted for 75 days, including a 14-day pre-feeding period and a 60-day formal study period. The pre-feeding period was the same as the test period in terms of feeding management and formula composition. The animals were fed twice a day at 08:00 and 18:00, with free access to water.

At the termination of the experiment, sheep were then slaughtered using commercial methods. The sheep were weighed (LWBS) after fasting for 12 h before being processed for slaughter. Carcase weight was recorded after removal of the hide, head, hooves and viscera. The heart, liver, spleen, lung and kidney were separated, and the proportion of each organ weighed. An organ weight to LWBS index was calculated. The GR value was measured by vernier caliper to measure the tissue thickness between the 12th and 13th ribs of sheep at the 110 mm from the midline of the dorsal spine. Eye muscle area (EMA) was the cross-sectional area of the LDM between the 12th and 13th ribs of the carcass.

Data were analyzed using Excel 2021 to calculate means and standard errors, and SPSS 25.0 software was employed for statistical analysis. Multiple comparisons of measured data were conducted using Tukey's method.

Results

The effects of TMR fermented for different durations on the slaughter performance of meat sheep are shown in Table 1. No statistically significant differences ($P > 0.05$) were observed among the three treatment groups for any of the indicators. However, the groups fed fermented total mixed rations (FTMR) showed higher live weight before slaughter, carcass weight, and slaughter yield compared to the group fed non-fermented TMR.

The effects of TMR fermented for different durations on the organ development of meat sheep are shown in Table 2. The FTMR2 group exhibited significantly greater spleen weight and spleen index when compared with CK and FTMR1, while no statistically significant differences were found between the TMR and FTMR1 groups. For the other organs, there were no significant differences in organ weight or their proportion to carcass weight among the three treatment groups ($P > 0.05$).

Table 1 Effects of FTMR with different fermentation duration on the slaughter performance of sheep

Item	CK	FTMR1	FTMR2	SEM	*P*-value
LWBS (kg)	41.45	42.10	43.83	1.53	0.711
Carcass weight (kg)	17.69	18.09	19.78	0.79	0.602
Carcass yield (%)	42.64	43.01	45.11	0.86	0.534
EMA (cm^2)	18.88	19.41	16.15	0.15	0.622
GR value (mm)	4.30	5.63	5.27	0.31	0.165

EMA = Eye muscle area of the longissimus dorsi.

In the same row, mean values with different superscripts were significantly different ($P < 0.05$).

Table 2 Effects of FTMR with different fermentation duration on organ development of sheep

Item	CK	FTMR1	FTMR2	SEM	*P*-value
Organ weight (g)					
Heart	229.50	231.75	269.33	4.84	0.366
Liver	495.00	564.00	535.33	18.21	0.365
Spleen	39.50b	45.75b	59.67a	21.86	0.010
Lung	419.50	427.75	510.00	19.55	0.082
Kidney	96.75	102.75	109.00	6.08	0.530
Percentage relative to empty BW[1], (g/kg)					
Heart	5.85	5.91	6.87	0.95	0.366
Liver	12.63	14.39	13.66	1.14	0.365
Spleen	1.01	1.17	1.52	0.25	0.010
Lung	10.70	10.91	13.01	1.02	0.082
Kidney	2.47	2.62	2.78	0.32	0.530

In the same row, mean values with different superscripts were significantly different ($P < 0.05$).

[1] Percentage relative to empty BW (%) = (the organ weight/empty BW) × 100%.

Discussion

Slaughter performance is a direct reflection of the production efficiency of livestock, serving as a key indicator of their economic value. Common metrics for assessing slaughter performance include carcass yield, EMA and the GR value. The EMA is an indicator of carcass quality, while the GR value serves as an indicator of carcass fat cover. In the present study, no significant differences were observed in slaughter yield, eye muscle area, or GR values across different treatment groups, suggesting that feeding meat sheep with fermented total mixed rations (TMR) yields results comparable to those achieved with non-fermented TMR.

Visceral organs play a fundamental role in an animal's metabolism. The weight and organ index of these organs reflect the animal's metabolic and developmental status. Under normal circumstances, organ development is closely coordinated with overall growth (Su et al., 2022). In this study, with the exception of the spleen, there were no significant differences in the weight and organ index of other organs between treatment groups, indicating that TMR fermented for varying durations does not adversely affect organ development. The spleen, a primary site for immune cell generation, differentiation, maturation, and immune responses, is crucial for immune function. Notably, the FTMR2 group exhibited a significant increase in both spleen weight and spleen index, suggesting that long-term fermentation of TMR promotes spleen development in sheep. Previous research has shown that lactic acid bacteria can significantly enhance spleen development in livestock (Sun et al., 2024), likely due to their proliferation during the fermentation process. As probiotics, lactic acid bacteria produce a range of bioactive compounds, including organic acids, short-chain fatty acids, and extracellular polysaccharides(A. Li et al., 2024), which may modulate the immune system and bolster immune responses (Vieco-Saiz et al., 2019).

The study demonstrates that FTMR maintains comparable slaughter performance to TMR in meat sheep while enhancing spleen development.

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THEME 7. MULTI-FUNCTIONAL LAND USE IN RANGELANDS – MOVING BEYOND NICHE OPPORTUNITIES

System wide alternative land uses

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3R's: Regenerative rangeland ranching in southern north America

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Abstract
Our research team proposes a sea change in southern North American rangeland from ranching solely for production to husbanding for stable, regenerative grasslands. Rangelands in southern North America are too often ecologically, biologically and economically dysfunctional, degenerating ecosystems. Plows, cows and bankers dominate, supported by equally short-sighted, discipline-focused academia and industry. We propose regenerative rangeland ecosystems research based on long-term, multi-functional, flexible-use goals sustained by interdependent hydrology, soil, climate, vegetation and animal components and carried out by multi-disciplinary teams. Flexibility in meeting food, energy and ecosystems service markets can take rangeland systems beyond niche production and its inherent inexorable degradation to stable, multi-functional rangelands in southern North America. Our research and development team brings together social and biological scientists with stakeholders focused on medium and long-term regenerative rangeland management.

Introduction

We propose a sea change in southern North American rangeland research from ranching solely for production to husbanding for stable, regenerative grasslands. We define regenerative ranching (RR) as herbage-based ruminant agriculture that uses resilient, ecologically and economically sustainable grasslands management with minimal environmental disruptions or outside inputs. According to Jayasinghe et al. (2023), regenerative agriculture restores and maintains ecosystem (hydrology, soils, plants, animals etc.) health while still feeding human populations. Our multi-disciplinary team proposes research that focuses on multiple functions within RR (Fig.1).

Figure 1. Multi-disciplinary research for multi-functional regenerative ranching.

One of the basic tenets we adopt as a multi-disciplinary approach to regenerative ranching research, outreach and implementation is biodiversity. Biodiverse grassland ecosystems, from soil to vegetation to animals and the human dimension, tend to be more resilient biologically and socioeconomically (Picasso et al. 2022).

Methods

Human dimensions of regenerative rangeland ranching

We have learned the hard way that we are far more successful when we incorporate human dimensions in RR research. These involve the social, cultural, and economic aspects that influence relevance, adoption and success of regenerative practices in rangeland management. These dimensions emphasize the importance of understanding landowners, communities, policymakers, public perception, and consumers interacting with, and depending on, rangelands (Tolleson and Metman 220; Giwa et al. 2024). Before initiating biological research efforts, we believe we should identify local challenges and priorities through key informant interviews, structured surveys and questionnaires, community meetings, participatory mapping, and data analysis aid in aligning ranching operations with community goals, such as improving soil health, increasing biodiversity, supporting livelihoods, preserving cultural heritage, and ensuring regenerative practices meet both ecological and socio-economic needs (Donaldson and Franck 2016).

The significance of human relationships and connections to the community and ranching itself directly benefits or undermines regenerative rangeland ranching efforts. Humans influence all decisions, and regenerative ranching trajectories starts and ends within communities, organizations, and government, most local to the system of interest (Berkley and Beratan 2021). Any effort at directed system change requires coordinated actions among our diverse participants, academic, management and government. This decision-action context means community and personal relationships are crucial to developing workable, adoptable regenerative ranching solutions (Lu et al. 2024).

Restoring rangeland health

Woody plant cover across semi-arid and sub-tropical grassland savannas is increasing on a global scale; multiple drivers contribute to this encroachment, including, but not limited to, land use changes, fire suppression, cattle grazing practices, and climate change (Archer et al. 1988). Most of these changes involve dramatic increases in native woody taxa that were historically present in low densities.

Such changes in woody cover impact overall system biodiversity, ecosystem function and related ecosystem services, including food production but not always in a negative way, as it can also add resilience. A review by Eldridge et al. (2011) indicated that encroachment had mixed effects on ecosystem structure and functioning at global scales, and that woody plant traits influence the functional outcome of encroachment. A simple designation of encroachment as a process leading to degraded ecosystems is not supported in every instance. The literature on the negative effects of woody encroachment has been strongly influenced by the prevalence of a single land use, for example pastoralism involving grass-feeding livestock. Woody plant expansion will likely continue based on past trends and future projections, especially in arid and semiarid ecosystems (Asner et al. 2004, Van Auken 2009). If animals are matched with the landscape, woody plants may add an aspect of resilience, given their resistance to long-term drought and their resilience with respect to overgrazing (Estell et al. 2012).

Adapting ranching to landscape rather than landscape to animal production

As an essential part of RR, we propose adapting extractive or environmental management goals to the ranch ecosystems rather than the other way around. Instead of manipulating grasslands to fit unsuitable agricultural practices, we seek to research and support land managers to utilize what the ecosystem is best adapted to producing for human needs. For example, if browse dominates plant populations in a ranch ecosystem, then manage for ruminants that prefer converting dicots into consumable products (Irob et al. 2021). This is far more regenerative than manipulating vegetation, at high economic and environmental costs, to favor monocots for mono-specific grazing ruminant herds.

On the animal side, we propose adapting ruminant species, both domesticated and native, to ranch soil and vegetation strengths (Muir et al. 2015). If Eurasian cattle, for example, prove detrimental to RR ecosystems, then we will consider non-traditional domesticated ruminants from Asia, Africa and the Americas. If quasi-domesticated species, both native and introduced, are best suited to an ecosystem, then these will replace cattle, goats or sheep. Likewise, if native bees are best adapted to a biodiverse rangeland, for example, then European bees will not be purposely introduced. If native wildlife are better adapted to the ecosystem, then white-tailed deer, elk and bison can replace cows, sheep and goats.

No matter how much we would like to think the contrary, native wildlife and domesticated animal grazing are not always compatible on North American Rangelands (McGinn et al. 2022). There is a preponderance of evidence, however, that well-managed domesticated livestock herbivory can contribute to regenerative rangeland conditions that favor a return to complex, native animal trophic levels based on healthy soils and diverse native plant communities (Gordon et al. 2021), by replacing extirpated native bulk grazers and browsers. Wildlife resources, whether as primary land-management efforts (e.g. food harvest) or secondary (e.g. conservation and ecosystems services), are a priority in regenerative ranching in southern North America.

Ecosystems services and other economic incentives

Ecosystem services (ES) are generally categorized as: a) provisioning, b) cultural, c) supporting, and d) regulating. Rangeland based examples of each are: a) animal source protein, b) open space, c) biodiversity, and d) pollination (SRM 2023). Modern ranchers not only produce food and fiber, but they also support wildlife habitat, enable watershed function, provide recreational opportunities, mitigate wildfires, and address their operation's impacts on climate change. And they do so under increased scrutiny from a public that typically does not understand who they are and what they do (Nolte 2021).

Fortunately, ecosystem goods and services are what "good" ranchers have always done. They have long understood that ranching begins with taking care of the soil, which retains the water and produces the vegetation that feeds and shelters the animals (Lien et al. 2017). Many have known that a variety of plants are required to keep rangelands, especially in drier climes, healthy. An appreciation for wild places and wild things has always been an integral part of their culture.

However, as with any human undertaking, not all ranchers have been good stewards (Angerer et al. 2023). Additionally, ranching is changing. New ownership demographics are evolving (Lopez et al. 2023). These new ranch owners may vary from large investors or companies who want to improve their "green" footprint, the next generation in a ranching family that has moved back to the ranch, or to new landowners who may or may not have the required knowledge and experience to effectively manage a ranch and often have different motivations for land ownership than traditional ranchers.

It is therefore incumbent on the scientific community to address the challenges facing modern ranchers, regardless of goals, background, and experience. Rangeland-based ranching decisions in North America have historically been driven by manager demographics and economic necessities (Peterson and Coppock 2001). More recent data indicate that public (economic incentives) as well as changing private (cultural priorities) initiatives factor into environmental concerns in some regions such as California, especially in regard to ecosystems services and conservation (Oyama and Huntsinger 2019) inherent in regenerative ranching approaches. If researchers have any chance of convincing rangeland managers to implement regenerative ranching in southern North America, we must be at the forefront of designing, testing and promulgating novel economic and cultural motivations.

Conclusions

Our proposed multidisciplinary, multi-objective and flexible approach to RR ultimately seeks to restore and maintain ranching sustainability while maximizing outputs. Through research and education, we hope to diversify management goals and socioeconomic outputs to include not just the traditional domesticated ruminants but flexible goals such as bioenergy, wildlife, ES, and human dimensions.

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Irrigated and rainfed cropping on northern Australian rangelands

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Key words: Agricultural development; Analysis of fodder, fibre and food production areas; Cropping expansion; Growth rate; Percentage of rangelands

Abstract

Over the last quarter of a century a small part of the northern Australian rangelands has been converted to cropping for fodder, fibre and food production. The expansion of cropping onto rangelands has been slow and still is small in percentage terms (0.04 %) when compared to the area of northern Australia (300 million hectares). Much of the cropping area is being used to grow fodder crops, however, cotton, grain sorghum, table grapes, citrus, watermelons, sweet corn, potatoes and vegetables are also being grown. State and Territory governments are encouraging development in cropping and horticulture on rangelands by undertaking research into water and soil resources and funding feasibility studies for development of new regional infrastructure such as cotton gins and water supplies. This paper analyses the changes that are happening, specifically in rangelands, and is based on a broader study that has assessed all cropping, horticulture and plantation forestry across northern Australia in 1999 and 2023 using Sentinel and Landsat imagery as well as other publicly available information. Irrigated cropping, horticulture and sandalwood plantations on northern Australian rangelands occupied 5,393 Ha in 1999 expanding to 17,481 Ha in 2023, a three-fold increase over 24 years, a net annual increase of 504 Ha or an annual compounded growth of 5 %. Rainfed cropping and forestry occupied 11,878 Ha in 1999 expanding to 94,963 Ha in 2023, an eight-fold increase over 24 years, a net annual increase of 3462 Ha or an annual compounded growth of 9 %.

Introduction

How much of northern Australian rangelands have been converted to cropping? At what rate are the rangelands being converted? Where is the conversion taking place and why? To be able to answer these questions we require land use data. Since 1990, State and Territory agencies have been mapping land use (DAFF 2024) however, this data is a mosaic of mapping products with varying time stamps and resolutions (ABARES 2023). It has, therefore, been impossible to answer the above questions without methodically examining satellite imagery. The objective of the original study was to adjust the publicly available land use data to a consistent time and resolution using satellite imagery and other publicly available information and map the changes that have occurred in cropping, horticulture and forestry on northern Australian rangelands. This rangelands analysis is based on the data collected in the broader study.

Methods

Scope

This analysis of fodder, fibre and food cropping was to analyse the expansion of cropping and horticulture onto rangelands in northern Australia (north of the Tropic of Capricorn). This analysis excluded the cropping and horticultural occurring in the Ord River Irrigation Area, Carnarvon Irrigation Area, Skuthorpe, Mataranka, Katherine, Douglas – Daly, Darwin, Gilbert River Agricultural Precinct and Julatten area. We also did not include catchments that drain into Great Barrier Reef lagoon (northeastern Queensland). Results are expressed to at least the secondary level of the Australian Land Use Classification (ABARES 2016) and are expressed in hectares (Ha) of land rather than crop yields or commodity values. For growth or decline in area, annual compounded percentage is used. For absolute change between 1999 and 2023 area is used.

Method

Land use data was collated from existing mapping undertaken by State and Territory agencies (ABARES and DPIRD 2018; DEPWS 2022; QLUMP 2024) and adjusted with publicly available Sentinel and Landsat satellite imagery from 1999 (Geoscience Australia 2022) and 2023 (Fuqin *et al.* 2019). Cropping or horticulture on rangelands was deemed to be present if it was visible on the satellite imagery at any time during the calendar years 1999 and/or 2023. Cropping or horticulture was not accounted for if it was established after the year 1999 and ceased before the year 2023. Cropping or horticulture that appears abandoned was not included in the data. However, land that appears fallow between crops and the crop can be identified using nearby fields was included. Commodity was confirmed where possible using publicly available data on the world wide web or local knowledge.

Results

Irrigated and rainfed fodder, fibre and food crops occupied 17,271 Ha in 1999 expanding to 112,368 Ha in 2023. This was a 6.5-fold increase in area or nearly 4000 Ha per year resulting in a compound growth of 8 % per annum. Fodder, broadacre cropping and forestry accounted for the largest percentage of this area. Most of the forestry was restricted to Melville Island as a plantation of *Acacia mangium* for pulp wood.

Irrigated cropping and horticulture occupied 5,393 Ha in 1999 expanding to 17,481 Ha in 2023, a three-fold increase over 24 years, an increase of 504 Ha per year resulting in a compound growth of 5 % per annum. Rainfed cropping occupied 11,878 Ha in 1999 expanding to 94,963 Ha in 2023, an eight-fold increase over 24 years, an increase of 3462 Ha per year resulting in a compound growth of 9 % per annum.

Most of the expansion in irrigated cropping has been to produce fodder such as hay and silage, pasture and forage sorghum. Irrigated horticulture is mostly restricted to single enterprises and has changed little over the 24 years of the study. Most of the expansion in rainfed agriculture has occurred as cropping to produce fodder mostly as forage sorghum (1894 Ha per annum). Expansion in rainfed broadacre cropping has occurred as grain sorghum and cotton (274 Ha per year). Plantation forestry (Mangium) on Melville Island and African mahogany (Daly catchment) are excluded from this summary but results are shown in the Table 1.

Cropping varies between regions and is affected by local drivers. In the Pilbara, water from mine dewatering activities has caused an expansion in irrigated fodder cropping. On the grazing country between the Great Sandy Desert and the Indian Ocean, fodder cropping and horticulture (sweet corn and melons) using groundwater resources was being grown. A single sandalwood plantation exists in the Ord River catchment using water from their own large gully dam. Cotton is establishing in the Daly catchment as well as vegetables and melons. Melons and table grapes are being grown in remote areas of central Australia. Cotton is expanding in the southern Gulf of Carpentaria catchments. Hay is being produced in the northern parts of the Channel Country of Queensland.

Table 1 Area and change in fodder, fibre and food crops on northern Australian rangelands

	Land use / Year	1999 (Ha)	2023 (Ha)	Change (Ha)	Growth* (%)
Rainfed	Forage sorghum	n/a	44,724		
	Hay & Silage	2,329	3,038	709	1.1
	Fodder	**2,329**	**47,762**	**45,433**	**13.4**
	Cereals	n/a	5,345		
	Cotton	n/a	4,188		
	Broadacre cropping	**3,003**	**9,577**	**6,574**	**5.0**
	Horticulture	**5**	**42**	**37**	**9.3**
	African mahogany	n/a	5,768		
	Mangium	5,200	31,766	26,566	7.8
	Plantation forestry	**6,517**	**37,558**	**31,041**	**7.6**
	All fodder, fibre and food	**11,878**	**94,963**	**83,085**	**9.0**
Irrigated	Irrigated pasture	111	1,846	1,735	12.4
	Forage sorghum	n/a	1,219		
	Hay & Silage	1,131	4,884	3,753	6.3
	Fodder	**1,242**	**7,949**	6,707	8.0
	Cotton	n/a	3,978		
	Broadacre cropping	**2,129**	**4,655**	**2,526**	**3.3**
	Table grapes	2	453	451	25.4
	Orchards**	261	305	44	0.7
	Perennial horticulture	**414**	**797**	**383**	**2.8**
	Melons	729	732	3	0.0
	Vegetables	327	1,027	700	4.9
	Seasonal horticulture	**1,090**	**1,800**	**710**	**2.1**
	Sandalwood	n/a	2,121		
	Plantation forestry	**518**	**2,130**	**1,612**	**6.1**
	All fodder, fibre and food	**5,393**	**17,481**	**12,088**	**5.0**

*Compound growth **Including mango, citrus and date plantations

Discussion

This research provides a more quantitative analysis of fodder, fibre and food cropping on northern Australian rangelands than has been done previously. This study has attempted to adjust / correct / update the available data as far as practical without doing a field survey and thus we believe provides more authoritative information on state and trend currently about fodder, fibre and food cropping on northern Australia rangelands. An ultimate inventory of land use would require a field survey, however, even a field survey can not provide the historical data for 1999. We used Sentinel satellite imagery to confirm land use in 2023, but we were limited by the lower resolution Landsat imagery available for 1999. Because ACLUMP is a multi-agency program with varying levels of implementation of the Australian land use and management classification (ABARES 2016), it is difficult to make a detailed assessment of current state and trends from their data.

Despite much recent interest and activity in northern Australian development, the increase in rainfed and irrigated cropping away from existing schemes and other clusters of development is relatively low in comparison to the area of rangelands as a whole. This is due to several factors including regulatory and legal constraints to land clearing and land use as well as access to water for irrigation. The economic viability of cropping also constrains expansion. Long distances to milling, markets or ports results in high transport costs which need to be offset by higher value crops. Commodity crops, or other crops of low value struggle to be viable. More promise is held for higher value crops or higher value horticulture aimed at supply gaps in southern Australian (or other markets).

What might the next decade or two look like? Two factors may limit increased area. Tighter restrictions on diversification of pastoral leasehold land may limit expansion. Some of the 'low hanging fruit' may have been developed in the past 24 years. By contrast, the construction of two new cotton processing facilities in northern Australia will make cotton production more viable, which may cause rapid increases in the area of (particularly rainfed) cotton.

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Grazing with Trees: upscaling silvopastoralism for improved dryland management

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Key words: silvopastoral systems; drylands; rangelands; sustainable land management

Abstract
This presentation describes the first results of the Grazing with Trees (GWT) initiative, promoted by FAO as a response to the Committee on Forestry (COFO) 26th session request to "promote greater and inclusive policy coherence between the agriculture and forestry sectors, including through integrated land use planning, landscape approaches". The main target of the initiative is to promote enabling environments for dryland Silvopastoral Systems (SPSs). These agroforestry schemes provide multiple benefits and ecosystem services in dryland regions as evidenced by the recent FAO publication *Grazing with Trees*, which seeded the initiative. Being uniquely adapted to landscapes with water scarcity and climatic variability, SPSs can evidently improve the resilience of landscapes and communities to the impacts of climate change, combat desertification, improve watershed management and provide diverse food sources and livelihood opportunities for dryland communities.

The GWT initiative aims to strengthen, at country level, the capacity to mobilize resources and investment tools to incorporate SPSs into Land Degradation Neutrality commitments and Intended Nationally Determined Contributions under the Paris Agreement. GWT seeks to improve effective policy, legislation and institutional arrangements supporting climate-resilient silvopastoralism, especially those adopted by pastoralist and forester communities. The presented outcomes include participation-based silvopastoral policies, strategies and land-use management plans developed and adopted by communities in target landscapes and additional outcomes related to improved governance, participatory institutions and enhanced investment options identified through multistakeholder consultations and application of FAO assessment tools and knowledge products.

Introducing the Grazing with Trees initiative
Drylands and presumed drylands account for approximately 48% of the Earth's land surface and are home to 25% of the human population. They support 50% of the world's forests, 50% of global livestock and 44% of global cultivated systems. Furthermore, they harbour 46% of global carbon reserves and 36% of the earth's biodiversity hotspots.

Woody vegetation and trees provide essential ecosystem services in dry areas, including animal feed, timber, fruits, shade and regulation of soil and water cycles. Equally, livestock production, in particular pastoralism, is critical for livelihoods and food security and supports the resilience of about one billion people throughout the Earth's dryland ecosystems.

Forests and livestock have been widely considered as antagonists; the latter considered a driver for the degradation of forests. Regardless whether it is important to address the real environmental footprint of pastoralism and encourage an adequate responsibility-sharing with other production systems, the impact of livestock also needs urgent action. Between 2000 and 2018, 68 Mha of dryland forests were cleared in South America and 49 Mha of dryland forests were cleared in Africa (FAO 2019). Cropland expansion was the highest driver of deforestation, accounting for almost 50% (many of them fodder-oriented), but it was closely followed by livestock production, accounting for 38.5% of the deforestation. Livestock is also considered a major source of greenhouse gas (GHG) emissions, accounting for almost 14.5% of the total.

Accordingly, there is an urgent need to adopt improved livestock management practices to both improve efficiency of natural resource use and decrease environmental impacts. FAO estimates that improved management practices alone could reduce net emissions from livestock systems by about 30% (FAO 2016). Halting deforestation and maintaining forests could avoid emitting 3.6 +/- 2 gigatons of carbon dioxide equivalent (GtCO2e) per year between 2020 and 2050, including approximately 14% of what is needed before 2030 to keep planetary warming below 1.5 °C, while safeguarding more than half the Earth's terrestrial biodiversity (FAO 2022b).

Integrating livestock with trees and other woody vegetation results in a complementarity of agroforestry systems – a silvopastoral system (SPS) – that can boost the local ecosystem, representing a positive transition towards an integrated perspective of livestock and forest production. SPSs support high-value food sources for livestock that can increase productivity, especially milk production, while acting as a primary pathway for forest restoration in dryland areas.

Being uniquely adapted to landscapes with water scarcity and climatic variability, SPSs can improve the resilience of landscapes and communities to the impacts of climate change, combat desertification, improve watershed management and provide diverse food sources and livelihood opportunities for dryland communities.

This paper describes the first results of the Grazing with Trees (GWT) initiative, started by FAO to develop enabling environments for mainstreaming dryland SPSs. This initiative is seeded by the FAO publication: *Grazing with Trees* (FAO 2022a) aimed to support silvopastoral approaches and develop enabling environments for dryland SPSs.

This initiative specifically responds to the Committee on Forestry (COFO) 26th session request to "promote greater and inclusive policy coherence between the agriculture and forestry sectors, including through integrated land use planning, landscape approaches" The initiative also answer the request of the country members of the COFO Working Group (WG) on Dryland Forests and Agrosilvopastoral Systems to generate evidence on how SPSs could contribute to the restoration of woody ecosystems in drylands, mitigating desertification and drought. Accordingly, the GWT initiative will strengthen countries' capacity to design on-the-ground drought-resilient SPS investment proposals and to mobilize resources to achieve their Intended Nationally Determined Contributions under the Paris Agreement. In doing so, it will enhance pastoral agrifood systems in dryland areas and improve communities' resilience to climate change and other crises. By building partnerships with communities, development actors and governments, the initiative will also facilitate South–South dialogue and investment fora so that communities can share challenges, opportunities and lessons learned, encouraging collaboration to strengthen drought-resilient and gender-responsive silvopastoral value chains in selected countries.

Methodological approach: first steps for a multilevel strategy

GWT focuses on creating enabling environments for developing SPSs in dryland areas. Its methodology intends to gather together country members to coordinate action. To this end, successful implementation requires well-designed, integrated cross-sectoral strategies with effective policies, governance and land management. Several pilot countries will implement those strategies at different levels: country, state and local and report to the project for analysis and discussion.

The first step is sourced by the GWT publications and delivers the rationale for mainstreaming silvopastoralism, gathering and operationalizing the conclusions and recommendations of the report.

A second step consists in delivering a roadmap for willing countries to promote enabling environments by improving effective policy, legislation, institutional arrangements, multistakeholder platforms and pilot experiences supporting climate-resilient dryland SPSs, especially those adopted by pastoralist and forester communities. This way, silvopastoral management could be integrated and mainstreamed into national grazing and forest policies, legislation and institutional arrangements in target countries. Specifically, a clear line of action is sought regarding the potential of SPSs for climate action, addressing at the same time adaptation to and mitigation of climate change. This line of work was derived to a new initiative focused on potential of SPSs for decarbonization.

The third step targets actual implementation on the field. While dryland developing countries often have or are able to develop policies that can support SPSs, effective implementation is generally lacking, and investment is not a priority, often due to a lack of awareness and appropriate investment solutions, and limited capacity for implementation or sustaining communities' practices and traditional systems. Investment is a bottleneck for dryland projects and, accordingly, improving financial and investment tools will be a critical outcome of the project. SPS investment opportunities are identified through multistakeholder consultations on targeted and inclusive value chains, to be assessed against the financial needs of the silvopastoral projects.

In addition, this initiative also addresses critical cross-cutting issues, often by close collaboration with other ongoing FAO Drylands projects, including knowledge management, gender equality and governance. For example, knowledge management tries to build capacities of stakeholders and decision-makers, but also targets the co-construction of knowledge with farmers, pastoralists and local communities (including grassroots associations and indigenous groups) in effective, integrated and silvopastoral management for sustainable production and forest and agricultural biodiversity.

First results

SPSs can derive multiple benefits from the ecological relationships between animals and woody plants (Plieninger & Huntsinger 2018). These benefits combine improved food production and security with increased livelihood adaption and resilience, while acting as a primary pathway for forest restoration and sinking carbon in dryland landscapes by enhancing the above- and below-ground carbon capture through improved pasture management, tree planting and assisted natural regeneration. The integration of trees in SPSs – where trees are introduced into grazed pastures – can be very effective in capturing and temporarily storing carbon. It also enhances productivity and protects against the extreme weather conditions (Agethen et al. 2021).

Benefits evidenced from previous projects in dryland regions that introduced SPSs were documented in *Grazing with Trees* (FAO 2022b). For example, microclimate measurements show lower soil temperatures in pastures with trees (2.2–2.3°C at 5 cm from the surface). Economic analysis of various intensified SPSs in Latin America found that the income generated was far higher than the investment in all cases (Chara et al. 2017). In India, the Jhansi dryland areas have increased their production tenfold using a ten-year silvopastoral rotation plan (Yadav et al. 2019). In Senegal, hundreds of villages have protected their common grazing lands over the last 30 years, transforming degraded shrubs into savannah landscapes and increasing woody cover by up to 65% (Pasiecznik & Reij 2020).

The scoping accompanying the production of the roadmap has also provided some results and key lines of work targeting the links between forests, agriculture and agroforestry systems. A first finding indicates that agroforestry systems constitute a clear asset for mitigation by sequestering atmospheric carbon dioxide both in roots and soil but also in aerial plant parts, (de Stefano & Jacobson 2018) in a way that crops and grasslands cannot. Agroforestry systems store more carbon in woody plant biomass, on average, 46.1 Mg/ha more than sole cropland or pasture-based land uses without trees, which shows a great potential to adopt mitigation measures while providing a wide span of options for increasing their capacity of adaptation (Zomer et al. 2016). This way, SPSs can enhance biomass as well as soil C storage in pasturelands through addition of woody components (Aryal et al. 2022). Precisely, increasing the complexity of crops and pasturelands by implementing agroforestry systems significantly increases soil organic carbon (SOC) (de Stefano & Jacobson 2018). Once this baseline is established, the incorporation of the role of domestic herbivores through agrosilvopastoral and silvopastoral approaches also has the potential to increase SOC stored in herbaceous plants roots, due to the effects of grazing on the plant communities.

The pathway to deliver those results was also established in the report and marks the key lines of action for adapting the project to a multi-country scale:

1) Monitoring, data gathering and assessment of the situation of targeted SPSs
2) Policy work, specifically the development of supportive and participatory policies and legal frameworks that allow the creation of enabling environments
3) Securing tenure rights and improving governance through upgrading and support of traditional governance systems and implementation of participatory and multistakeholder institutions
4) Co-creation of knowledge, capacity building, training and education to empower pastoralist communities and generate the conditions to allow their full participation in decision-making
5) Adopting a gender-sensitive approach to sustainable land planning and management, recognizing the role of people in risk of marginalization, women, youth, employees, elders...

Discussion and conclusion

Silvopastoralism emerges as an innovative solution for improving management and restoring dryland ecosystems. Both traditional and modern SPSs can contribute to increased productivity and income, while preventing erosion, protecting the soil from land degradation and improving other ecosystem services. Moreover, silvopastoralism has evolved in drylands and co-evolved with its ecosystems, as a climate-coping and risk-management system, to maintain production and natural resources even in the occurrence of drought periods and extreme weather conditions (Soni et al. 2016). The main lines of the project – policies, governance, capacity and planning – offer a roadmap for implementation at a country level. In parallel, as the project targeting the role of SPSs for decarbonization is advancing with the first results from a literature review and model-building, Grazing with trees has completed its rationale and global assessment so the project is ready for local implementation.

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Diversification of uses in South Australia's pastoral lands

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Key words: rangelands; diversification; pastoral; South Australia

Abstract

Recent changes to South Australia's legislative framework are designed to enable a diversity of new industries and activities on pastoral land. These changes open up new opportunities for collaboration and diversification of a pastoralist's income streams, supporting the sustainable operation of pastoral businesses, improving long term conservation in a changing climate and increasing use of pastoral lands for a range of different purposes.

South Australia's pastoral lands have been developed from the 1850s to provide a sustainable resource for cattle and sheep grazing, producing high quality food and fibre as part of the state's thriving agriculture industry.

There are 322 pastoral leases making up 219 stations over an area of 40 million hectares, roughly 40% of South Australia.

However, pastoralism is now only one industry thriving on our pastoral lands, and pastoralists have increasingly needed to work in partnership with a range of other users, including First Nations, mining, tourism, and conservation. Major new industries and markets are also emerging on pastoral land, including carbon farming, renewable energy and nature markets, providing new opportunities and challenges.

Regulation of South Australia's pastoral lands commenced in 1842 and legislation has been regularly updated to reflect changing community values and uses. Recent changes to the *Pastoral Land Management and Conservation Act 1989* were made to clarify that pastoral leases can be used for conservation and carbon farming. The *Hydrogen and Renewable Energy Act 2023* has also been introduced to provide the ground rules for a major renewable energy industry that will be developed in collaboration with pastoralism.

Introduction

South Australia's pastoral lands have been developed from the 1850s to provide a sustainable resource for cattle and sheep grazing, producing high quality food and fibre as part of the state's thriving agriculture industry.

However, pastoralism is now only one industry thriving on our pastoral lands, and pastoralists and First Nations people have increasingly needed to work in partnership with a range of other users, including mining, tourism, and conservation organisations. Major new industries and markets are also emerging on pastoral land, including carbon farming, renewable energy and nature markets, providing new opportunities and challenges.

Regulation of South Australia's pastoral lands commenced in 1842 and legislation has been regularly updated to reflect changing community values and uses. Recent changes to the *Pastoral Land Management and Conservation Act 1989* were made to clarify that pastoral leases can be used for conservation and carbon farming. The *Hydrogen and Renewable Energy Act 2023* has also been introduced to provide the ground rules for a major renewable energy industry that will be developed in collaboration with pastoralism.

Discussion

Background

To enable the development of the pastoral industry, this Crown (government) land was allocated via pastoral leases (originally for 14 years under the Waste Lands Act 1846, then for 21 or 42 years under the first Pastoral Act in 1893). There are currently 322 pastoral leases making up 220 stations over an area of 40 million hectares, roughly 40% of South Australia. Pastoral leases originally enabled the occupation and use of Crown (government) land for the purpose of grazing or raising livestock (pastoralism).

Pastoral leases exist alongside Native Title, which protects the rights of First Nations peoples to access and use this land for traditional purposes. Native Title exists over most of the state's pastoral lands. Some Native Title owners also own pastoral leases or manage them under sub-lease from another lessee.

The *Pastoral Land Management and Conservation Act 1989* regulates pastoral land. Leases are issued by the Minister (on behalf of the Crown) for 42 years. The Pastoral Board oversees management of these leases, undertaking assessments of the condition of each lease every fourteen years. Providing the land condition remains good, the lease is extended again to 42 years, providing certainty for lessees. It also provides the opportunity for the Board to intervene and change the lease conditions if that land is at risk of degradation.

Changing land uses

After this land was allocated as leases for pastoralism, a range of other industries and demands have grown over time. Historically, mining and tourism have been the other major industries utilising these lands, generating significant economic returns for the state.

- Mining is managed through a separate regulatory system, which also recognises the important role of pastoral lessees and First Nations people. There are important interactions between these systems, to enable access, operation and rehabilitation of mining operations on pastoral land in a way that accommodates the other uses of the land.
- Tourism has included a mix of activities, some based on pastoral leases, and others needing access through pastoral leases, travelling on station tracks, camping or staying in lodgings. Many of these activities benefit pastoralists by adding an income source. Outback tourism has been considerably boosted in recent years as travellers have had a greater choice of inexpensive equipment for remote area travel.

In recent times, both external and internal drivers are also demanding new, flexible approaches to pastoral land.

- Within the industry, pastoralists have increasingly sought to diversify their businesses, seeking other revenue sources that can help to provide stability and resilience to offset the seasonal and market variations that continue to challenge agricultural enterprises. This need for diversification is likely to increase in the future as climate change continues to increase risks to production.
- Outside the pastoral industry, there is also strong demand for pastoral land to support carbon emissions mitigation, take advantage of emerging renewable energy industries, and enhance conservation measures to help to address the biodiversity crisis.

Carbon farming

Carbon farming is a growing industry in Australia, and potential for carbon storage in rangelands provides for the mitigation of carbon emissions, which can help producers achieve carbon neutral agricultural production, and/or provide an alternative revenue stream to provide pastoralists with greater resilience and options to complement their livestock businesses. With low rainfall and low rates of vegetation growth, carbon storage per hectare is low, but with projects over very large areas, there is still potential for significant vegetation-based sequestration. Carbon farming projects have been approved on eleven leases to date, mainly in the Gawler Ranges and Murraylands & Riverland districts. Carbon storage assessment is based on a change in management practice such as changing the extent and intensity of grazing which can include the control of feral animals. This may also include the exclusion of livestock at times but dual use of rangelands for carbon and pastoralism is encouraged. Existing methods which recognise these activities, are currently being reviewed by the Australian Government.

Renewable energy

The renewable energy industry is seeking to use pastoral land, which provide some of the world's best solar and wind resources. The industry is developing at a very significant scale, particularly to support the emerging hydrogen industry. The South Australian Government has established a new legislative framework to enable this industry to flourish on both pastoral and other land, while accommodating the existing uses of land, including pastoralism. The initial focus for projects will be in the Gawler Ranges area where it is close to electricity transmission infrastructure and to a new hydrogen production hub on the Eyre Peninsula.

Development of these industries are likely to provide significant benefits to pastoral leaseholders and Native Title holders, through increased revenue streams that will help to complement their businesses. However, there is also likely to be significant impacts on these landscapes, such as development of track networks which alter water flow, spread of weeds and a reduction in the area available for grazing. Regulators are working with developers and pastoralists to manage these impacts and support sustainable outcomes.

Conservation

The increasing prominence of the global and national biodiversity crisis has placed emphasis on the need to look after these lands. While grazing has transformed the region's landscapes over the last 175 years, there remains significant biodiversity on South Australia's pastoral lands which have been less intensively developed than densely settled areas. This complements several large and valuable protected areas established in the region, such as the Kati Thanda – Lake Eyre, the Ikara-Flinders Ranges and the Munga-Thirri-Simpson Desert National Parks.

Many pastoralists work to protect this biodiversity alongside their pastoral operations, supported by regulatory instruments such as Heritage Agreements and funding from biodiversity offsets associated with mining and other developments in the region.

Several leases have also been purchased by conservation organisations in a range of land systems, to dedicate large areas of private land to conservation. Many of these purchases were supported by national and state government funding to protect biodiversity on pastoral land, and in more recent times crowd funding has also been used to support the purchase and operation of these leases.

Currently, 21 pastoral leases, are wholly used – with the Pastoral Board's approval – for conservation, and a further nine pastoral leases include part of their area dedicated to conservation purposes. In total, around 14,400 square kilometres or 3.4% of pastoral land is dedicated to conservation purposes.

Regulatory change

Mining and renewable energy is managed under separate legislation, but otherwise, alternative uses must be approved by the Pastoral Board.

There has been debate in recent years over whether the *Pastoral Land Management and Conservation Act 1989* gave primacy to pastoral uses, and therefore whether any other uses can override pastoralism as the primary use of a pastoral lease.

Similarly, debate arose in recent years about whether pastoralists could undertake carbon farming projects on pastoral land, given the length of tenure is limited to 42 years.

The Government undertook to clarify that pastoral leases could be used for conservation and carbon farming purposes, and in 2024 the *Pastoral Land Management and Conservation Act 1989* was updated to address the areas of doubt and confirm that these activities were valid.

While there is provision to remove land from the pastoral estate and convert it to a different tenure, the preference in South Australia is to retain pastoral leases, under the oversight of the Pastoral Board, to provide a consistent set of tenure requirements and a single body to oversee it, rather than increasing the level of fragmentation and potential for conflict between neighbouring landholders.

The Board will continue to assess the condition of land on these leases every 14 years. This will help to ensure that lessees are actively managing their land and addressing issues that may be emerging in the landscape.

Lessees will still be required to meet their obligations under other legislation, such as controlling weeds and pest animals, and managing water resources.

While there is sometimes tension between pastoralists and conservation organisations, there are also opportunities for collaboration and shared learning. Joint efforts to sustainably manage pastoral landscapes and protect biodiversity, and develop new techniques, such as measuring carbon storage and vegetation growth, provide opportunities for shared outcomes.

Challenges for the future

Further challenges and opportunities will continue to test the system for managing pastoral lands. Climate change is expected to affect South Australia's rangelands dramatically, with substantial increases in temperature and changes in rainfall patterns. Vegetation growth and distribution, livestock production and biodiversity conservation are all likely to be significantly impacted, testing the ability of native species and grazing systems to adapt. Regulation will need to be alert to the changing requirements to maintain sustainable grazing regimes in the long term.

Conclusion

Building on the state's long history of adapting to emerging needs, recent changes to South Australia's legislative framework for pastoral land are designed to enable a diversity of new industries and activities. These changes create new opportunities for collaboration and diversification of pastoralist income streams, supporting the sustainable operation of pastoral businesses, improving long term conservation in a changing climate and increasing use of pastoral lands for a range of different purposes.

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Examining the dynamic shift between pastoralism and agropastoralism: comparative insights from South Africa and south Asia

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Keywords: Land use; livestock; drylands; climate change; governance

Abstract

Often, pastoralism conflicts with cropping for land and other resources, leading to tensions between these two land uses. Nevertheless, pastoralism and agropastoralism can coexist, with the same people often engaging in both land use practices. However, the dominance of each land use is dependent on various factors, which are often dynamic. In South Africa's arid zone, pastoralists have become spatially constrained through land grabbing during colonialism and apartheid, and due to the smaller size of the grazing lands, both land uses operate in proximity but vary according to climatic and socio-economic conditions and the governance of the land. Due to increases in rainfall variability and a reduction in rainfall, and drought recurrences, dryland cropping has declined whereby only about 12% of all croplands are utilized. These croplands are located within a matrix of arid, yet biodiverse shrublands that have been used by indigenous Nama pastoralists for centuries. On the other hand, in the arid zone of Rajasthan, India, livestock mobility as practiced by the Raika people is a mechanism to cope with climate change in search for better forage and water resources. Our results indicate that 80% of the grazing time was spent on cropland and fallow land along migration routes. In both cases, the rapid decline of cropping practices has had negative implications for livestock and concerted efforts needs to be undertaken to support this historic land use in rangelands that have shown to complement pastoralism in the face of rapid environmental and socio-economic change.

Introduction

Rangelands cover about 54% of the globe's terrestrial surface and these agroecological systems are key for maintaining planetary health including their ability to sequester carbon, sustaining biodiversity, water regulation, and other services (ILRI et al., 2021). For millennia, livestock grazing managed by pastoralists, have been the dominant land use in rangelands and this has shaped the ecological, cultural and economic character of those regions (Reid et al. 2014). As such, these landscapes are also support more than two billion livelihoods worldwide, along its value chain. Despite its importance, rangelands are under threat from various competing land uses such as urban development, mining, agriculture, conservation etc. and these make rangelands very dynamic. However, some land uses are complementary to the pastoral way of life in rangelands.

Dryland cropping, particularly in semi-arid and arid regions have co-existed, became integrated and therefore complemented livestock farming for centuries resulting in new agropastoral societies that have diversified income streams. For example, crop residues are used by livestock during the dry periods whereas livestock manure act as a fertilizer for crops (Samuels et al. 2008). This is particularly true in southern Africa where small-scale dryland cropping has been practiced by the indigenous Nama people to grow winter cereals that they use to make bread and to grow supplementary forage for their livestock (Samuels 2013). In the south of India, livestock provide draught power, transportation, milk and manure for crop farmers and crops serve as food for livestock. This mutualistic interaction has allowed agropastoralists to adapt to the variability in their climate, local economy, and socio-political contexts (Rangnekar 2006).

Then again, the relationship between cropping and livestock farming is dynamic and has been influenced by numerous factors that can shift the balance in favour of the other. For example, large expansions of cropping areas will encroach onto valuable rangelands and fragment grazing areas whereas the absence of cropping could lead to forage shortages in times of drought. The integration of cropping and livestock farming is one of the fundamental elements for climate change adaptation and sustainable land use in drylands around the world (Valbuena et al. 2012). Therefore, understanding the dynamic shift between these two land uses is important for policy development and programmatic interventions. This paper assessed the changes in cropping activities in two dryland pastoral regions in South Africa and South Asia and makes policy recommendations.

Materials and Methods

The research on agropastoralism in South Africa was done over two decades as part of larger national and international projects. Thus, the information reported on in this paper reflects the experience and observations of the authors who were part of that research working with pastoralists using quantitative and qualitative methods. Results also reflect information conveyed by local and indigenous knowledge holders. A stratified random sampling method was applied to select households across districts, tehsils (administrative units), and villages. Villages were chosen based on their livestock migration patterns to neighbouring states. A comprehensive inventory of migratory and non-migratory livestock households was conducted in the selected villages (Louhaichi et al. 2014).

Description of the Study Areas

The study in South Africa was conducted in the Leliefontein communal area that is 192,000 ha in size. The climate is semi-arid with predominantly winter rain from May to August. In summer, temperatures exceed 40 ^{0}C and in winter, it often falls below freezing point in the uplands above 1,000m above sea level. The vegetation falls within two global biodiversity hotspots, namely the Mediterranean shrubland called Fynbos, and the semi-arid Succulent Karoo, which comprises about 90% of Leliefontein. The pastoral area is divided into ten villages with each having associated (unfenced) grazing lands, cropping units and watering points. The cropping units are 12% of Leliefontein and about 10% had been used actively (Samuels 2013). Crops grown are wheat and oats and sometimes lucerne, rye, and barley. The primary livestock kept are goats and sheep, which are herded daily from corrals.

Rajasthan state in India is semi-arid with 70% being desert. Rajasthan has four seasons: summer, monsoon, post-monsoon, and winter. The climate varies from arid to humid. June is the warmest, with temperatures nearly 40°C. The state hosts extensive rangelands, forming the core of its pastoral system, which also relies on croplands. The vegetation is predominantly xerophilous and includes several grass and scrub-type vegetation of low trees species. Livestock serve as food security, and protection against economic and environmental shocks.

Results

In South Africa, environmental factors such as increases in rainfall variability and drought recurrences have resulted in a decline in dryland cropping (Table 1). However, during good rainfall periods, agropastoralists will attempt to plant winter cereal crops for their livestock. Socio-economically, the lack of seed, farming implements, and labour, have also contributed to a decline in cropping. Poor governance that led to the neglect of infrastructure further added to this decline. The erosion of indigenous knowledge amongst Nama agropastoralists has resulted in the inability to know when and how to plant cereal crops.

Rajasthan faces unique vulnerabilities to climatic extremes. Unlike South Africa, recent pre-monsoon rainfall in Rajasthan has caused severe flooding. Despite increased mechanization in India, much agricultural work remains labor-intensive. In irrigated areas, farmers rely on flood irrigation, while micro-irrigation is mostly used by larger landholders. Improper cropping systems and continuous cultivation have depleted soil quality, leading to land degradation, high production costs, and low productivity.

Table 1: Drivers of cropping abandonment in the study areas.

Drivers	**South Africa**	**South Asia**
Environmental		
Reduced rainfall	✓	
Increased rainfall variability	✓	✓
Soil fertility depletion		✓
Socio-economic		
Lack of seed	✓	
Lack of farming implements	✓	
Lack of labour	✓	
Poor adoption of mechanization		✓
Poor irrigation facilities		✓
Stray livestock incl. donkeys	✓	
Older agropastoralists passing on	✓	
Cheaper & convenient to buy feed	✓	
Lack of marketing		✓
Inadequate access to crop insurance schemes		✓
Indigenous knowledge		
Lack of farming skills to plough & threshing of chaff	✓	
Lack of knowledge to read weather conditions on when to plough	✓	
Breakdown in indigenous livestock management to protect crops	✓	

Discussion

While dryland cropping has declined in Leliefontein, it persisted over recent decades due to the need to maintain exclusive cropping rights and to continue to earn its benefits such as supplementary fodder. Here, cropping is one of the major drivers of livestock mobility as herders move their animals away to protect growing crops (Samuels et al. 2008). In western Rajasthan, livestock rely heavily on common grazing lands, fallow fields, and post-harvest crop areas. Livestock mobility is critical for local livelihoods, trade, and coping with climate change (Clifton and Louhaichi, 2015). Cropland and fallow land comprised the majority land type utilized by cattle, totaling 80%. Grasslands, deciduous trees, and scrub forest lands accounted for >10% of the area utilized by cattle (Louhaichi et al. 2015).

If rainfall variability, droughts, poor governance, and other constraints persist, it is uncertain whether cropping will continue in both regions. This outcome will have consequences for Nama and Rajasthani agropastoralists and there is a need to work towards solutions to continue cropping in these dryland systems. These include co-developing early warning systems based on science and local ecological knowledge, preservation of Indigenous and local knowledge, development of drought resistant indigenous fodder crops as in the case of South Africa from the diversity of native forage legumes found in the winter rainfall region (Muller et al. 2017). Furthermore, we need to protect the rights of crop farmers, implement policies that encourage cropping, and support croppers financially and technically.

In both cases, the rapid decline of cropping practices had negative implications for livestock and a concerted efforts needs to be undertaken to support this historic land use in rangelands, that have shown to complement pastoralism in face of rapid environmental and socio-economic change.

Acknowledgements
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Agriculture and water resource assessments in the extensive rangelands of northern Australia

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Key words: Intensification; irrigation; Indigenous values and rights; ecological assets; development impacts and risks

Abstract

Sustainable regional development is a priority for all governments which have jurisdiction in northern Australia. The land and water resources of most of northern Australia's rangelands have not been mapped in sufficient detail to provide for reliable resource allocation, mitigate investment or environmental risks, or build policy settings that can support decisions about development.

Since 2012 CSIRO has led large multi-disciplinary assessments across about 620,000 km^2 of northern Australia. These assessments have considered; Indigenous rights, values, interests and development aspirations; climate drivers; surface water hyrdology; groundwater hydrology; ecological assets and impacts; soils and land suitability; surface water storage; and agricultural and socio-economic considerations. The assessments have included a combination of field data collection, desktop studies and modelling to provide a comprehensive analysis of the kinds of intensified water resource development which might be possible and the risks which would accompany those developments.

The catchments studied are largely 'greenfield', i.e. potential development would occur on land which is not already within a matrix of existing water resource development or intensified agricultural production. The majority of the land is Indigenous held and/or is used for extensive beef cattle grazing on native pastures.

The work has shown that there are considerable soil and water resources which could be developed, however these resources are not always found together and intensified production would only be economically viable under certain, often difficult to meet, conditions. Beyond financial considerations, there are many other issues which influence the extent to which development might occur. These relate to the social licence to develop water resources, to grow certain crops such as cotton, and to clear native vegetation - as well as regulatory and legislative conditions which reflect this social licence.

Introduction

Northern Australia is remote and sparsely populated and decisions made about development need to be based on the best available data and information, provided in a manner which the public can access and digest. We used a multidisciplinary approach to examine the resources in eight study areas (14 catchments) in the rangelands of northern Australia and then investigated how these might be used to support increased economic activity. We also considered the risks (social, cultural, environmental and financial) which might accompany this activity.

Methods

A wide range (and large number) of quantitative and qualitative methods were used. Topics covered are shown in Figure 1. The approach was to provide a number of detailed technical reports, typically more than 10 reports for each catchment, a synthesis of which was provided in Catchment Reports, then pared back into much shorter Summary Reports. Data layers were made available through CSIRO's Data Access Portal. Several web-based tools were developed along with short videos. The full set of more than 110 reports is provided at https://www.csiro.au/en/research/natural-environment/water/water-resource-assessment

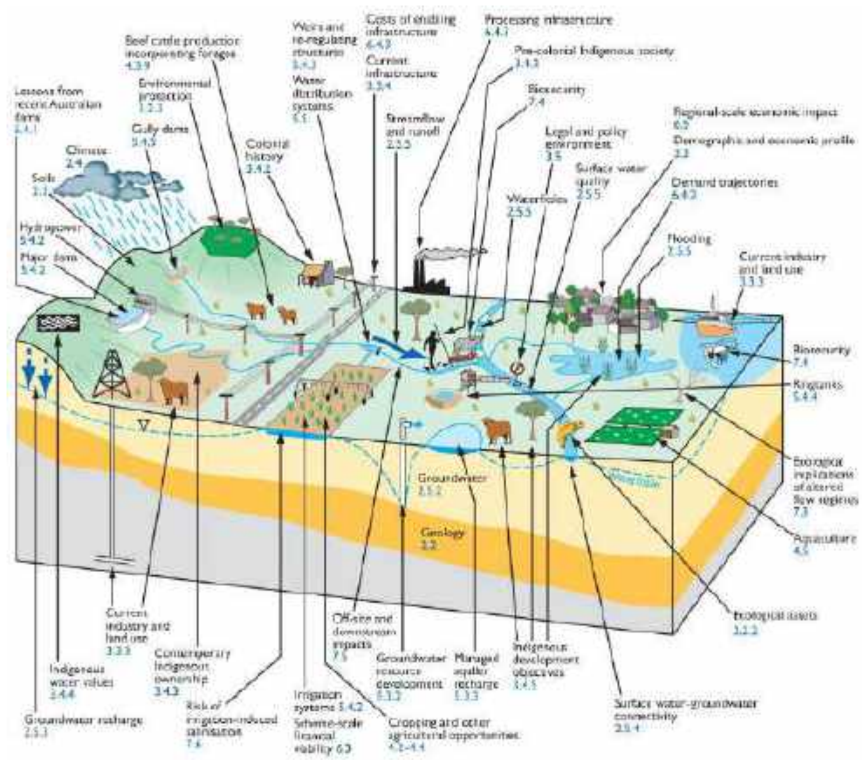

Figure 1. Schematic diagram of key components and concepts considered in the Assessments. Section numbers are from Petheram et al., (2024).

Results

Streamflow is highly variable both within years (due to the wet-dry climate) and between years. For example, the mean annual streamflow is 34% higher than the median annual streamflow in the Fitzroy River and more than double in the Flinders River. Streamflow is more variable than for catchments found in similar environments elsewhere in the world. The catchments are largely unregulated, being free of dams or weirs except in a few cases. Modelled median annual streamflow is shown in Figure 2.

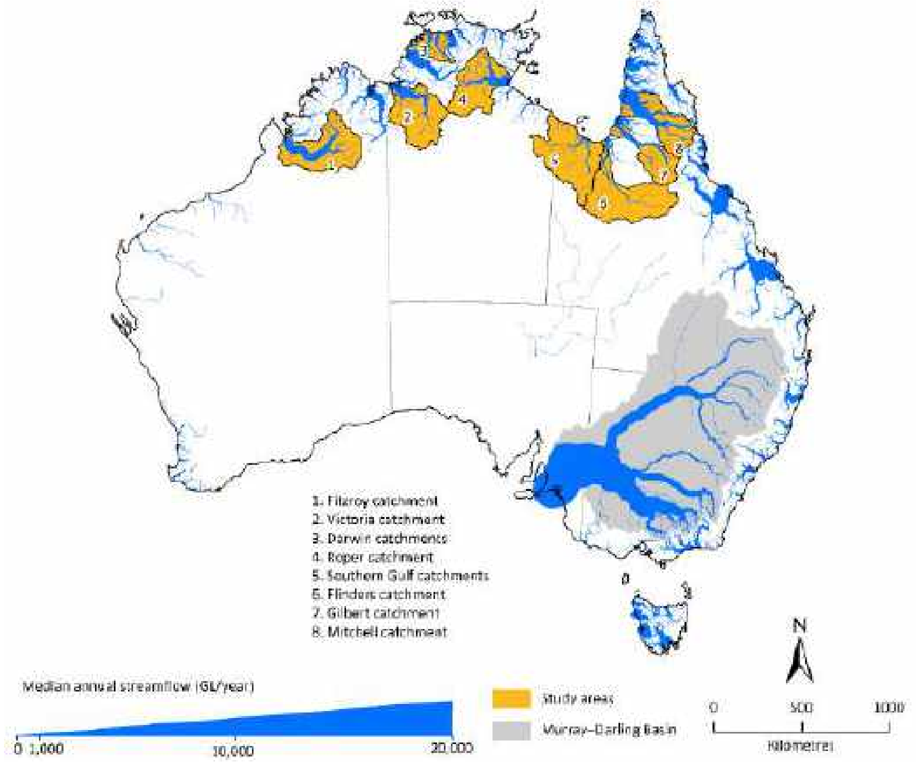

Figure 2. Schematic showing modelled median annual streamflow of Australian catchments (prior to European settlement and development). Study areas shown in orange.

Only one assessment (Darwin catchments) contained a population centre in excess of 20,000. The population density is very low (Table 1) and in all catchments the proportion of the population which is Indigenous exceeds the Australian average of 3.2%. The level of socio-economic disadvantage is high.

Soils mapping and consequent land suitability assessment suggested that between 35% and 76% of each catchment was suitable for growing irrigated Rhodes grass using spray irrigation (Table 1) such as might be fed to cattle on-farm. Note that land suitability does not consider risk of flooding, secondary salinisation, water availability or other factors, it is an upper bound.

The dominant agricultural land use was extensive beef cattle grazing, which occupied between 37% and 95% of the catchments. Almost all cattle grazing occurred on pastoral leasehold land, owned by the Crown. Indigenous-owned freehold land makes up nearly one half of the Northern Territory. In the Victoria and Roper catchments Indigenous freehold was 31% and 45% respectively. While freehold, these lands are held in communal ownership and unlikely to be intensively developed beyond very small scale activities. From a regulatory and legal basis, the extent to which pastoral leasehold land can be intensively developed for cropping is disputed. While diversification is sometimes permitted, the extent to which pastoral land can be used for cropping depends on the jurisdiction and is the subject of recent court cases.

Table 1: Key characteristics of each study area. 'Suitable land' is percentage area for Rhodes grass under spray irrigation (first number) and for cotton under furrow irrigation in the dry season (second number), noting that suitability includes various limitations. References for all study areas are provided below.

Study area, jurisdiction & year released	Area (km^2)	Median annual streamflow (GL/yr)	Population (Indigenous)	Grazing land	Suitable land
Flinders, Qld, 2013	109,000	*1,241	8,952 (19%)	96%	76%, 71%
Gilbert, Qld, 2013	46,000	*2,647	2,948 (37%)	84%	43%, 19%
Fitzroy, WA, 2018	94,000	4,925	7,533 (65%)	95%	58%, 6%
Darwin, NT, 2018	30,000	10,188	139,052 (9%)	37%	43%, 2%
Mitchell, Qld. 2018	72,000	14,237	6,365 (26%)	95%	46%, 18%
Roper, NT, 2024	77,400	4,341	2,500 (73%)	46%	51%, 4%
Victoria, NT, 2024	82,400	5,370	1,600 (75%)	62%	35%, 8%
Southern Gulf, NT & Qld, 2024	108,200	4,961	22,500; (27%)	77%	47%, 17%

* Modelled for the most downstream gauging station. All others modelled for end of system.

The amount of water made available for uses such as irrigated agriculture is a matter for legislation and regulation under the Western Australian, Northern Territory and Queensland governments. Ideally, this is laid out in water resource, or water management plans, but not all catchments are the subject of such plans. Typically, water extraction rules are conservative. Released in February 2024, the NT's 'Surface water take – wet season flow policy' states '*The volume of water available from wet season water flows to consumptive uses will be five per cent of the 25th percentile of total flows for the three highest flow months of the year based on the previous 50 years flow or modelled rainfall data of the river basin …*'. Note that a greater volume of water than this could be made available if it was established in a water allocation plan. In the absence of a water allocation plan, the policy would restrict surface water take in the Victoria catchment to about 2.5% of median annual flow.

Indigenous Traditional Owners were not necessarily averse to water resource development, however they have strong views, consistent across northern Australia, about the nature of that development. Traditional Owners were not in favour of large in-stream dams but could see benefit in small scale surface water capture or use of groundwater to irrigate such things as forages for cattle, or fruit and vegetables for local markets. Typically, they want to be owners, partners, investors and stakeholders in any future development. This reflects their status as the longest-term residents (tens of thousands of years) with deep inter-generational ties to the catchment. In at least one catchment, the Martuwarra (Fitzroy) Elders from independent First Nations groups have formed an alliance to limit the influence of 'extractive industries' (including water resource development) to 'forever economies' (https://martuwarra.org/protect_martuwarra).

While these catchments are not pristine, their low human density and minimal (in global terms) level of development has meant they retain high-value (often iconic) ecological processes, habitats and species. Examples include monsoon vine forest, large numbers of groundwater dependent ecosystems, nationally important wetlands, seagrass habitats, the freshwater sawfish (*Pristis pristis*) the northern river shark (*Glyphis garricki*) and the Rosewood keeled snail (*Ordtrachia septentrionalis*) as well as a number of migratory shorebirds.

Irrigated agriculture was found to be financially viable only if there was an alignment of good prices for high-value produce and market advantages. Other factors include availability of suitable markets for the products, investment in fundamental infrastructure such as all-weather roads, bridges and processing facilities, and land tenure arrangements that support development. Rainfed cropping was determined to be largely opportunistic and depend upon farmers' appetite for risk and the extent to which it could be an adjunct to an irrigation enterprise. Growing forages or hay to feed cattle to be turned off at a younger age was determined unlikely to be financially viable. Feeding irrigated forages or hay increases beef production and total income, but increased costs mean that gross margins would be less than baseline cattle operations, and the high capital outlay would in most cases be prohibitive.

Discussion

The catchments assessed were not homogenous. Each had different characteristics which provided a range of opportunities and risks. The coincidence of soil and water (within the context of bio-physical and regulatory constraints) could result in irrigated development of less than 2% of the land area across all catchments. That is, the essential rangeland characteristics of these areas would remain into the future, that being; Indigenous held land, land set aside for nature conservation, and land used for extensive beef cattle grazing.

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Rangelands in a global carbon economy

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Green energy and grazing in the rangelands: a just transition?

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Key words: energy justice; land alienation; pastoralism; renewable energy

Abstract

Growing global awareness of the climate crisis and the need to switch from fossil to renewable energy (RE) has led to growing interest in acquiring land to generate it. Tropical and subtropical rangelands are prime targets for producing RE. Investors, governments and project planners often regard rangelands as "empty", yet pastoralists, hunter-gatherers and cultivators have long used these areas as a common pool resource, through multipurpose use of the land, for their livelihoods.

Globally, large-scale land acquisition for RE projects often displaces local people from their land, contrary to their traditional rights, disadvantaging especially pastoralists by blocking access to and fragmenting pastures. This reduces pastoralists' ability to use herd mobility to deal with climatic variability and change and to support their livelihoods. Moreover, project planners rarely manage to obtain locally meaningful free, prior and informed consent (FPIC) for using pastureland to produce renewable energy. Even where communities have a chance to negotiate placement of energy installations, they typically enjoy little bargaining power or subsequent benefits, not least because governments and developers may greatly underestimate the value of pastoralism in terms of food production, economic value and ecosystem services and therefore afford low value to rangelands.

We analyse the impact of land acquisition in rangelands for RE in Kenya and Mongolia, especially in relation to considerations of climate and energy justice. We explore possibilities of multifunctional land use as part of a 'just transition' that combines pastoralism with generating RE. We identify the type of research needed to help local people gain evidence about the value of their production systems and their contribution to ecosystem services, putting them in a better position to negotiate sharing of land for and benefits from RE generation.

Introduction

Confronted by the climate crisis, countries are striving to meet the Sustainable Development Goals (SDGs) and to deliver on their zero-carbon pledges at the UN Climate Change Conferences by transitioning from fossil to renewable energy for their industries and citizens. This has led to rapid expansion of large-scale renewable energy (RE) projects, particularly in sparsely populated regions or on land regarded by governments as "unproductive". Investors from more industrialised countries are making agreements especially with governments of less industrialised countries to use their land to produce solar, wind or hydropower. They frequently draw on discourses of “empty”, “underutilised” or “degraded” wastelands – discourses that have historically underpinned injustices to local land users, particularly pastoralists, in the name of development since colonial times (Lind et al. 2020).

In many of these areas now coveted for generating RE, pastoralists have been grazing their herds in mobile systems of production on land used in common with other herders, smallholder farmers and hunter-gatherers. The large-scale RE projects could have adverse impacts on pastoral production systems, which rely on flexible and highly mobile use of large expanses of diverse types of land at different times of the year in order to produce food (milk and meat) for themselves and other consumers. These production systems typically use few or no fossil-fuel-based inputs.

We therefore conducted research into the impact of large-scale RE projects on pastoralists in the drylands with a view to i) helping policymakers and civil society shape the expansion of producing RE so that, at minimum, it does no harm, and ii) helping pastoralists become better prepared to deal with the expansion of RE projects and possibly even benefit from them.

Methods

We made a desk-based study of literature on pastoralists’ experiences with RE projects worldwide, searching in SCOPUS and Web of Science on terms around pertinent livelihood strategies and environments (e.g. pastoralism, agropastoralism, rangelands, drylands); RE; just transition; and consultation and consent. We delved deeper into cases in Kenya and Mongolia, countries in which we had prior experience, by seeking “grey literature” (policy documents, reports and media sources), conducting interviews with affected community members, RE developers and government staff, and visiting some wind and solar power sites in the two countries.

On the basis of these information sources, we analysed how land acquisition processes in the name of the energy transition affected mobile pastoralists, the role of Free, Prior and Informed Consent (FPIC), whether the land was used for both RE and pastoralism rather than as mutually exclusive alternatives, pastoralists’ responses to displacement and the extent to which energy justice was achieved. Sovacool et al. (2017) define “energy justice” as an “energy system that fairly distributes both the benefits and burdens of energy services, and … contributes to more representative and inclusive energy decision-making”. It forms part of the concept of “just transition”, connecting social justice with environmental, climate, resource and energy reasons for the transition (Upham et al. 2022).

Results

The desk study revealed that, globally, governments and investors largely ignored or downplayed the impact of their RE projects on pastoralist communities. Large-scale land acquisition for RE in the drylands has been dispossessing pastoralists of their traditional grazing areas, reducing the mobility of herds over diverse landscapes that is essential for sustainable use of the drylands, and blocking access to key seasonal resources for pastoralism. This is making the pastoral production systems less viable.

Furthermore, pastoralists were usually excluded from access to the power generated by large-scale RE on their land and also lost access to natural sources of energy (e.g. firewood) on that land. Pastoralists thus became victims of not only “land grabbing” but also “energy grabbing”.

Most governments and investors showed little understanding of pastoral production systems and their value, and – even if, on paper, governments legally recognised the communal land systems needed for flexible and mobile pastoral systems to function effectively – did not respect these when implementing their RE projects. Expansion of RE generation was typically justified by “climate emergency narratives” (Borras et al. 2022). Project implementers often saw no need to seek FPIC, which would require that the current land users be fully informed about possible impacts of the project on their lives. Key international agreements such as the African Commission’s Africa Charter for Human and Peoples’ Rights and the United Nations Declaration on the Rights of Indigenous

Peoples (UNDRIP) uphold the principle of FPIC and do not limit it to indigenous peoples. However, most governments, although having formally endorsed these agreements, did not adhere to them when dealing with local communities in areas foreseen for RE projects. These communities were often unaware of their rights and of ways in which they could legally oppose RE projects or negotiate benefits for local people.

In the less industrialised countries, governments and investors rarely considered possibilities of shared use of the land for pastoralism and RE – and shared benefits from the energy generated. Most pastoralist communities in these countries did not consider these possibilities themselves and were, in any case, in a weak position to negotiate a fair deal.

Kenya case study

In Kenya, investments in geothermal, solar and wind energy have been mainly in the drylands (Hughes & Rogei 2020). They have given little or no attention to impacts on traditional dryland production systems and reflect a continuation of the historical lack of recognition of mobile pastoralism as a meaningful form of livelihood that generates economic value (Lind et al. 2020).

North Kenya hosts the largest wind-power plant in Africa: Lake Turkana Wind Power (LTWP) near Marsabit, completed in 2019. This generates over 300MW of electricity on 60,700 ha of rangeland leased from the Government in 2009. According to Achiba (2019), because developers regarded the land as uninhabited, they did not consult the Turkana, Samburu, Rendille and El Molo herders who used the land seasonally. The Government of Kenya's refusal to endorse UNDRIP was a factor in investors' disregard for FPIC principles (Cormack & Kurewa 2018). The developers allegedly exploited pre-existing ethnic conflicts over natural resources to de-emphasise some "indigenous" claims over others (Renkens 2019). These intercommunity tensions constrained emergence of a united grassroots resistance (Achiba 2019). Instead, LTWP presence and actions created greater divisions among the local land users, as stated by a Turkana elder in our 2022 interviews: *"this has affected the social relations, intercommunity dialogue, peace and social cohesion between these communities"*.

Construction of the turbines began in 2014. LTWP (2011) stated that herders could continue grazing animals between the turbines but the process of land acquisition without consultation or compensation nonetheless made the herders feel robbed. As a Rendille elder said in 2022: *"even if the communities are allowed to graze the animals, they are not happy to settle or move freely within the project area because the land does not belong to them anymore"*. Moreover, herders stated that noise and frequent vehicle movements made the land unusable for grazing. Thus, the capture of resources and authority by LTWP disrupted traditional patterns of land use and decreased the resilience of pastoralists to adapt their land-management and grazing systems in the face of climate change.

The benefits for local people have thus far been very limited: they have no direct access to the power produced by LTWP on their land; jobs on the project are few and LTWP does not share the RE revenues with the local communities, which therefore feel excluded and unfairly treated.

In 2014, the pastoralist groups managed to overcome intercommunity tensions and organise themselves to resist this energy injustice. They formed the Sarima Indigenous Peoples' Land Forum and took the case to district court, which ruled in 2021 that the process of transferring communal land to investors had been illegal. The Kenyan High Court upheld this ruling in 2023. However, the wind park was by then in full operation. The LTWP will either have to return land to the pastoralist communities or find some way to compensate them.

Mongolia case study

Mongolia aims to meet all its energy demands by domestic production and become an energy exporter by 2040 (State Great Khural 2020). As of 2023, its RE energy is derived from seven small hydropower plants (HPPs), three wind farms (WFs) and nine solar-power plants (SPPs) (Dimovska 2024).

Pastoralists have *de facto* customary rights to pasture, which is officially state property; they thus have little defence against land alienation. Thus far, RE projects claim to have no negative impacts on pastoralism, and the few accessible publications on RE largely concur. All RE projects in Mongolia are officially classified as having no impact on indigenous peoples; the herders do not self-identify in this way and the associated safeguards are therefore deemed inapplicable (Waters-Bayer & Wario 2022). However, Environmental and Social Impact Assessment reports indicate that herders' consent was obtained. Those we interviewed reported that their initial reactions were negative, but their views changed after they received more information and saw that the impacts on grazing were minimal. The herder families' perceptions of energy justice were also influenced by their own access to household solar energy through Mongolia's 100,000 Solar Ger Electrification Programme and the fact that their extended families in nearby settlements had access to the energy generated through the RE projects.

Very few herders at case-study sites reported significant loss of pasture access: *"We are not adversely affected. The pasture, water and salt are all in good condition. We got used to living with this solar station. … The station does not affect grazing and migration"* (herder, Khushig Khundii SPP, 2022).

To date, the RE projects in Mongolia have been on a smaller scale than in Kenya. However, larger projects are now planned, e.g. the 28,000 ha Chinese-backed Erdeneburen HPP project in western Mongolia will impact some 270 herding households. Some affected herders protested publicly in the capital, Ulaanbaatar, against this project, mobilising resistance around potential impacts on herders' livelihoods and land rights and on biodiversity, e.g. in the nearby wetlands (Dugersuren 2022).

Discussion and conclusion

Large-scale RE projects as responses to governments' net-zero commitments and the "climate emergency" intersect with land issues and livelihoods. Specificities of the pastoral mode of production and rangelands, e.g. herd mobility and use of common land, render them especially vulnerable to acquisition for large-scale RE. Exclusion from meaningful participation in decision-making and from opportunities to give informed consent have often led to energy injustice – rooted primarily in lack of due process and transparency. Especially where the pastoralist communities do not have access to the RE being generated on their land, they experience a sense of land alienation and encroachment on their rights because of restrictions on access to resources essential for their livelihoods. However, availability of sufficient information and accessibility to household energy can moderate herders' perception of (in)justice when rangeland is taken to generate RE.

What are the prospects for energy justice for pastoralists faced with large-scale RE projects in the future? Inclusive participatory design of energy projects together with pastoralist communities could lead to forms of multipurpose land use for energy and pastoralism, as well as for biodiversity and equitable economic benefits. This has clear implications for developers' approaches to impact assessments and FPIC and requires, above all, considerable time to develop relationships with and to adequately inform all the pastoralist groups in the project area.

RE investors would be well advised to provide the resources and time for researchers to engage with affected pastoralist communities in transdisciplinary research to co-develop a place-based understanding of the heterogeneous local communities and opportunities for sharing the land and the benefits from RE production. This type of research would reveal the local people's values around land and the way that they use it, strengthen pastoralists' capacities to know and defend their land rights, and strengthen their ability to negotiate for fairer treatment in the energy transition.

A just transition to RE can be made only if governments manage the transition in open and inclusive discussion with well-informed pastoralists and seek synergies between producing energy and producing food to sustain local livelihoods.

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Carbon farming on the margins: Unlocking carbon sequestration potential in rangelands under expanded eligibility criteria

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Key words: ACCU Scheme; Paris Agreement; Australia; Bioeconomic Assessment

Abstract

Adoption of the Paris Climate Agreement has expanded Kyoto Protocol rules for carbon abatement actions from forest vegetation to include all land management actions. This change has the potential to significantly increase the area eligible for vegetation-based carbon sequestration actions and will allow countries to include these actions across extensive areas of low-biomass within national carbon abatement plans. Using the Australian rangelands as a case study, an area comprising approximately 5.55 million km^2, we assess the latent terrestrial carbon abatement potential under two eligibility scenarios. Firstly, areas of the Australian rangelands that meet the Kyoto Protocol minimum 20% tree canopy cover potential (forest) and secondly the large, previously unaccounted for part of the Australian rangelands where dominant cover potential is less than the Kyoto 20% requirement (sub-forest). We define areas eligible for assisted natural regeneration under the Australian national Emissions Reduction Fund ACCU Scheme using national scale land use, forest and vegetation spatial datasets and model carbon abatement potential across these areas using the Full Carbon Accounting Model (FullCAM 2.0). Results show up to 512,089 km^2 and 354,770 km^2 of eligible land under the forest and sub-forest scenarios respectively providing a total abatement potential of 1,882.4 MtCO$_2$e and 866.4 MtCO$_2$e over a 25-year modelling period. In an economic assessment of this opportunity, we found most of this latent abatement potential was economically viable at current low carbon prices (between AUD 17 tCO$_2$e^{-1} and AUD 32 tCO$_2$e^{-1}) available within the Australian government and secondary markets. This is the first study that assesses latent carbon sequestration potential in Australian "sub-forest" ecosystems. We highlight the prospects for (particularly Indigenous) economic development in remote Australia.

Introduction

Regeneration using assisted natural regeneration (ANR) was included in the definition of afforestation and reforestation under the Kyoto Protocol and the UN Clean Development Mechanism if the vegetation met minimum thresholds for stand size (0.05-1.0 ha), canopy cover (10-30 per cent) and height (2-5 m) (Chazdon et al., 2016; Smith, 2002; UNFCCC, 1992). However, with the adoption of the Paris Agreement, eligible abatement actions have been expanded while removing specific reference to forests and the requirement that vegetation meet the threshold definition of forest cover for eligibility (Dooley, 2018).

Currently large areas of Australia's rangelands deemed capable of regenerating Kyoto compliant forests are home to carbon sequestration projects incentivized by Australia's national carbon policy, the ACCU Scheme. However, the Paris Agreement changes provide new impetus for Australia's carbon abatement plans to now include areas of sparse woody vegetation (what we term sub-forests) that were previously ineligible including recently modified rangeland areas, particularly across drier biomes. However, the size and economic viability of this opportunity is yet to be investigated.

This article presents a bioeconomic assessment of latent terrestrial carbon abatement potential across extensive marginal and low-biomass Australian Rangeland zones. We explore two vegetation canopy cover scenarios, firstly Kyoto compliant forest with a minimum canopy cover of 20% and sub-forest which does not meet this threshold, having canopy covers between zero and 20%. We estimated carbon sequestration potential in rangelands Australia for both forest types. We report the carbon prices required for land use change to be profitable under conventional investment criteria and discuss implications for economic development in remote communities.

Methods

This case study covers the extensive Australian Rangelands (Figure) and includes vast tracts of northern and central Australia and incorporates climates and biomes ranging from tropical grasslands, savanna and shrublands in the north to deserts and arid shrublands in the south (Department of Agriculture, 2021).

Suitable areas for the Forest and sub-forest scenarios ((Figure) were defined using a series of spatial datasets relating to forest cover, land use and vegetation type. Forest cover was defined using the Australian National Carbon Accounting System (NCAS) forest mapping dataset (DISER, 2021; Furby, 2002). Current land use was defined using the Australian Land Use and Management (ALUM) data (ABARES, 2016). Vegetation types were defined using the Australian National Vegetation Information System (NVIS) major vegetation groups (MVG) data (NVIS, 2017). Areas were included in the analysis as eligible for Forest carbon farming if they were defined as having non-forest or sparse woody vegetation in the NCAS data and having MVGs that can achieve forest cover (e.g. forest, closed woodlands, tall closed shrublands) in the NVIS data. In contrast, areas were included as eligible for Sub-Forest carbon farming if there was no forest or sparse woody vegetation present in the NCAS data and only MGVs that can achieve between zero to twenty per cent canopy cover (e.g., open woodland) in the NVIS data.

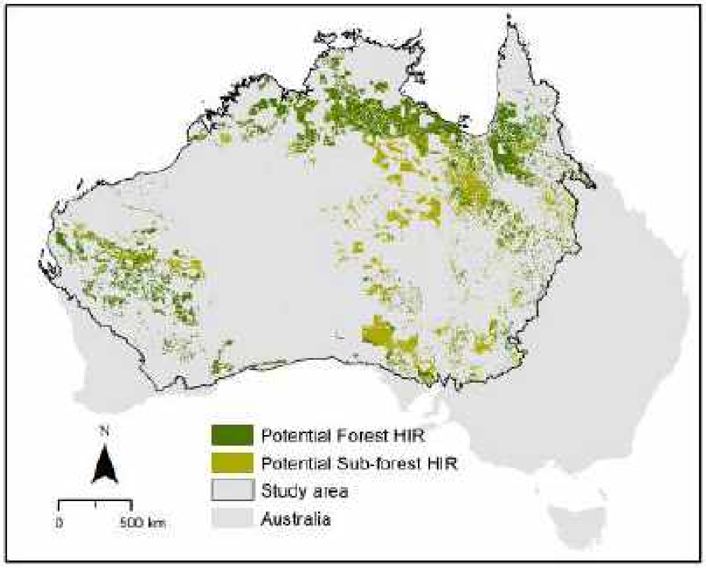

Figure 1: The Australian Rangelands study area and potential areas for regeneration under current forest and sub-forest suitability requirements.

Annual carbon sequestration estimates in tonnes of CO_2e per hectare were modelled using the ERF approved software Full Carbon Accounting Model (FullCAM) 2020 (DISER, 2020a). Carbon estimates were modelled on a 0.05-degree grid across all suitable areas and over a 25-year timeline starting in 2020. The same FullCAM settings were used for both the Forest and sub-forest scenarios. The difference between the two scenarios was based solely on location. All FullCAM modelling was carried out in line with the legislation (Commonwealth of Australia, 2013) and the FullCAM Guidelines for the Human Induced Regeneration method (DISER, 2020b)

Net present value (NPV) was used to evaluate the economic viability of land use change from the business-as-usual land use to carbon using the ACCU Scheme HIR methodology. The NPV of the Forest and sub-forest scenarios was calculated considering project establishment costs including the opportunity of lost agricultural revenue, fencing costs, brokerage/transactions costs and maintenance costs.

Functionally, the NPV_{ANRp} of changing from current agricultural land use to carbon land use ANR at carbon credit price p can be expressed as:

$$NPV_{hir} = PVR_{ANRp} - PVC_{ANR} \tag{1}$$

In equation 1, PVR_{ANRp} is the present value of returns to ANR at price p was calculated as:

$$PVR_{ANRp} = \sum_{t=0}^{T} \frac{p \times Cseq_{ANR}}{(1+r)^t} \tag{2}$$

Where $Cseq_{ANR}$ described sequestered carbon in each year t. Spatially differentiated estimates of $Cseq_{ANR}$ annual incremental and cumulative values over a 25-year and 100-year horizon were estimated across relevant areas for ANR using the FullCAM model.

The term r is the discount rate applied in discounting future costs and returns and T is the time horizon in our case 25 years and 100 years. We assumed a real rate of 5.25%.

The term PVC_{ANR} in equation 1 is the present value of all costs for ANR: it is calculated as:

$$PVC_{ANR} = FC_{ANR} + \sum_{t=0}^{T} \frac{MC_{ANR} + BC_{ANR} + PFE_t}{(1+r)^t} \tag{3}$$

Four elements of cost are considered in equation 3: FC_{ANR} is the fencing costs assumed to be \$24 ha^{-1} for ANR. This value is not discounted as it occurs at project initiation. MC_{ANR} are the maintenance costs that occur in each year t over the investment horizon and assumed to be \$1 ha^{-1} over the first 5 years following establishment and \$0.5 ha^{-1} for every year thereafter (Cockfield et al., 2019). And brokerage costs BC_{ANR} (including measurement, compliance and auditing costs) assumed to be 20 percent of the total value of the carbon. This percentage was considered fixed with no spatial variation and were taken from Cockfield et al. (2019). The final term considered in calculating the present value of costs is the opportunity cost of forgoing previous agricultural land use returns. This is expressed as the profit at full equity (PFE_t) at time t. These spatially explicit layers of agricultural profit at full equity (PFE), produced by Marinoni et al. (2012), were updated following the method outlined in (Regan et al., 2020). Consistent with this approach, the input layers were updated with price and inflation indices from the Australian Bureau of Statistics (ABS) (ABS, 2017a, b) yield data from the ABS Agricultural Commodities 2015/16 dataset at SA2 resolution (ABS, 2016). It should be noted that arid areas, in particular have very low to negative returns for agriculture. In this analysis, we assumed all positive agricultural revenue was ceased (e.g. the areas is destocked) with implementation of an HIR project.

Results

Over the 25-year period total carbon abatement potential across all eligible areas was estimated to be 1,882.4 $MtCO_2e$ and 866.4 $MtCO_2e$ for the Forest and sub-forest scenarios respectively. Figure 2 shows the spatial distribution of total per hectare carbon abatement across the study area over the 25-year modelling period.

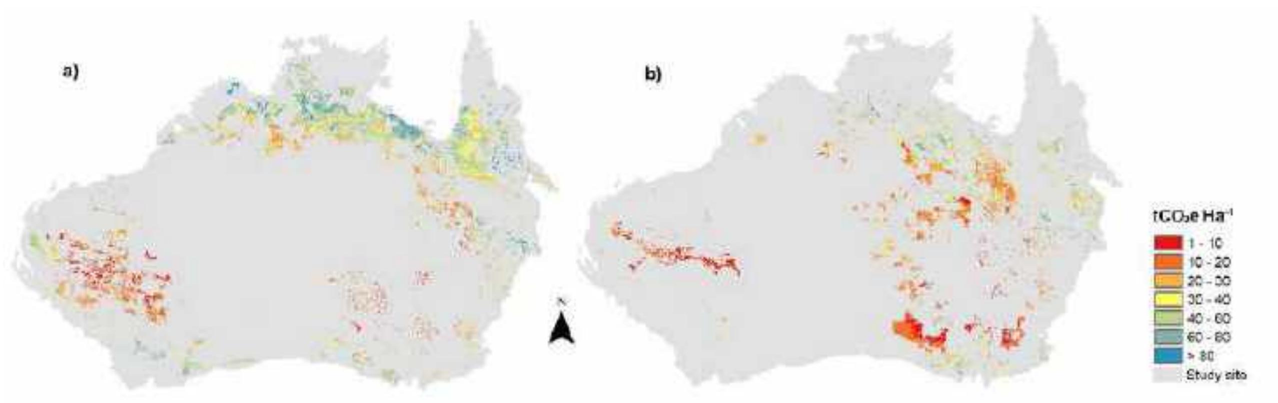

Figure 2: Estimated total carbon abatement (tCO_2e ha^{-1}) over 25 years for forest (a) and sub-forest (b) eligible areas.

Figure 3 shows the spatial distribution of the minimum carbon prices required for a project to be viable for the Forest (a) and sub-forest (b) scenarios.

Under the Forest scenario, economically viable carbon is available from AUD 2 tCO_2e^{-1} with 21.4 $MtCO_2e$ available at this price. At the low carbon price (AUD 17 tCO_2e^{-1}) there are 1569.0 $MtCO_2e$ available while at the high market price (AUD 32 tCO_2e^{-1}) 1855.5 $MtCO_2e$ is economically viable. These carbon sequestration amounts account for approximately 83% and 98% respectively of the total latent abatement potential under this scenario.

Under the sub-forest scenario limited carbon abatement potential is available at very low prices with just 2.4 $MtCO_2e$ available at AUD 2 tCO_2e^{-1}. At the low carbon price (AUD 17 tCO_2e^{-1}) there is 661.2 $MtCO_2e$ available while at the high carbon price (AUD 32 tCO_2e^{-1}) there is 834.4 $MtCO_2e$ available. This accounts for approximately 76% and 96% respectively of the total estimated carbon available under the sub-forest scenario across the modelling period.

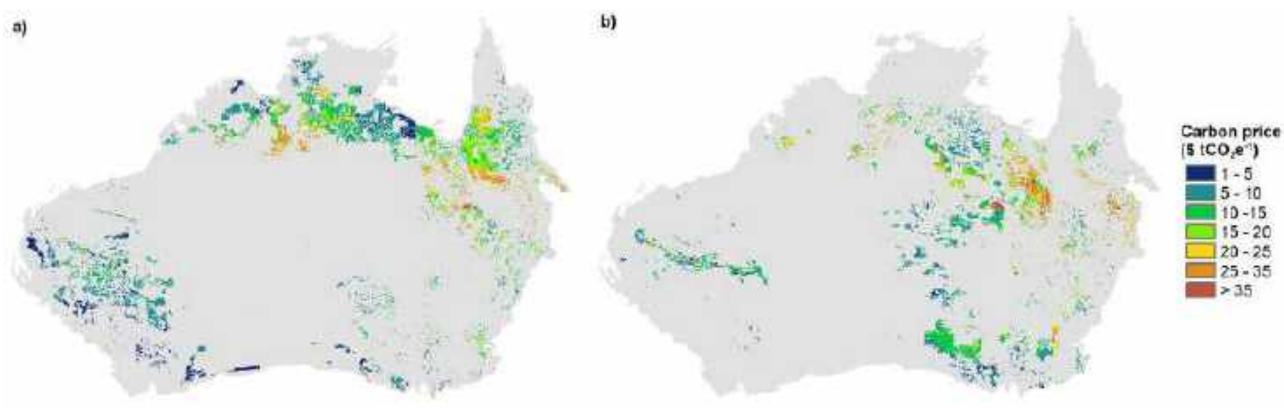

Figure 3: Estimated minimum carbon price ($ tCO_2e^{-1}) at which the carbon becomes economically viable for forest (a) and sub-forest (b) eligible areas.

Discussion [Conclusions/Implications]

Despite recognition in the Paris Agreement, no method currently exist in the Australian ACCU scheme that would include non-Kyoto compliant forest types like those found over much of the Australian rangelands. However, our results found that despite the low per hectare biomass productivity, significant abatement potential is available from this *sub-forest* category across the extensive rangeland areas of central and northern Australia. We found latent potential for economically viable carbon storage on over 350,000 km^2 using ANR for the sub-forest canopy cover scenario.

Relevant globally and in Australia is the potential for regeneration projects to produce significant co-benefits such as improved biodiversity and habitat provision, soil quality and fertility, water quality, reduced salinity and nutrient cycling (Baumber et al., 2020; Crossman et al., 2011; Lin et al., 2013; Muenzel and Martino, 2018; Tang et al., 2016). Consequently, revegetation projects over such a vast area have the potential to contribute simultaneously to Australia greenhouse gas mitigation and nature repair objectives.

In addition, evidence suggests carbon abatement actions can also promote a flow of positive economic benefits to participants including increases in landholder income, diversification of income sources and increased availability of capital for farm improvement (Baumber et al., 2020; Cowie et al., 2019). This may be particularly relevant for remote Indigenous communities where the income from carbon projects can offer transformative benefits for community well-being, economic and social development (Russell-Smith et al., 2015). Evidence from ACCU Scheme projects to date demonstrate that Indigenous environmental planting and fire management projects can deliver multiple benefits (Robinson et al., 2016; Russell-Smith et al., 2015; Sangha et al., 2021). Indeed, Sangha et al. (2021) estimated Indigenous well-being benefits from fire management activities in northern Australia to be in the order of USD 189 million $year^{-1}$. While connection to and interaction with 'Country', specifically the opportunity to care for Country, have been recognised as a key health determinant for Indigenous people (Garnett et al., 2009; Robinson et al., 2016).

The results suggest that developing a scientifically robust methods for inclusion of sub-forests in the ACCU Scheme, alongside revised HIR methods for Kyoto-compliant forests, could provide a significant economically viable additional carbon sink while catalysing remote community economic development and enhancement of ecosystem function and should be prioritised.

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Assessing organic soil carbon stock in extensive livestock system based on native grasslands

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Key words: livestock production, soil classification, Uruguay, natural capital

Abstract

Soil organic carbon content is a central characteristic for sustaining the productive system and the provision of important ecosystem services, including carbon sequestration. Knowing the carbon stock in the soil is important in order to design and manage strategies for its conservation and capture. The main objective of this work is to characterize the carbon stock in livestock systems in Uruguay and explore estimation methods based on satellite information.

Twelve farms with extensive mixed livestock production (cattle and sheep) located on the basaltic slope geomorphological region of Uruguay were evaluated. Three categories of soil were defined (superficial, medium and deep) with an average depth of 9.0, 18.5 and more than 30 cm depth respectively. This classification of soils was done through the normalized vegetation index (NDVI) obtained for selected dates when low soil water content was evident. The ability to maintain green vegetation due to soil water content is strongly linked to depth. Ten sites were randomly selected for each soil category also considering the representativeness of the main soil cartographic units (CONEAT) where 20 soil core samples up to 30 cm deep were extracted with a drill and divided into four strata: 0 to 5, 5 to 10, 10 to 20 and 20 to 30 cm. A specific sampling was performed for determining bulk density. The organic carbon stock was calculated for each soil category. The sampling locations were geo-referenced and the soil carbon values and average NDVI for the last 5 or 10 years was calculated for determination of correlations. The determined carbon stocks we found varied between 16 Mg/ha in extremely superficial soils and 144 Mg/ha up to 30 cm deep in deep soils. Based on these results, we now propose to develop a reliable method for estimating carbon stocks across the basaltic slope region using models based on remote sensing variables.

Introduction

Soil organic carbon content is a central characteristic for sustaining a productive livestock system and the provision of important ecosystem services, including carbon sequestration. Knowing the carbon stock in the soil is important to manage and design strategies for its conservation and capture.

The heterogeneity of soils in the conditions of the native grasslands of Uruguay makes it essential to categorize them using remote sensing tools which are complementary to available cartography and carry out exhaustive sampling to determine the carbon contents. On the other hand, given the few studies carried out in the basaltic slope region of the country, this work seeks to provide a referential baseline and demonstrate the association of the soil carbon content with the physicochemical characteristics of the soils.

The objective of this study was to characterize soil carbon stocks in livestock systems in this region, analyzing the relationships with other soil physical variables and the possible influences of livestock management.

Methods

Study sites and sampling design

Twelve farms located on the basaltic slope geomorphological region in the north of Uruguay, corresponding to extensive mixed livestock farming (cattle and sheep), were evaluated.

For the field sampling design, a classification of soils was carried out according to soil depth based on the normalized vegetation index (NDVI) obtained from Sentinel images. These images are selected on dates with marked water deficit, which allows us to differentiate the water retention capacity and therefore maintain green vegetation, where higher NDVI values indicate deeper soils. Three categories of soil were defined: superficial. medium and deep. In each of these categories, 10 sampling sites were randomly selected and identified on the map. Moreover, a national cartography of soils -CONEAT- (MGAP, 2024) was overlapped to assure equitable representation of soil type classification in the sampling design (Fig 1).

Field sampling

Soil sampling was carried out by extracting columns 30 cm deep with a drill, which were then divided into strata from 0 to 5, 5 to 10, 10 to 20 and 20 to 30 cm. In each sampling unit, samples were composed of sub-samples (30 in average) taken from a virtual circle of 15 m radius. For soil categories that did not reach 30 cm in depth, the depth of soil until contact with the rock in each subsample was determined, thus obtaining an average depth for each site. Additionally, with the same stratification, samples were taken in metal cylinders of 5 cm deep and 5 cm diameter to determine the bulk density.

In the laboratory, the first step is the drying of samples for grinding and the removal of roots, rocks and remove any fraction that exceeds 2 mm. In the sieved samples, organic carbon in soil was determined by dry combustion of the sample and subsequent detection of CO2 by infrared. Determinations of organic carbon was done in INIA´s soil laboratory, using a Leco CN-2000 dry combustion analyzer, with a test method conforming to Wright and Bailey (2001). Additionally, soil texture analysis was performed at each sampling site.

Stock calculation

In the last stage. the calculation of the soil organic carbon stock was carried out for each depth, multiplying the value obtained in the laboratory by the bulk density and depth of the stratum. By adding the different strata, the quantity in the profile for a unit of area was obtained, providing the stock in Mg C/ha. The final SOC stock for each soil category was obtained by multiplying the total surface area of each soil category by the soil carbon stock

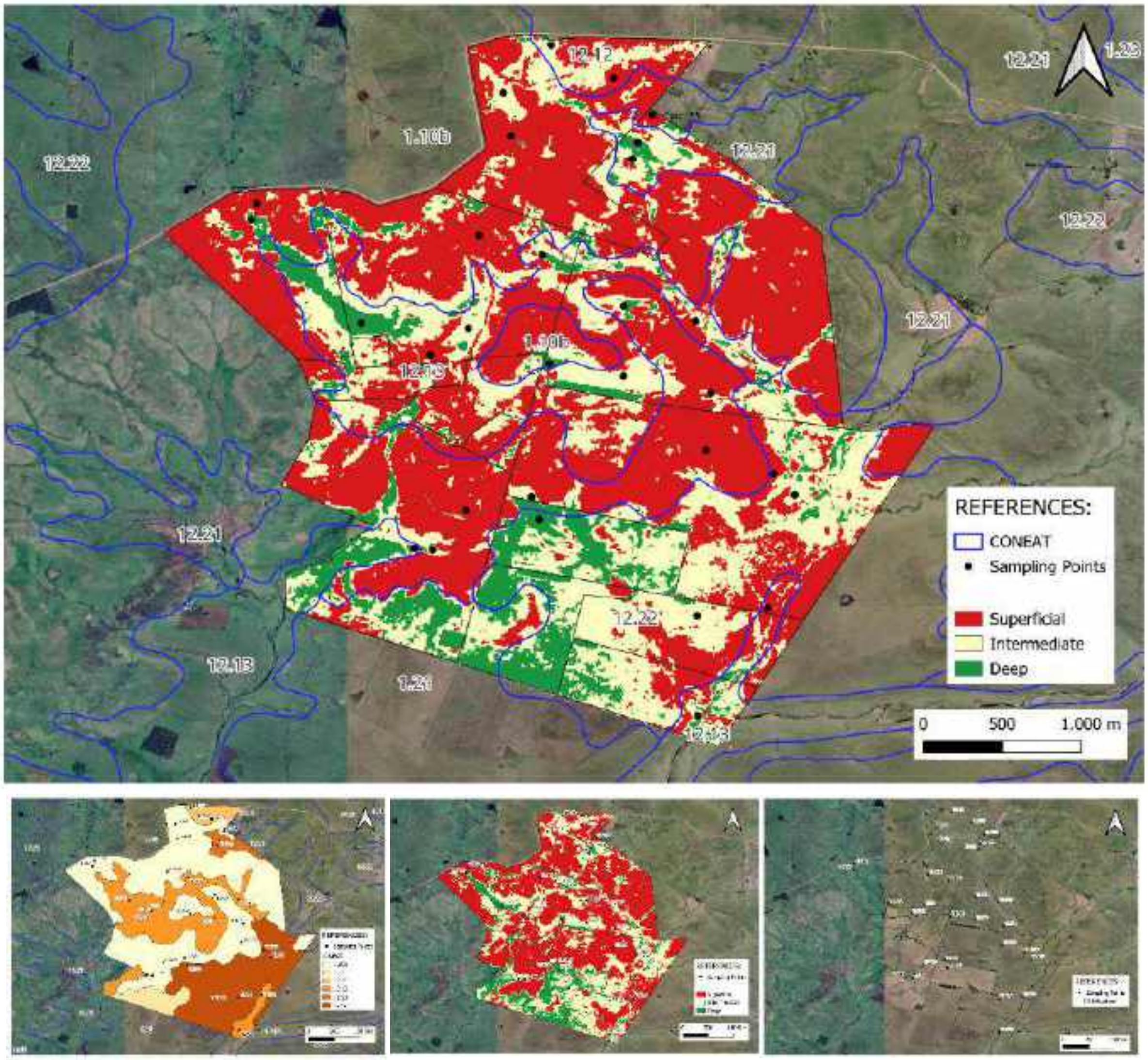

Fig 1- Example of sampling design considering the three categories of soil determined by NDVI (superficial. intermediate and deep) and the representation of the CONEAT cartogtaphy.

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Results

Physical-chemical variables

The result of analysis showed a tendency for reduced carbon contents and increased bulk density in deeper strata. Within each depth strata, no differences were detected for different soil depth categories or CONEAT soil categories. Table 1 shows the average values of the variables determined in the soil samples.

Table 1 – Results of physical-chemical analysis of soil

Depth strata (cm)	Organic carbon (%)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g/cm^3)	pH	Org. carbon Mg/ha
0-5	5.32 ±1.45a	20.3±14.2a	32.6±12.0a	47.1±11.6a	0.92±0.17c	5.8±0.5d	22.9±5.6b
5-10	3.68 ±0.87b	17.8±17.8ab	30.3±12.4ab	51.9±13.9ab	1.06±0.14b	6.0±0.5c	17.2±5.4c
10-20	3.30±0.75c	14.7±11.5ab	28.3±12.1ab	57.0±13.2bc	1.11±0.16a	6.3±0.6b	29.2±11.1a
20-30	2.85±0.61d	13.2±10.4b	26.7±10.1b	60.2±12.4c	1.12±0.13a	6.5±0.6a	24.0±11.5b

Table 2 shows the average depth of each soil category, the proportion of area for the different categories in the farms and the total carbon stock by hectare are presented.

Table 2- Contents of organic carbon, depth and proportion occupied in farms for each soil class.

Soil class	**Depth cm (mean ± SD)**	**Proportion (%)**	**Org. C stock Mg/ha (mean ± SD)**
Deep	30.00±0.00	46.3±18.9	118.4±17.3
Intermediate	18.50±7.71	36.0±12.5	60.7±25.6
Superficial	8.95±6.99	17.7±12.8	26.9±11.4
Farm average			82.0±10.6

Within each strata correlations between organic carbon content and texture were intermediate, ranging from 0.43 and 0.57 with clay content and -0.9 and -43 with sand content. The strongest correlation was obtained for bulk density ranging from -0.59 and -0.74.

In the exploratory analysis, no significant correlations were found between soil carbon content at each sampling point and the NDVI average of the last 5 and 10 years.

Discussion

The results show a large stock of carbon in the soil, with an average of 82 tons per hectare, even when about 54% of the area did not reach a 20 cm of soil depth. Shallow soil depth creates a real challenge to increase soil carbon stocks and sequester carbon, although some studies predict a potential (Dondini et al, 2023). However, it emphases the importance of grazing land use to maintain large amounts of carbon in the soil.

As expected, the carbon content decreases with soil depth, which is probably partly explained by the heavy textural horizon of these types of soil that prevents a massive penetration of roots deeper in the soil profile.

Considering the different types of soil according to CONEAT cartography or the three depth categories, no differences were found in the soil carbon contents within the same depth strata. This indicates that any variations found between different farmers and points within the same farm should be explained by other variables. We consider that one of these variables may be the management history of the farm or paddock within a farm, which could have led to change in vegetation biomass and consequently change in soil carbon stock over time. This possibility is impossible to verify given the absence of this information, but it indicates that conditions unrelated to the texture or type of soil may explain any changes in carbon stocks.

The NDVI extracted from Sentinel has not allowed us to detect differences in soil carbon content between different points in basaltic soils, perhaps because of the very small variations in the carbon stock found in this study. Future work to predict carbon stocks using models should be based on other remote sensing variables, such as radar images or combinations of multispectral measures. Use of models supported by remote sensing variables would undoubtedly be an important step forward in carrying out faster analyses, without consuming so much time and effort, and which could be extrapolated to large areas.

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Carbon farming in rangelands: Policy lessons from Australia

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Key words: carbon, sequestration, incentives, co-benefits

Abstract

Australia was one of the world's earliest adopters of carbon farming incentives via its 2011 Carbon Farming Initiative, with rangelands at the forefront of project development. Since that time, policy incentives for rangeland carbon sequestration have been introduced from Canada to China and the European Union has embraced the language of carbon farming. So, what has Australia learnt in the past 15 years that could provide insights for other countries embarking on their rangeland carbon journey? This paper traces the history of Australian carbon policy and presents perspectives from diverse stakeholders based on interview data collected through five research projects undertaken between 2009 and 2025. This analysis maps the changing issues and attitudes amongst rangeland landholders, government agency staff, researchers and the carbon industry.

One notable trend apparent in the interview data is the way that concerns raised by landholders in earlier interviews, such as long commitment periods, taxation rules and inflexible trading rules were addressed through subsequent policy adaptation, only to be replaced by new concerns such as absenteeism, sequestration shortfalls or credit integrity. Whilst these concerns have evolved over time, the interviews also provide a record of carbon farming's progression from a potential income stream to a reality for many landholders, with reported benefits for economic resilience, sustainable land management and socio-cultural wellbeing. Amidst all this change, one factor that has been a constant throughout is the perception that carbon farming is a complex activity facing considerable uncertainty relating to biophysical outcomes, market conditions and policy shifts. These lessons may help other countries to anticipate issues that could emerge as their own carbon industries mature and design carbon farming policy proactively rather than reactively.

Introduction

Carbon farming is increasingly recognised as a significant strategy for climate change mitigation. Numerous jurisdictions, including the European Union, China, India and Canada have established frameworks for landholders to generate income by storing carbon in their soils and vegetation (Baumber et al., 2024). Australia established itself as an early pioneer of carbon farming policy with its 2011 Carbon Farming Initiative (CFI) and 2015 Emissions Reduction Fund (ERF). The ERF involved direct government purchases of carbon credits while also creating the policy infrastructure to support a private market in carbon offsets. Australia's early adoption of, and experimentation with, carbon farming may provide lessons for more recent developments in other jurisdictions, including the use of results-based payment schemes for carbon sequestration under the European Union's Green

Deal initiative (Bumbiere et al., 2022), the Alberta offset scheme in Canada (Government of Alberta, 2023) and the emergence of public-private partnerships focused on trading farm-based carbon credits in India (Jat et al., 2022).

In this paper, the term "carbon farming" is used to refer to practices aimed at maintaining or increasing carbon sinks in vegetation and soils, such as afforestation or reforestation to increase above-ground biomass and the alteration of grazing or cropping regimes to increase soil organic carbon. It should be noted that other research and policy literature employs a broader definition that covers all farm-level management of carbon pools, flows and greenhouse gas fluxes, including on-farm emissions from transport, livestock and fertilisers (EC, 2021).

Carbon farming in Australia received its first major policy boost via the creation of the Carbon Farming Initiative (CFI) in 2011. This created a set of prescribed methods that could be used to generate carbon credits through sequestration in vegetation and soils. The original plan to link the CFI to a comprehensive cap-and-trade scheme did not survive a change in government in 2013, but it did lay the foundation for the Emissions Reduction Fund (ERF), a AUD4.5 billion initiative that was established in 2015. The ERF utilised a reverse auction system to provide financial incentives for projects that reduce emissions or sequester carbon, with government funds directed to the lowest-cost abatement methods. This was a boon for vegetation projects in the rangelands (Figure 1), with the two key methods of Human-Induced Regeneration (HIR) and Avoided Deforestation (AD) making up almost half of all Australian Carbon Credit Units (ACCUs) issued by 2020 (Baumber et al., 2020).

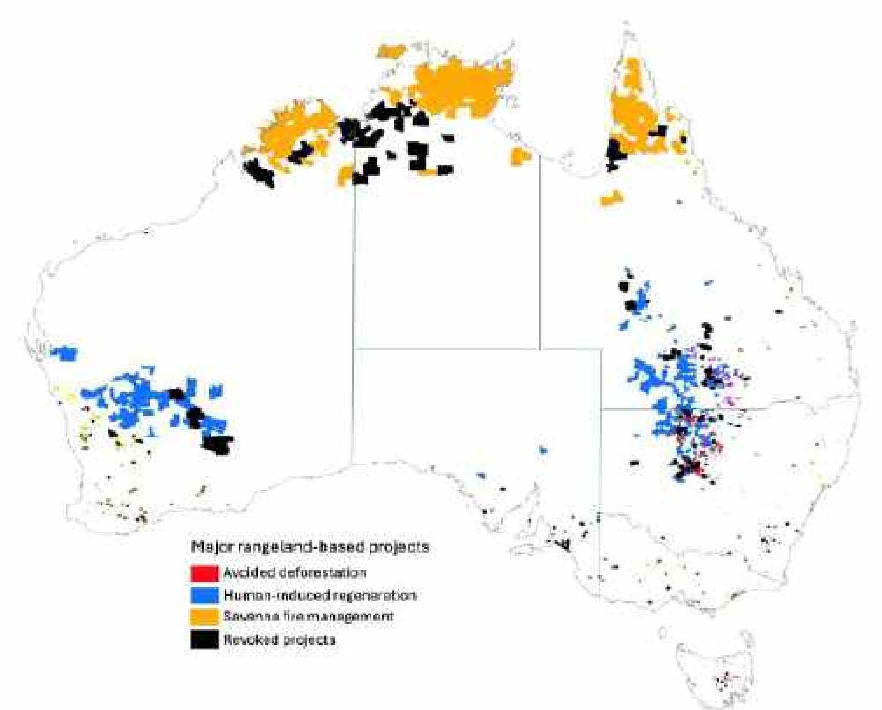

Figure 1: Australian ERF projects as of 2020 (adapted from Baumber et al., 2020). Note that savanna fire management involves emissions reduction rather than sequestration and is not covered in this paper.

The AD method involved a landholder agreeing not to clear trees they hold a legal right to clear, while the HIR method required a change in management to allow trees to regenerate (e.g. fencing out livestock). The rapid growth in these rangeland-based methods attracted some criticism, including "additionality" concerns around AD, given that some of the areas were unlikely to have ever been cleared, and concerns that HIR models were over-estimating the amount of carbon that was actually being sequestered through changes in land management (Macintosh et al., 2024). The independent "Chubb Review" recommended some changes in 2022 aimed at improving transparency around project reporting and method development and separating responsibilities for scheme regulation from government procurement of credits (Chubb et al., 2022). The AD method was revoked and HIR was allowed to expire, meaning no new projects could be registered after 2023. Other recent trends include a shift in policy terminology from "ERF" to "ACCU Scheme", an increased interest in soil-based sequestration in higher-rainfall areas and an expansion of the "Safeguard Mechanism", which has increased demand for carbon offsets amongst large emitters and shifts the carbon market in Australia away from its earlier reliance on government purchases of carbon credits (Baumber et al., 2024).

Overview of previous research projects

The policy lessons discussed in this paper are drawn from the following five research projects involving carbon farming across Australia, with a particular focus on the rangelands of New South Wales (NSW):

1. A 2009-11 study involving farmer interviews on woody crops for multiple purposes, including bioenergy, eucalyptus oil and carbon credits in western NSW (Baumber et al., 2011)
2. A 2017-18 study involving a technical workshop and online survey of landholders, researchers and agency staff linked to carbon farming in western NSW (Cowie et al., 2019)
3. A 2018-20 study involving an online survey, semi-structured interviews and focus groups with carbon farming stakeholders in western NSW (Baumber et al., 2022)
4. 2022-24 study on collaborative approaches to soil-based carbon farming with national key informant interviews and a western NSW case study (Baumber et al., 2024)
5. Ongoing 2023-26 study of landholder information sources and intended actions on carbon farming, involving ten interviews in NSW so far (unpublished)

The studies listed range from the period just prior to the introduction of the CFI, when federal carbon farming policy was being developed and debated, through the period of rapid growth in rangeland projects following the introduction of ERF payments (2015-2020), to the period of policy reform in 2022-2025. The research questions focused on in these studies cover perceived risks and benefits of carbon farming, perceptions of carbon farming versus other land use activities, carbon farming's potential contribution to socio-ecological resilience, social licence (i.e. community acceptance), information sources and adoption support, and the potential for collaboration between landholders.

Policy lessons

Lesson 1: The need for policy adaptation

One of the characteristics of Australia's global leadership on carbon farming has been a willingness to change rules and policy settings to increase adoption. A notable result in Study #1 on woody crops (Baumber et al., 2011) was that interviewed landholders preferred bioenergy over carbon due the perceived inflexibility of carbon farming, with comments including "It's inhibitive, it devalues the land" and "You lose control of your land for 99 years". A requirement to maintain sequestration for 100 years was incorporated into the CFI in 2011, but the introduction of the ERF in 2015 also provided a 25-year option. Farmers could commit to the shorter permanence period in exchange for a 20% discount on the credits they received (designed to cover the risk that sequestration may be reversed after that time).

The focus studies record the shift over time as carbon farming changed from a potential to a real income stream, with socio-economic benefits for landholders and surrounding communities. As income was generated, taxation emerged as another area in which policy adaptation was required to achieve fairness and increase incentives for adoption. Tax treatment was a common complaint amongst landholders in Study #2, including "Got 3.5 years' worth of carbon payments and lost a lot to tax" and "Why isn't it primary production?" (Baumber et al., 2022).

Taxation rules were later changed to allow concessional tax treatment for ACCUs generated by primary producers from 1 July 2022. Another example of a policy change that was designed to increase flexibility and the incentive to participate was the 2022 decision to allow carbon farmers to exit fixed delivery contracts they held with the government under the ERF in order to capitalise on higher prices available on the ACCU spot market (IEEFA, 2022).

Lesson 2: The need to overcome complexity and uncertainty

Landholder concerns about the complexity of carbon farming rules and uncertainty around future policy changes are a key theme running through each of the five focus studies – and other studies as well (e.g. Cotton and Witt, 2024). Landholders expressed these concerns in remarkably similar ways over the 15-year timeframe covered by the focus studies, including:

- "Carbon trading is very political… too susceptible to political change" (Study #1).
- "Where do you go to for info?" and "I have found that there is a lot of uncertainty in the future direction of carbon farming" (Study #3)
- "I think the main barriers are understanding it" and "I think the biggest prohibitor is the lack of education and the confusion around carbon farming" (Study #4)

While improvements in information provision and landholder support may help to address uncertainty, confusion and complexity, there is also a fundamental tension between Lesson 1 on the need for policy adaptation and Lesson 2 on the need to overcome uncertainty. This tension was highlighted in Study #2 on socio-ecological resilience (Cowie et al., 2019) and Study #3 on social licence (Baumber et al., 2022). Confidence in governance is a key determinant of social licence and continual policy changes can erode trust. However, the potential loss of trust and social capital from continual policy changes needs to be weighed against the benefits of increased flexibility and adaptability, which can improve the resilience of farming enterprises and rangeland communities more broadly (Baumber et al., 2020).

Lesson 3: The need for confidence and integrity

This lesson was most clearly highlighted by the Chubb Review in 2022, including some of the concerns and claims that surrounded it (Macintosh et al., 2024) and the review's recommendations to close down the AD method, suspend the HIR method, and separate scheme regulation from government credit procurement into different agencies. This review was highly topical during Study #4 and was linked to several statements of cynicism about the carbon farming industry from landholders and other stakeholders, including: "farmers are inherently suspicious of any government scheme", "cover for the fossil fuel industry to continue business as usual" and numerous references to "sharks" in the industry.

Study #3 considered the social licence to operate with regard to carbon farming and found that a lack of confidence in governance was one of the biggest barriers to obtaining a broad-based social licence in affected communities. A narrow focus on maximising carbon was also found to be problematic in cases where it clashed with local values, such as the preferred balance between grass and trees and a feeling that people should stay on the land rather than become "absentee" landholders producing carbon only. Recommendations for building and maintaining social licence include using trusted information sources to disseminate information (e.g. landholders, local agencies), considering norms and values when designing carbon farming policy (e.g. perceptions of what good land management is), closing the gap between global-scale policy frameworks and locally-relevant actions, valuing co-benefits such as biodiversity and soil health, and decreasing dependence on a single program (i.e. the ERF).

Lesson 4: The need to overcome barriers of cost and bureaucracy

The costs involved in becoming a carbon farmer were a prominent barrier in each of the focus studies. These include costs associated with obtaining information and advice, baselining current carbon levels in vegetation or soils, registering projects, entering into contracts, changing practices, measuring carbon sequestration and compliance and auditing of projects. These cost factors were a particular issue in Study #4, which looked at soil carbon and the potential for collaboration. While models exist to estimate above-ground carbon based on predicted tree growth, developing similar models for below-ground carbon has been challenging. Without reliable models, the costs involved with baselining carbon levels and measuring sequestration levels in subsequent years can be prohibitive, for example: "how much would it probably cost me… maybe 30, 50 grand to do the baselining…that's a fair bit of money then I'd have to recoup that in a sale." (Baumber et al., 2024).

As with Lessons 1 and 2, there is also a trade-off required between Lesson 3 on the need for integrity and Lesson 4 on the need to reduce costs. Bringing down the costs of measurement and compliance has been identified as a critical goal for expanding the adoption of carbon farming and realising its potential in Australia. However, the experiences with the Chubb Review and the ongoing questioning of the models used to calculate carbon sequestration from HIR highlight the need to tread carefully when replacing on-ground measurements with modelling and assumptions.

Conclusion

Australia's experiences with policy innovation, experimentation and learning over the past 15 years not only places it in a strong position to continue Australia's global leadership on carbon farming, but also to help inform the policy decisions made in other jurisdictions. However, challenges remain around the barriers of complexity and cost, the need to increase confidence in the integrity of carbon farming schemes and the need to balance continual adaption with landholders' desires for certainty and clarity. The Australian Government has demonstrated an ability to respond to concerns raised by landholders, such as around long commitment periods, taxation and inflexible trading rules. As these concerns are replaced by newer ones, such as around credit integrity or absenteeism, further adaptation will be needed, while also keeping key actors informed and avoiding a sense of constantly changing rules. By drawing on Australia's policy lessons, other countries may be able to anticipate issues that could emerge around their own carbon industries and design carbon farming policy proactively rather than reactively.

This paper also demonstrates how ongoing social research with landholders, government agencies, industry players and other members of rangeland communities is essential for sustaining a successful and responsible carbon farming industry. Semi-structured interviews, focus groups and surveys can all provide valuable data for this purpose, as can a mix of national-scale and locally-specific case studies.

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What lurks beneath the surface: Contribution of profile soil to total organic carbon pools in vertosols of central Queensland, Australia

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Key words: carbon accounting; carbon sequestration; natural capital; soil carbon; subsoil.

Abstract

The standard practice for calculating carbon stocks in soil is tonnes per hectare (t/ha) to a depth of 0.3 m. Such calculations are influenced by the greater proportion of carbon in the 0.0 to 0.1 m depth, but sampling to 0.3 m provides additional information on the impact of management practices. Regardless, only sampling to a depth of 0.3 m neglects a substantial portion of carbon in profile soil. Intrigued by this conundrum, profile samples from the Brigalow Catchment Study were analysed for Walkley and Black soil organic carbon (SOC) for three land uses: remanent brigalow woodland, cropping and grazing. Samples were collected from Vertosol soils to a maximum depth of 4.4 m in 2018, 36 years after clearing of the two agricultural land uses. In agreement with earlier studies, there was less carbon under cropping than grazing or brigalow woodland. On average there was 42 t/ha of carbon in the top 0.3 m of soil under grazing and woodland which accounted for 56% of the SOC stock to 4.4 m, compared with only 28 t/ha under cropping which accounted for 48% of the SOC stock to 4.4 m. Carbon stocks were steady below 1.8 m for all three land uses, and carbon in the 0.3 to 1.8 m depths accounted for 30% of the total SOC stock to 4.4 m. Root biomass is the main input of organic carbon into soil, and land management practices that promote perennial pastures and native vegetation with deeper root systems increase the opportunity of profile soil to sequester carbon.

Introduction

Many studies focus on SOC in the top 0.3 m of soil due to its concentration at the surface and ease of sampling, but this depth has limited potential to sequester further carbon due to its high mineralisation rates and subsequently shorter residence times (Button *et al.* 2022; Hicks Pries *et al.* 2023). Globally, 68% of SOC is in the 0.3 to 2.0 m depth yet many studies still focus on carbon in the 0.0 to 0.3 m depth (Hicks Pries *et al.* 2023). Whether soil becomes a sink or source of atmospheric CO_2 depends on plant growth (carbon input into soil) and organic matter decomposition (carbon output to the atmosphere), and estimates under future climate warming scenarios indicate that SOC globally will become a source of carbon to the atmosphere but that losses would be proportionally lower from the subsoil (Wang *et al.* 2022). This indicates that subsoils have the potential to offset anthropogenic emissions by sequestering carbon into stabilised pools which decompose more slowly with turnover times of thousands of years (Button *et al.* 2022). However, it is possible that new plant inputs in profile soil may alternatively increase the decomposition rate of extant carbon due to priming (Hicks Pries *et al.* 2023). The present study demonstrates the substantial contribution of carbon in the 0.3 to 1.8 m depths under native vegetation with two agricultural systems to the total organic carbon (TOC) pool to 4.4 m and discusses opportunities to optimise carbon sequestration in the subsoil.

Methods

This study was conducted at the Brigalow Catchment Study located in central Queensland, Australia. The area has a semi-arid to subtropical climate, with a long-term (1965 to 2023) mean annual rainfall of 643 mm. Data was collected from three land uses: 1) virgin brigalow woodland representative of the pre-European landscape; 2) cropping, typically with annual wheat or sorghum; and 3) grazing on a perennial improved grass pasture. The three land uses are adjoining paddocks within an area of about 80 ha and have similar soil and landscape characteristics. The two agricultural systems were cleared and developed in the early 1980s with commencement of their respective land uses in 1983. The cropping system also had a ley pasture of butterfly pea planted in 2010 to improve soil fertility. Further details are provided in Elledge and Thornton (2022).

Samples were collected in 2018 from all three land uses, which was 36 years after the commencement of grazing and cropping in the two agriculture systems. Soil was sampled at 0.1 m increments to a depth of 2.0 m and then 0.3 m increments until either bedrock or a maximum depth of 5 m. However, only data for key depths is presented in this paper: 0.0 to 0.1, 0.1 to 0.2, 0.2 to 0.3, 0.5 to 0.6, 0.8 to 0.9, 1.1 to 1.2, 1.4 to 1.5, 1.7 to 1.8, 2.0 to 2.3, 2.6 to 2.9, 3.2 to 3.5, and 4.1 to 4.4 m. There were two Vertosol sites within each of the three land uses. Five cores per site were bulked by sampling depth, and then analysed for Walkley and Black organic carbon (method 6A1, Rayment and Lyons 2010). Organic carbon concentrations (%) were converted to total carbon pools (t/ha) using bulk density for each of the key depths with values standardised to a 0.1 m increment for the 0.3 m cores. Bulk density was determined by weighing individual cores after air drying, oven drying a subsample of each core, and then correcting the sample mass to the equivalent oven dry soil mass (Thornton and Shrestha 2021). Averages are presented for the two Vertosol soils, with values graphed using the sample mid-point depth.

Results

TOC to 4.4 m was 80 t/ha under grazing, 71 t/ha under brigalow woodland, and 59 t/ha under cropping. Unsurprisingly, most of the carbon was in the 0.0 to 0.3 m soil depths. However, across all three land uses there was on average 30% of TOC in the 0.3 to 1.8 m depths and 17% in the 1.8 to 4.4 m depths (Table 1). Differences were observed in the 0.0 to 0.6 m soil depths with SOC lower under cropping than from brigalow woodland and grazing, which had similar TOC. Although carbon stock declined with depth for all three land uses, it tended to stabilise below 1.8 m (Figure 1).

***Table 1*:** Soil organic carbon under virgin brigalow woodland compared with two agricultural systems.

Total Organic Carbon	Woodland	Cropping	Grazing
t/ha in 0.0 to 0.3 m depth	42	28	43
t/ha in 0.3 to 1.8 m depth	19	19	24
t/ha in 1.8 to 4.4 m depth	10	12	13
% in 0.0 to 0.1 m depth	26	18	25
% in 0.1 to 0.2 m depth	16	16	16
% in 0.2 to 0.3 m depth	16	15	13
% in 0.0 to 0.3 m depth	59	48	54
% in 0.3 to 1.8 m depth	27	32	30
% in 1.8 to 4.4 m depth	14	20	16

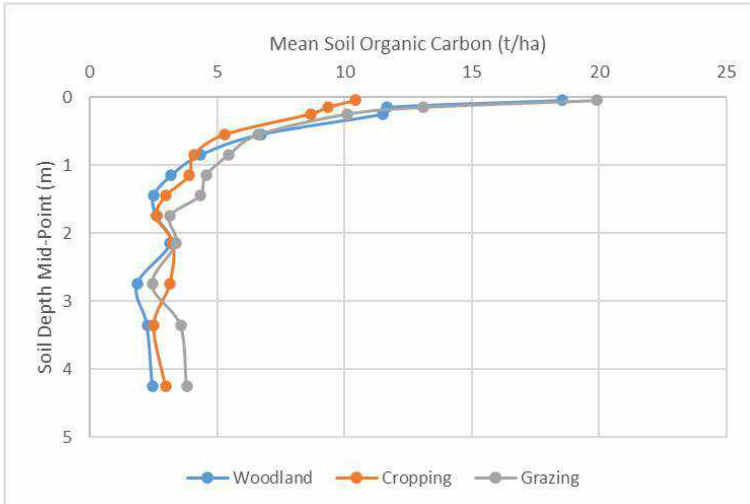

Figure 1: Soil organic carbon under virgin brigalow woodland compared with two agricultural systems.

Discussion

SOC under brigalow woodland and grazing were similar throughout the soil profile, but cropping typically had less, especially in the 0.0 to 0.6 m depths. This is logical given the considerably greater removal of carbon in the form of harvested grain from cropping compared to cattle live weight gains from grazing (Radford *et al.* 2007). A study by Dalal *et al.* (2021), also conducted at the Brigalow Catchment Study, reported an initial 12% decline in SOC when brigalow woodland was converted to grazing due to land development and pasture establishment (≤1.75 years). But particulate, humus and resistant fractions of carbon remained constant over the following 33 years in the 0.0 to 0.4 m depths due to ongoing inputs from root biomass. In contrast, conversion of brigalow woodland to cropping decreased SOC by 38% in the 0.0 to 0.3 m depths over 26 years (declines reported for all carbon fractions), but there was no statistical difference for the 0.3 to 0.4 m depth indicating that deeper carbon stock remains steady (Dalal *et al.* 2021). Furthermore, the planting of a ley pasture to improve soil fertility in this cropping system had arrested further decline (Dalal *et al.* 2021). These carbon trends between land uses are consistent with other studies (Murty *et al.* 2002).

It is important to note that although grazing appears to have greater TOC than brigalow in this study, which occurred 36 years after clearing and development for agriculture, this is not the case when the pasture catchment was compared to its original condition with multiple studies reporting a decline in TOC over time (Dalal *et al.* 2021; Thornton and Shrestha 2021). An earlier study by Dalal *et al.* (2013) at the study site also found that 62% of SOC under the two agriculture systems was derived from the original brigalow woodland. That is, 23 years after land use change, carbon incorporated into the soil (0.0 to 0.3 m) from either pasture or crops had replaced 41% and 36% of the carbon source, respectively. Although these results are from a long-term (decadal) study, the turnover of SOC at this site was reported to be 31 years in the 0.0 to 0.1 m depth which almost doubled to 60 years in the 0.1 to 0.2 m depth, where it then retained a similar age to the maximum sampled depth of 0.4 m (Dalal *et al.* 2011). However, SOC in the subsoil can have turnover times from 1,000 to more than 10,000 years which is where the potential for climate change mitigation via the sequestration of carbon occurs (Hicks Pries *et al.* 2023). This highlights the important contribution of carbon in profile soil below 0.3 m depth.

TOC in the three land uses of this study stabilised at about 1.8 m depth, which is logical given the known rooting depths of the different plants. That is, annual crops such as wheat and sorghum used in this study have a maximum rooting depth of 1.8 m, but with most of the root biomass in the top 0.3 m (Fan *et al.* 2016; GRDC 2017; Demissie *et al.* 2023). Cropping also involves the harvesting of above ground biomass and soil disturbance from machinery which leads to a decline in soil organic matter, which may have contributed to the apparent difference in SOC in the top 0.6 m depth in this study. This is aligned with a global meta-analysis that reported reforestation of croplands increased SOC to 0.6 m (Hicks Pries *et al.* 2023). The rooting depth of grass pasture on brigalow soils was also reported to be about 2 m (Shelton and Dalzell 2007), but with the added benefit of no disturbance to the soil surface. Considering that native vegetation in this region have rooting depths greater than 5 m (Shelton and Dalzell 2007) and that the original brigalow woodland contributed to most of the SOC under all three land uses (Dalal *et al.* 2013), this highlights the importance of adopting plants with deeper root systems for SOC sequestration. That is, the progression from annual crops to a perennial pasture and then to native vegetation not only increases the potential for carbon sequestration in the subsoil, but also improves drought tolerance under future climate warming scenarios by allowing for the enhanced use of water and nutrients at depth (Button *et al.* 2022).

Furthermore, a vegetation survey at the Brigalow Catchment Study in 2015 found that there was 10 times more live tree biomass (overstorey and understory) in brigalow woodland than the grazing system (56.8 t/ha vs 5.1 t/ha, respectively) (Elledge, pers. comment), and brigalow trees (*Acacia harpophylla*) at the site have been estimated to be about 100 to 150 years old (Brooks English 2024). This indicates that if agricultural land is converted back to native vegetation for the purposes of carbon sequestration, it may take more than a century to reach a stable state of carbon at depth.

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Comparison of techniques for estimating soil bulk density in arid and semi-arid rangelands: implications for estimation of soil carbon stocks

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Key words: soil bulk density; method comparison; carbon stock estimation

Abstract

In Australia, arid and semi-arid rangelands cover vast areas, and contribute to the livestock industry, carbon market, and provision of other ecosystem services. Because of their extent, even minor changes in rangeland soil organic carbon (SOC) stocks on a per-area basis may significantly impact the terrestrial carbon budget. Estimation of SOC stocks from soil C concentrations requires estimates of gravel content, sampling thickness and soil bulk density (*BD*). However, *BD* is a major source of uncertainty, and determination of SOC stocks is often limited by challenges in *BD* estimation. In the absence of measured *BD* values, alternatives such as digitally mapped spatial layers are used to derive *BD* but these values are at relatively low resolution, are static and have relatively high uncertainty. Due to inherently low SOC stocks in rangeland ecosystems, accurate estimation of *BD* is important to detect temporal change.

The most effective method for measuring *BD* will depend on factors such as soil type and moisture conditions at sampling. Here we compared estimates of *BD* to 50 cm sampling depth across several rangeland sites derived from different field methods including: i) the mass of whole soil and volume of carbon concentration cores, corrected for oven-dry moisture content; ii) the mass of whole soil and volume of brass rings collected from soil pits corrected for oven-dry moisture content; and iii) *in situ* gamma-neutron gauge measurements of dry density adjacent to a subset of the cores. Under relatively dry soil conditions, the soil core method gave inconsistent and sometimes spurious results. By comparison, the other methods gave more consistent results. These differences have significant implications for the subsequent estimation of SOC stocks. Our results inform optimal pathways for estimating *BD* in arid and semi-arid rangelands to allow more accurate calculation of stocks and change detection over time.

Introduction

Arid and semi-arid rangelands cover vast areas of Australia and contribute to the livestock industry, carbon market, and provision of other ecosystem services (Department of the Environment 2014; NRMMC 2010; Woinarski et al. 2007). Because of their extent, even minor changes in rangeland soil carbon stocks on a per-area basis may significantly impact the terrestrial carbon budget (Conant et al. 2017).

Estimation of SOC stocks (Mg C ha^{-1}) from soil C concentrations requires estimates of gravel content and soil bulk density:

$$C_s = C_m \times BD \times D \times (1\text{-}G/100) \qquad \text{(Eqn 1)}$$

where C_m is the mass of soil organic C in the soil (%), *BD* is the soil bulk density (g cm^{-3}), *G* is the gravel content (%), and *D* is the thickness of the layer (cm). *BD* is a major source of uncertainty (e.g. Poeplau et al. 2017; Taalab et al. 2013), and determination of SOC stocks in arid and semi-arid rangelands is often limited by challenges in *BD* estimation.

BD can be estimated from 'direct' methods, such as core, clod, and excavation sampling, or 'indirect' methods including radiation and regression approaches such as pedo-transfer functions (Al-Shammary et al. 2018). Digital soil maps can also be used to derive BD but are typically of relatively low resolution, are static and have relatively high uncertainty. The most effective method for measuring *BD* will likely depend on the soil type and moisture conditions at the time of sampling. For example, if soils are dry and crumbly, cores may not be fully intact, resulting in large variation between cores, potentially resulting in spurious estimates. Using rings collected from soil pits largely removes the issue of crumbling cores, but typically lacks spatial coverage. Spatial representation could be addressed through excavating multiple pits, but this is time consuming and expensive. Indirect methods such as using gamma-radiation attenuation may be useful for increasing spatial representation in a more time- and cost-effective way, but accuracy is influenced by soil depth (Alam et al. 2001). Therefore, the aim of this study was to compare and assess the utility of three alternative methods for estimating *BD* and subsequent estimation of SOC stocks to inform future sampling strategies in arid and semi-arid rangelands.

Methods

Field sampling and measurement

The study sites included six long-term experimental trials in Australian rangelands (Table 1). Sampling was undertaken between September 2023 and August 2024 to compare three methods for determining soil bulk density (*BD*):

i. Soil was sampled from 12-30 random locations per plot depending on plot size using a corer (internal diam. 43 mm) to 50 cm depth, with three depth intervals 0-10, 10-30 and 30-50 cm;

ii. Soil was sampled from a single excavated pit per plot, with pit ledges at 0, 10 and 30 cm. Where soils were dry and crumbly, pits were irrigated overnight to 'wet up' the soils prior to sampling. Three brass rings (internal diam. 98.5 mm) were collected from each of three depth intervals 0-10, 10-30, 30-50 cm per plot;

iii. *In situ* measurements of BD were taken using a surface gamma-neutron gauge (Troxler Model 3440+, Troxler Electronics Laboratories, Inc, NC, USA) at 4-12 locations per plot depending on plot size adjacent to a random subset of cores from method i., at three depths (10, 20 and 30 cm). Deeper measurements were also made on each of the pit ledges from method ii), corresponding to depths of 10, 20 and 30 cm, 20, 30 and 40 cm and 40, 50 and 60 cm for the pit ledges at 0, 10 and 30 cm, respectively.

Sample processing and BD estimation

For i., soil samples were air-dried (40°C oven until constant weight) and bulked into 4-5 composite samples per depth per plot. For each bulked sample, peds were crushed using a mortar and pestle, and sieved to <2 mm to remove gravel and large organic matter (e.g. woody roots). The moisture content in the <2 mm soil samples after air drying was quantified gravimetrically by oven drying a 20-30 g subsample at 105°C for 48 hours. For each >2 mm sample, gravel was separated from organic matter and the weight recorded. Gravel content (*G*, %) was calculated as:

$$G = G_m / W_m \times 100 \qquad \text{(Eqn 2)}$$

Where G_m is the mass of the gravel in the >2 mm sample and W_m is the oven-dry corrected mass of the whole (>2 mm + <2 mm) soil sample.

For ii., the fresh weight of each sample was recorded before drying at 105°C to constant mass. For iii., the gauge measures BD by gamma source and moisture by neutron source, correcting wet BD to dry BD.

Using these data, we estimated *BD* (g cm^{-3}) of each depth interval in three ways:

i. *Core BD*. From the mass of the whole soil (fine and gravel fractions) and volume of the cores, corrected for oven-dry moisture content, as recommended in the Guidelines for the Soil Carbon Measurement Methodology (Australian Government 2021);

ii. *Pit BD*. From the mass of the whole soil (fine and gravel fractions) and volume of the rings collected from a single soil pit per plot corrected for oven-dry moisture content;

iii. *Gauge BD*. From *in situ* gamma-neutron gauge measurements of dry density.

To provide a preliminary test of the implications of differing *BD* estimates in the estimation of SOC stocks, alternative estimates of carbon stocks were derived (Eqn 1) using a consistent total carbon concentration for each of the 0-10, 10-30 and 30-50 cm depths layer as 4, 3 and 2 mg g^{-1}, respectively. Two contrasting sites – one with dry soils at the time of sampling (Wapweelah), and another with relatively moist soils at the time of sampling (Boatman) were compared.

Data analysis

Bland-Altman analysis (Bland and Altman 1999) measures the agreement, and quantifies the difference, between two methods compared with correlation and regression analyses where only the association between two methods is assessed. Here, Bland-Altman plots (also called Tukey mean-difference plots) of the differences against the averages of the alternative methods for the plot-level data were used to evaluate bias between the mean differences, and to estimate an agreement interval, within which 95% of the differences of the second method, compared to the first one, fall. The 95% limits of agreement were estimated by mean difference ±1.96 standard deviation of the differences. Because three measurement methods were compared here, plots were compared for each pairwise combination (Core vs. Pit, Core vs. Gamma, and Pit vs. Gamma). Data were checked for the assumption of normality. All analyses were performed using R statistical software (R 4.4.1) (R Core Team 2024).

Results

BD obtained from individual cores gave inconsistent and sometimes spurious results, with values ranging from 0.49-3.46 g cm^{-3} (Figure 1a). By comparison, *BD* obtained from individual rings (method ii) or individual gauge measurements (method iii) gave more consistent results in the range 1.21-1.88 g cm^{-3} (Figure 1b) and 1.09-1.86 g cm^{-3} (Figure 1c), respectively. Plot means for *BD* obtained from cores, pits and gauge measurements were 1.17-2.15 g cm^{-3}, 1.27-1.83 g cm^{-3} and 1.18-1.86 g cm^{-3}, respectively.

Bland-Altman analysis of the Pit BD and Gamma BD methods (Figure 2a) showed the mean difference was 0.10 and the 95% limits of agreement ranged from -0.10 to 0.31. There was no clear proportional bias, indicating that the difference between the two methods was consistent across the average bulk densities. By comparison, Bland-Altman analysis of the Core BD and Pit BD methods (Figure 2b) showed the mean difference was 0.01 and the 95% limits of agreement ranged from -0.37 to 0.39. Although the mean difference was close to zero, the plot indicated a proportional bias, with the difference between the two methods varying as the average soil bulk density increased. Analysis of the Core BD and Gamma BD methods (Figure 2c) showed the mean difference was 0.09

and the 95% limits of agreement ranged from -0.19 to 0.38. The Bland-Altman plot indicated a proportional bias, with the difference between the two methods varying as the average soil bulk density increased, although less steeply than for the Core and Pit BD comparison.

SOC stocks at 0-10, 10-30 and 30-50 cm depth estimated at a site where soils were dry at the time of sampling, were 15.1%, 9.5 and 0.1 % higher, respectively, using *BD* estimated from individual cores compared with the plot mean for the pit. By comparison, at a site where soils were relatively moist at the time of sampling, SOC stocks at 0-10, 10-30 and 30-50 cm depth were 18.8%, 8.8 and 16.3 % lower, respectively, using BD estimated from individual cores compared with the plot mean for the pit.

Table 1. Site characteristics, experimental designs and previous studies relating to the experiments used in this study.

Site name	**State**[1]	**Latitude**	**Longitude**	**Experiment type**	**No. of plots**[2]	**Year trial established**	**Vegetation type**
Oakvale	NSW	-30.95	146.46	Grazing exclosure	4	1975	*Eucalyptus* woodland
Wapweelah	NSW	-29.26	145.32	Grazing exclosure	4	1996	*Acacia* woodland
Croxdale	QLD	-26.46	146.13	Grazing exclosure	3	1981	*Acacia* woodland
Lanherne	QLD	-26.74	145.09	Grazing exclosure	3	1984	*Acacia* woodland
Boatman	QLD	-27.24	146.98	Thinning trial	7	1963	*Acacia* woodland
Monamby	QLD	-26.64	145.38	Thinning trial	6	1965	*Acacia* woodland

[1] NSW = New South Wales, Qld = Queensland; [2] number of plots sampled for bulk density. May not represent all plots in the experiment.

Discussion

A key finding of this study was that *BD* obtained from individual cores (method i) gave inconsistent and sometimes spurious results, while *BD* obtained from individual rings (method ii) or individual gamma-neutron gauge measurements (method iii) gave more consistent values within the expected range for soils. Although the plot means derived for core *BD* were more reasonable, in some cases they were still erroneously high (>2 g cm^{-3}). Further, because SOC stocks are typically calculated based on individual cores (or several cores where samples are bulked), SOC stock estimates using *BD* estimates from cores are likely to be significantly affected. This was demonstrated by the differences between SOC stocks using *BD* estimated from cores versus pits, particularly in the surface 10 cm of soil. The Soil Carbon Measurement Methodology Guidelines (Australian Government 2021) specify estimation of *BD* volumetrically using cores. Our results suggest that, depending on the soil conditions at sampling, alternative methods should be considered for determining *BD* in rangeland soils.

Results here confirmed that *BD* samples from pits that were irrigated overnight to ‘wet up’ the soils prior to sampling removed the issue of crumbling cores in dry soils. However, pit sampling lacked spatial coverage across the plots, and sampling multiple pits would be time consuming and expensive. Here, data from the gamma-neutron gauge provided better spatial coverage and more consistent *BD* estimates than cores. Although *BD* estimates from pit rings were typically higher than those from the gamma-neutron gauge, Bland-Altman analysis indicated that bias was relatively constant. By comparison, Bland-Altman analysis of core and pit estimates of BD showed that although the mean difference was close to zero, bias was proportional, with the difference between the two methods varying as the average soil bulk density increased. Bland and Altman (1999) recommended that 95% of data points should fall within 2 standard deviations of the mean difference. The method only defines the intervals of agreements, and not whether those limits are acceptable or not, therefore acceptable limits must be defined a priori (Giavarina 2015).

The main outcome of this work has been to progress knowledge on the trade-offs between three approaches to measurement of soil bulk density in rangelands. Although not sampled in this study, vertosols are a relatively common soil type throughout parts of the Australian rangelands. Determining *BD* in vertosols has the additional challenge of periodic swelling and cracking of these soils in relation to moisture content (Yule 1981), and further work is required to test the utility of methods in vertosols.

It should be noted that in the Soil Carbon Measurement Methodology Guidelines (Australian Government 2021), stocks are expressed on an equivalent soil mass (ESM) basis rather than on a specific thickness basis. The next phase of this work will investigate whether the ESM approach can avoid these differences in stock estimates resulting from different *BD* measurement approaches.

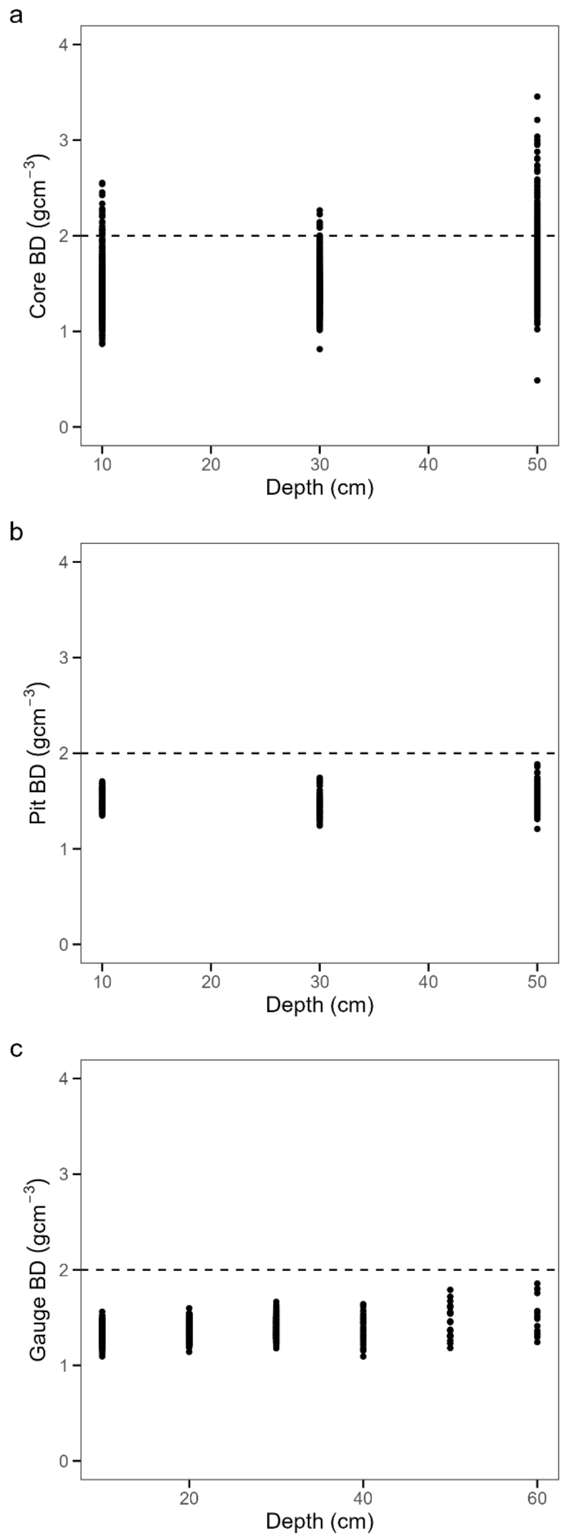

Figure 1 Scatterplots of individual soil bulk density (BD) estimates obtained from: a) individual cores (method i), b) individual gamma-neutron gauge measurements (method iii), and c) individual rings (method ii) by lower depth of sample (Depth). The dashed line indicates a value of 2 g cm^{-3}, the typical upper limit for soil.

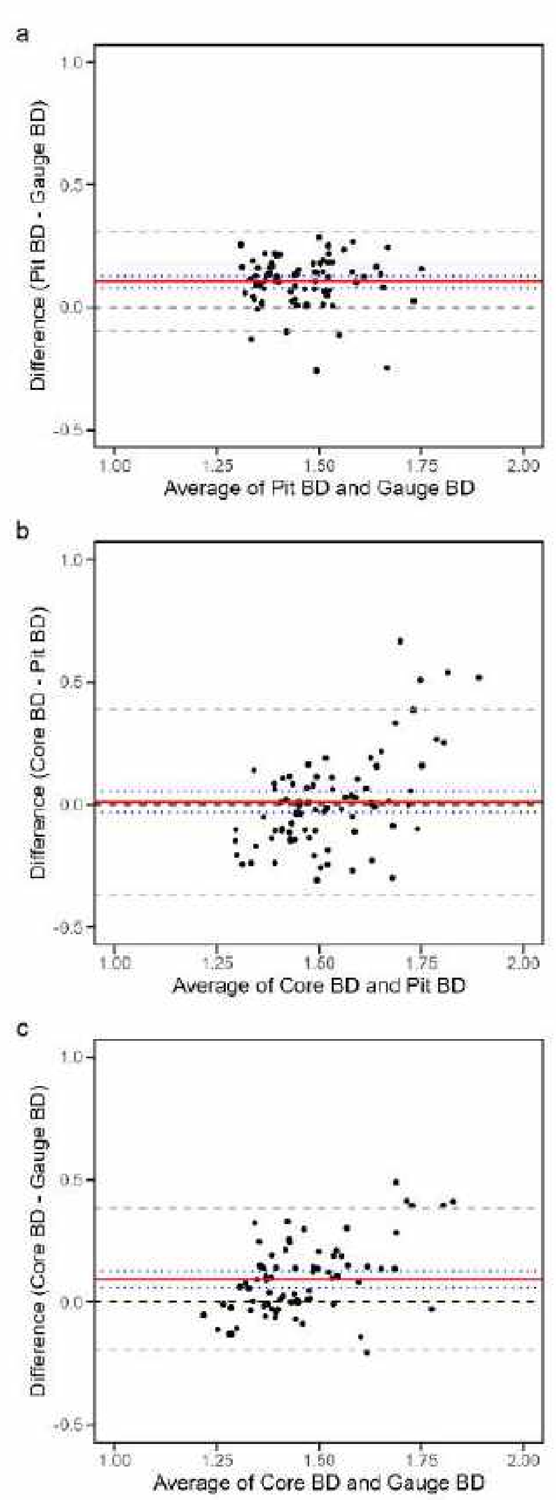

Figure 2 Bland-Altman plots showing the difference between pairs of bulk density (BD) methods plotted on the y-axis against the average of the methods on the x-axis for: a) Pit BD and Gauge BD, b) Core BD and Pit BD, and c) Core BD and Gauge BD. Solid red horizontal line shows the mean difference, dotted blue lines show the 95% confidence interval of the mean difference, dashed grey lines show limits of agreement (±1.96 standard deviation of the differences) and dashed black line shows the line of equality (zero difference). Difference and average values are calculated from three depth intervals (0-10, 10-30 and 30-50 cm) at each of the 27 plots across the six rangeland sites.

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Oil, gas, and mineral industry role in rangeland restoration: a systematic review

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Key words: Oil, gas, and mineral industry; rangeland restoration; investment.

Abstract

The rapid expansion of unconventional oil and gas development in the oil-gas-mineral (OGM) states has been controversial because of numerous environmental and social impacts. OGM industries have existed on rangelands for many years with various impacts depending upon the scope of operations and level of professional management (Walsh and Rose 2022; Allred et al. 2015; Chomphosy et al. 2021). In the last decades, energy production has become the largest user of rangelands in several parts of the OGM produced countries, occupying large areas and becoming the largest driver of land-use change (Kreuter et al. 2016). Although emerging energy resources, such as wind and solar, are growing rapidly due to the new advanced technologies, fossil fuel production continues and is predicted to expand in the future (Covert et al. 2016). This will have significant increases in damages to rangelands in terms of reduction of biodiversity, loses in vegetation, increase in carbon emissions, disruption on the natural ecological process, reduction and contamination of ground water, and decrease on the ecosystem services – the potential benefits that natural rangelands provide to humanity.

In the frame of STELARR (Sustainable Investments for Large-scale Rangeland Restoration) project, this paper aims to give a comprehensive overview on the role this industry could play on rangeland restoration in the West Asia and Middle East (WAME) region and what is expected from it in terms of sustainable business practices and what roles the OGM countries-governments are to play given that are currently confronted by overlapping rangeland-oriented demands from ecologists and industry.

Introduction

OGM industries have existed on rangelands for many years with various impacts depending on the scope of operations and level of professional management (Walsh and Rose 2022; Allred et al. 2015; Chomphosy et al. 2021). Advanced technology has stimulated growth in mineral, oil and gas development, not only in the number of wells, but also in the size of operations around the oil, gas and mining countries. In the last decades, energy production has become the largest user of rangelands in several parts of the oil and gas-producing countries, occupying large areas and becoming the largest driver of land-use change (Kreuter et al. 2016; Holechek et al. 2015; Moran et al. 2017; Covert et al. 2016; Hosseini and Shakouri 2016). Although emerging energy resources, such as wind and solar, are growing rapidly due to new advanced technologies, fossil fuel production continues and is predicted to expand (Covert et al. 2016; Hosseini and Shakouri 2016). This review aims to give a comprehensive overview on the industrial foundation of oil and gas and looks at what is expected from this industry in terms of sustainable business practices and focuses on how rangeland restoration can be an economic and environmentally friendly investment opportunity that the oil and gas sector should investigate.

Methods

The proposed method is a two-stage process analysis relying on quantitative and qualitative data. First, we used a quantitative framework developed by Derek (2024, *pers.comment*), to identify the potential value chains for potential investment in rangeland rehabilitation in the WAME region. The selection process was based on specific factors such as: (1) Availability of inputs and production capacity in the target regions/countries; (2) Existing market demand and growth potential; and (3) Diversification in the use of the final product. The results emerging from this framework regarding the oil, gas, and minerals value chain are displayed in Table 1.

Table 1. Oil, gas, and minerals value chain characteristics for rangeland products

Value Chain	**Oil, Gas, and Minerals (OGM)**
Main product and application	Minerals, oil, gas, oil by-products (i.e. derivates, etc.)
Location	Gulf Cooperation Council countries
WAME largest producer/target	Saudi Arabia

Source: Adapted from Derek (2024, pers.comment).

In the second step, we used qualitative data based on various published and unpublished sources. The data was analysed to provide an overview of the oil and gas industry including its main actors, the key challenges facing this industry and its impact on the environment. In addition, a comprehensive analysis on the potential rangeland restoration investment and support opportunities for the oil and gas industry was conducted.

Results

The oil and gas industry plays a central role in the global economy, constituting 3.8% of the world's Gross Domestic Product (GDP). The United States of America, Saudi Arabia and Russia are the largest producers and exporters of crude oil and gas worldwide. These three nations have a combined total of 43% of the market relative to the world figure in 2022, with production levels standing at 43.3 million barrels a day (MDD Forensic Accountants, 2023). Most rising economies such as the BRICS nations (Brazil, Russia, India, China and South Africa) have accelerated the escalating demand for oil and gas production. In 2022, BRICS members accounted for 25.8% of total world GDP, while the G7 nations held 51.9%. (Energy Information Administration 2023; IMF 2021). In 2023, the oil and gas industry employed over 41 million people worldwide (IEA 2022).

Numerous organizations play crucial roles in forming policies, standards and practices within the oil and gas sector. The International Energy Agency (IEA) delivers data, analysis and recommendations for reliable, affordable and clean energy to its member nations and beyond (Esu and Sindico 2016). OPEC, or the Organization of the Petroleum Exporting Countries, is committed to stabilizing prices by coordinating oil policies among member states (Heath-Brown 2015). Also known as API, the American Petroleum Institute is a standardization body for operational and environmental safety in both the oil and gas sectors (Miller 2014). The International Association of Oil and Gas Producers serves as a global voice for the upstream oil and gas industry, advocating for sound regulatory practices and sustainable operations, as stated on their website (iogp.org) (Threadgold 2018). The World Bank's Oil, Gas and Mining Policy Division offers economic and technical support to developing nations to help them develop their mineral, gas and oil industry in effective and sustainable ways (Toussaint 2023). These companies have made several commitments concerning the environment and society, aiming to reduce emissions and invest in renewable energy projects as well as supporting local development schemes (Al-Fattah 2013; Victor 2013). Sometimes, these efforts have been criticized by environmental activists and researchers as greenwashing and insufficient to mitigate the industry's substantial environmental and social impacts (Parafiniuk and Smith 2019).

Discussion

Possible rangeland restoration investment and support opportunities for the oil and gas industry

The oil and gas sector does not consider rangelands as raw material sources. Nonetheless, its accompanying activities influence local communities and ecosystems, especially in regions with delicate environments or native populations. It is imperative that responsible development practices, stakeholder engagement and environmental protection measures are employed in mitigating these impacts and ensuring social licence to industry officers (Elijah et al. 2021; Ruble 2019). Oil and gas firms invest in restoring land in several ways. Economic benefits of capping and remediating abandoned wells include eliminating pollution. In the past, all lands lying around shut-in wells in the Lower 48 states of America were rehabilitated for approximately US$7 billion. Research shows that reviving unused oil or gas land may have greater economic returns if there is enough crop yield from such areas, if we consider carbon-sequestration efforts and general improvement in environmental quality services. The industry could further evaluate these potential returns to justify investments in rangeland restoration (Moran and McClung 2021).

Mobilizing private sector funding for rangeland restoration: The STELARR project approach

The STELARR project (ILRI, 2024) is intended to reverse rangeland degradation and impact productivity through sustainable livestock value chains that benefit pastoralists and other land users globally. As the project engages with livestock value chain actors, particularly the private sector, it promotes sustainable practices and incentives for investment in rangeland restoration. The project encourages businesses to allocate a portion of their profits toward restoring degraded rangelands through a rangeland's stewardship scheme, which includes a certification standard that rewards sustainability efforts. Companies that meet the highest criteria for restoration investments receive Platinum-level recognition, providing a market-driven solution to rangeland degradation. A key component of STELARR is the development of a global rangelands monitoring system and data platform. This system consolidates datasets into an interactive platform, offering data on rangeland health, trends, and educational resources for policymakers, researchers, and pastoralists]. The platform ensures transparent monitoring and compliance, guiding decision-making and promoting sustainable management practices. It is designed to facilitate the adoption of globally recognized monitoring frameworks for rangeland stewardship and restoration. Capacity building is also central to STELARR's approach, providing support for value chain actors to implement monitoring systems and improve sustainability practices. By aligning its efforts with international initiatives such as the Land Degradation Neutrality targets and the UN Decade on Ecosystem Restoration, STELARR highlights the critical role of collaborative governance and private-sector engagement. It addresses the intricacies of rangeland governance and improves pastoral livelihoods. It will serve as a good example for all future interventions toward demonstrating how such sustainable value chains for livestock can steer economic development and ecological restoration to help in enhancing long-term resilience at the global scales of rangeland systems.

Conclusions and future directions

OGM development significantly impacts rangelands in the West Asia and Middle East (WAME), affecting pastoral livelihoods and ecosystems. The STELARR project explores investment opportunities for rangeland restoration to benefit pastoral communities and promoting sustainable rangeland management, including specific actions to mitigate OGM-related challenges and enhance the resilience of pastoral systems. The review provides some avenues on how rangeland restoration can be a viable investment for the oil and gas sector, aligning economic development with environmental sustainability and improved livelihoods for pastoralists. This initiative would potentially contribute sustain the transformed rangeland system, also raising the chances for successful environmental outcomes.

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Biodiversity and environmental services, markets, offsets

Contributions of science to add value to rangeland-based livestock products: the case of Uruguayan ultrafine wool

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Key words: biodiversity; regenerative agriculture; native grasslands; greenhouse gases; life cycle assessment

Abstract

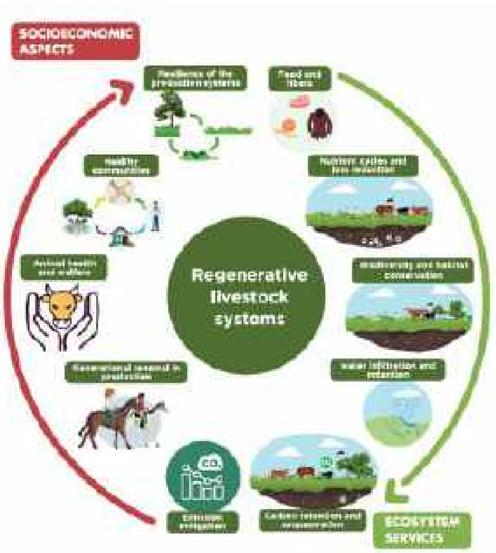
The conservation of native grasslands implies the safeguard from various threats, such as a change in land use. For achieving the objective native grassland conservation, it is necessary to strengthen extensive livestock systems by sustainability improving their performance and by increasing value of emerging products. We developed a regenerative livestock farming proposal based on research evaluating several environmental aspects of the livestock ecosystem functioning on Pampas biome and production technology developed over decades. The conceptual proposal consists of ten points that consider environmental and socioeconomical aspects. The baseline for environmental indicators includes: estimate of carbon footprint through life cycle assessment; organic carbon stock in the soil; assessment of the ecosystem integrity index (EII); the assemblages of wild birds' communities and the assessment of the genetic level of the flock. The latter is included based on its potential for reducing the greenhouse gases (GHG) emissions by improved genetics. We carried out a pilot project with 15 producers which led to the first "regenerative wool" exports from Uruguay to first world-class fashion brands. The results of the study were: a carbon footprint of 60 kg CO_2 equivalent per kg of greasy wool, 83,5 Mg/ha of soil organic carbon stock, an EII value of 3.5, with a bird richness of 104 and 4.26 of Shannon-Weaver Index. The average potential reduction of GHG emission by genetic improvement ranged from 13 to 18% depending on selection criteria used (improving feed efficiency, increasing wool production or reducing methane emissions). In terms of biodiversity, both the IIE results and the richness and diversity of birds are considered very satisfactory. A new collaborative project between INIA and the wool-textile industry seeks to incorporate 110 farmers reaching a total of 200,000 hectares.

Introduction

The livestock sector in Uruguay is the primary user of native grasslands, which in turn are the dominant ecosystem in the country. The conservation of these ecosystems and the significant ecosystem services they provide depends on preventing their replacement by other land uses and ensuring proper management by farmers. On the other hand, livestock farmers face pressures to maintain the sustainability of their operations, both economically, to sustain or improve profitability and continue land use, and environmentally, to reduce negative environmental externalities. To reconcile both objectives—conservation and economically viable production—it is necessary to establish a foundational framework: environmental diagnostics based on scientifically robust, multidimensional indicators, in-depth productive diagnostics, a conceptual proposal that allows for the integration of environmental and economic objectives, the appropriate methodology for implementing this proposal in production systems, and mechanisms for the market to recognize the added environmental value and make production economically viable. Our proposal for regenerative livestock farming (Blumetto et al, 2024), was applied in a pilot project with 15 farms and is being applied in a scaling project. This new collaborative project between INIA and the wool-textile industry seeks to incorporate 110 farmers into this productive scheme through a co-innovation initiative that implies a productive and environmental diagnosis of the farms, expanding the influence of this management to 200.000. The conceptual basis and the environmental baseline of the pilot project with commercial stakeholders is described here.

Methods

Conceptual proposal



INIA's proposal, framed in research projects with a co-innovation approach, accompanies the transition towards regenerative livestock farming based on its environmental diagnosis of the farming systems and in agreement with farmers for the productive redesign of the systems. The main objective of the first stage is to implement process technologies and strategic use of inputs, with an adequate native grasslands management (Jaurena et al., 2021), adapting the recommendations for each case and measuring its response in productive and environmental terms. The proposal includes aspects related to soil care and restoration, the care and re-introduction of native tree species, the strategic use of sown pastures and off-farm inputs, and the adaptation of a technological package for animal production. Additionally, INIA carries out the genetic evaluations of sheep and beef, which allows, by using genomics, the identification of animals that are more efficient in feed conversion and with lower methane emissions.

Environmental indicators

A) Life Cycle Analysis (LCA) for greenhouse gases (GHG) emissions

A LCA is carried out to estimate the carbon footprint of the farm system and its supply chain using the methodology proposed by FAO (2017) and the software OpenLCA. In our case, the analysis is carried out from the "cradle" (origin of all inputs) to the gate of the farm (sale of animals or wool). As a result, we obtain emissions of GHG expressed as kg of CO_2 equivalent per kg of co-products and for hectare of production system. The period evaluated is a productive exercise (July 2022-june 2023).

B) Ecosystem Integrity Index (EII)

The index of ecosystem integrity (EII) was applied for each field within the farms (Blumetto et al.,2019). It combines different ecosystem traits assessed by trained operators. Its application involves an assessment of four components: vegetation structure, plant species, soil and watercourses (streams or rivers), obtaining after calculations a value in a scale from 0 to 5, where five is the best possible state (fig 1).

$$IEI = \sum_{n=1}^{n} \frac{(VE_i + SPp_i + S_i + RZ_i)APi}{4RA}$$

Fig 1. Where, VEi = vegetation structure score for paddock i, SPpi = species presence score for paddock i, Si = soil score for paddock i, RZi = riparian zone score for paddock i, APi = area of paddock, and RA = total ranch area, adapted from (Blumetto et al, 2019).

The EII reflects the distance of the current state of the agroecosystem in relation to the best potential state of the ecosystem in that ecoregion (level 5 of the qualification). The results are calculated globally (the whole farm) but also by paddock or any spatial management unit.

C) Soil carbon stocks

Soil categorization and calculation of organic carbon stock is carried out throw a four steps methodology classification of soils using satellite image classification, field sampling in 30 sites determining bulk density and sending to laboratory for soil organic carbon (SOC) assessment up to a maximum depth of 30 cm, and finally the calculation of the total carbon stock.

D) Associated wild biodiversity

An evaluation of avian assemblage (Gibbons and Gregory, 2006) is carried out, estimating species richness, diversity and priority species for conservation (Soutullo et al., 2013). The study involves bird specialists using the MacKinnon lists methodology (MacKinnon and Phillips, 1993). Although there are numerous groups of wild organisms affected by productive activity, the flora is included within the EII and therefore a fauna indicator is added. The birds were selected for a series of practical advantages: they use all the ecosystems present in the country, they are mainly diurnal and it is possible to identify vocalizations, there are enough specialists to be able to scale the use of the indicator and there is more information available to interpret the results.

E) Productive and environmental genetic level of cattle and sheep

The most relevant rams from each flock (n=10-20) are genotyped, and their genetic value for relevant traits (feed efficiency, wool production, methane emissions, resistance again parasites) is estimated based on predictive genomics. This approach informs farmers about their flock's genetic level and the best options (evaluated rams) to achieve their productive and environmental goals (Vera et al, 2022). To calculate the potential for genetic improvement, a theoretical scenario was proposed where the entire flock of each farmer is replaced by the top 25% of the genetic evaluation. For this, variables that affect emissions were used separately: dry matter intake, metabolizable energy intake and daily methane emission.

Results

Results present the base line including the five indicators for the 15 farms involved in the pilot project.

Greenhouse gases emissions were estimated for a period of one year-round resulting in an average of 2192 ± 351 kg CO_2 eq /ha and the emission intensity for the co-products was 19 ± 6, 13 ± 3 and 60 ± 13 kg CO2 eq /kg of product for bovine meat, ovine meat and greasy wool respectively.

For sheeps, a simulated scenario were the whole flock of every farmer was substituted by the fenotipically top 25% of animals of the genetic evaluation, produced a reduction of CO_2 eq. emission of 12,8, 17,9 and 13,9 %

considering as the evaluated trait dry matter intake, metabolizable energy intake and daily methane emission, respectively.

The average of global EII for all farms was 3,5 ± 0,2. However, analyzing the variability of the values by single paddocks, it increased the SD to 0,6 which implies that exists an heterogenity in the results considering individual paddocks at each farm. An example for a single farm of geografic representation of IIE and the breakdown of the values obtained for each individual paddock and its components is presented in the fig 2.

Figure 2 – Example for a farm of spatial representation of EII and the breakdown of the values obtained for each individual paddock and its components (left) and soil categories and soil sampling points (right).

Average soil carbon stock for the involved farms was 83,7 ± 10,6 Mg per hectare, ranging between 67 and 94 Mg/ha. The variability is mainly explained by type and depths of soil, mainly in those farms located on the basaltic slope region, which have a high proportion of soils that do not reach 30 cm deep.

In terms of associated wild biodiversity, birds assemblages records results in an average richness of 111 ± 25 and the average Shannon Index was 4.2 ± 0.3. Aditionally 30 species are considered conservation priority for the Uruguayan Environmental Ministry (Soutullo et al., 2014).

Discussion

The environmental results obtained when quantifying the environmental baseline were considered good considering the published references for EII and birds' diversity (De Santiago *et al*, 2022; Aldabe *et al*,2023) and recently evaluations of 110 CREA federation farmers a of multiple production systems distributed throughout the country (2024, unpublished data). Therefore, it is challenging to propose improvements in these systems. However, there are opportunities for improvement in some aspects. This is only possible with an exhaustive planning such as the one proposed by co-innovation processes. In terms of reducing methane emission intensity, the main strategy is using genetic improvement. Nevertheless, there are improvement opportunities, in some cases, by improving pasture utilization and management, based on increasing forage allowance, allowing food selectivity and therefore improving nutrients acquisition by animals. Carbon stocks are high, near the reported stocking potential (Dondini et al, 2023). For this reason, the main objective is to maintain this status, although Piñeiro et al. (2024) reported a potential of sequestration of 187 kg of C/year by increasing the net primary production.

EEI presented good values in average (de Santiago et al, 2022; CREA 2024, unpublished data), but the variability obtained for the different paddocks inside each farm show opportunities of improving through management strategies, specially by improving vegetation structure, reducing erosion predisposing factors and by the protection of riparian zones. This last objective has specific actions through special temporary exclusion of grazing in some streams and riparian zones. The high richness and diversity of bird species make the main objective the preservation of this diversity. Parallelly, special management (e.g. pasture mass, conservation of native trees, streams, rivers and wetlands) will be performed in some areas for improving the habitat for priority conservation species.

The co-innovation process will assure the applicability of environmental measures without compromising the productive results or improving productive and economic outcome. This strategy, based on robust indicators and a medium-term action plan, will allow farmers and industrial processors to access high-value markets for superfine wool.

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Quantifying multiple ecosystem service responses to adaptive multi-paddock grazing management in a north American semi-arid sagebrush steppe ranch experiment

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Key words: carbon; cattle; soils; water; wildlife;

Abstract

The provisioning of ecosystem services (Food & Fiber, Water, Carbon, Biodiversity, Wildlife) by rangelands used for livestock production is critical for social and ecological sustainability globally. Adaptive management through adjustments to grazing intensity, timing, and duration are of increasing interest to optimize multiple ecosystem services with increasing pressures from climate change and other environmental stressors. Yet, there is a need for more empirical grazing research at ranch-scales that quantifies management impacts on the suite of ecosystem services. In 2023, we established a ranch-scale experiment (943 ha) in a semi-arid sagebrush steppe rangeland in Wyoming, USA with grazing treatments stratified by ecological sites. Specifically, we established pairs of pastures (ranging in size from 39 to 149 ha) on five soil types: Saline Loamy, Clayey, Loamy, Sandy, and Shallow Loamy soils. Grazing was in the summer. Treatments included 5 Prescriptive (PR) herds grazed continuously for 11 weeks (ranging in size from 10 to 31 cow-calf pairs depending on pasture size; 100 cow-calf pairs total) and 1 Adaptive (AD) herd (100 cow-calf pairs) rotating through 5 pastures every 0.5 to 3 weeks based on adaptive decision making relative to animal behaviour, forage utilization, and weather. Grazing treatments had the same planned system-level stocking rate (meaning a similar number of cow-calf pairs for similar total treatment areas) but were managed with a different stock density -- with the higher density in the AD treatment with potentially different duration. We concurrently sampled multiple ecosystem services at the pasture scale including soil moisture and carbon, forage biomass and quality, wildlife habitat and populations (native rodents, predators, ungulates, and birds), cattle (movement and productivity), and CO_2 fluxes. We present data from the 2023 and 2024 seasons for the suite of ecosystem services with implications for the refinement of adaptive grazing management and intensification in semi-arid sagebrush steppe.

Introduction

Rangelands have the ability to provision a suite of ecosystem services simultaneously, broadly including food & fiber, water, carbon, biodiversity, and wildlife (Goodwin and Porensky 2023). From a multifunctional landscape perspective, rangelands sustainably managed may accomplish this provisioning of multiple ecosystem services through supporting livestock production which is critical for social and ecological sustainability globally (Godde et al. 2020; Monlezun et al. 2024). Yet, quantifying the full suite of ecosystem services presents a challenge in terms of sampling, instrumentation, cost, and infrastructure. Moreover, empirical approaches to understanding how manager decision making influences multiple ecosystem services simultaneously, and relevant tradeoffs, returns on investment (ROI), and temporal trajectories for improvement, remain limited. Given the threats of climate change, urbanization, desertification, and other threats to the people, flora, and fauna on rangelands, enhanced sampling is a critical and emerging need. Concurrent with the need to enhance broad sampling of rangeland ecosystem services has been the emergence in the interest about adaptive grazing management. Adaptive management through adjustments to grazing intensity, timing, and duration are of increasing interest to optimize multiple ecosystem services with increasing pressures from climate change and other environmental stressors. There have been variable claims about the singular benefits of such adaptive grazing management (Briske et al. 2008; Mosier et al. 2021; Jorns et al. 2024); therefore there is a need for more empirical grazing research at ranch-scales that quantifies impacts of adaptive management on multiple ecosystem services. Here we describe a new experiment quantifying multiple ecosystem service responses to adaptive multi-paddock grazing management in a North American semi-arid sagebrush steppe ranch experiment which will have implications for western North America but also arid and semi-arid rangelands globally.

Methods

The study site is managed by the University of Wyoming's (UW) Agricultural Experiment Station (AES) – Laramie Research and Extension Center (LREC) and is known as the McGuire Ranch (latitude 41° 41' 11.54" N, longitude 105° 33' 24.09" W). The ranch is located in Albany County, Wyoming, USA on the west side of the Laramie mountain range and on the east side of the Snowy Mountain Range and is in the Deserts and Xeric Shrublands Ecoregion according to the The Nature Conservancy classification and more specifically, is in the Wyoming Basin (18) Level III Environmental Protection Agency (EPA) Ecoregion which is a broad arid intermontane basin characterized by grasslands and shrublands. The climate is an arid cold steppe (BSk according to the Köppen classification) due to it being temperate, continental, with winter snow, and having a broad thermal gradient. The cold climate is, in part, associated with the high altitudinal position which is 2,190 m above sea level. Annual rainfall averages from 230 to 467 mm yr^{-1} with an average of 353 ± 14 (SE) mm yr^{-1} since 2000. Average annual air temperature since 2000 was 5.4 °C. Average air temperature ranges from -5.5 °C (winter) to 17.2 °C (summer), with mean minimum and maximum temperature of -1.3 °C and 12.2 °C, respectively. The McGuire Ranch is an area of 2,246 ha that is dominated by cool-season perennial grasses and sagebrush (*Artemisia* species) shrubs. The ranch was acquired by UW in 1992 and has been managed in a 3 or 4 pasture system since then for summer seasonal grazing (June through October) of cow-calf pairs. In 2022, 19 km of new internal fence [4-strand wildlife friendly for pronghorn (*Antilocapra americana*) and mule deer (*Odocoileus hemionus*)] and 3 new water tanks (1 – 9 m diameter tank providing water to 4 pastures and 2 – 15' diameter tanks providing water to 2 pastures each) taking the ranch to 14 pastures. This ranch is considered a semi-arid sagebrush steppe ecosystem and is a predominantly native rangeland co-dominated by grasses and shrubs with no trees. The dominant native cool-season grass species include muttongrass (*Poa fendleriana* (Steud.) Vasey), prairie Junegrass (*Koeleria macrantha* (Ledeb.) Schult.), and western wheatgrass (*Pascopyrum smithii* (Rydb.) Á. Löve). In a few study pastures (n = 4) with a history of tillage there are a few non-native cool-season grass species including crested wheatgrass (*Agropyron cristatum* (L.) Gaertn.), meadow brome (*Bromus biebersteinii* Roem. & Schult.), and Russian wildrye (*Psathyrostachys juncea* (Fisch.) Nevski). The dominant shrub species include Wyoming big sagebrush (*Artemisia tridentata* Nutt. ssp. wyomingensis Beetle & Young) and yellow rabbitbrush (*Chrysothamnus viscidiflorus* (Hook.) Nutt.). We established a ranch-scale experiment using approximately 42% of the ranch (943 ha) with grazing treatments stratified by ecological sites in 2023. In order to understand the role of soil texture and ecological site responses to management, we established pairs of pastures (ranging in size from 39 to 149 ha) on five ecological sites with variable soils including saline loamy, clayey, loamy, sandy, and shallow loamy soils. We applied grazing in the growing season due to the severe winters in this area which renders winter grazing practically impossible.

Grazing treatments included 5 Prescriptive (PR) herds grazed continuously for 11 weeks (ranging in size from 10 to 31 cow-calf pairs depending on pasture size; 100 cow-calf pairs total) and 1 Adaptive (AD) herd (100 cow-calf pairs) rotating through 5 pastures every 0.5 to 3 weeks based on adaptive decision making relative to animal behaviour, forage utilization (50% target based on Wyoming Rangeland Monitoring Guide using the Landscape Appearance method) , and weather (Figure 1). Grazing treatments had the same planned system-level stocking rate (meaning a similar number of cow-calf pairs for similar total treatment areas) but were managed with a different stock density -- with the higher density in the AD treatment with potentially different duration.

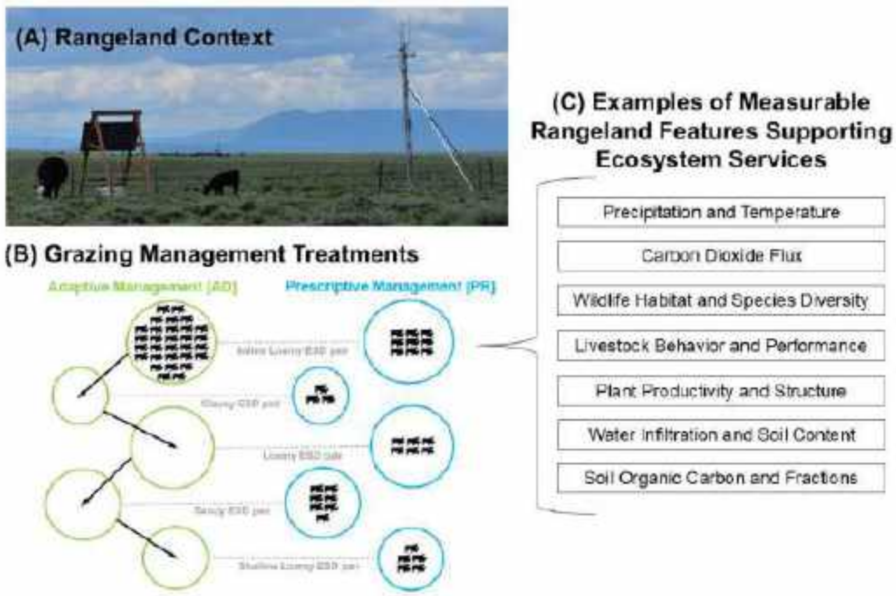

Figure 1. (A) Rangeland context, (B) Grazing management treatments with pastures represented by circles and treatments stratified by soils and ecological site descriptions (ESDs), and (C) measured rangeland features supporting a suite of ecosystem services on the McGuire Ranch in southeastern Wyoming, USA.

We implemented a suite of sampling at the pasture scale. Soils are sampled in each pasture using 12 triangles using a truck-mounted Giddings probe down to 1 m (if possible) with cores cut and sub-sampled at 4 depths: 0-15 cm, 15-30 cm, 30-50 cm, and 50-100 cm. Soil samples were cooled and sent to the laboratory for measurement of SOC/N, isotopes, SOC fractions (chAOM, lPOM, MAOM), BD, pH, texture, IC, and WSA. Soil moisture is being measured using SATURO infiltrometers with three samples per pasture with 10 cm rings to 10 cm depth to assess saturated hydraulic conductivity. In addition, in each pasture volumetric soil water content is being measured at three locations at 10 cm, 20 cm, and 30 cm depths using TEROS 10 (METER Group) capacitance sensor. Weather and greenhouse gas flux, specifically CO_2, is measured with solar powered flux towers that include a 3D sonic anemometer, a four component net radiometer, an ambient air temperature/humidity/pressure and rain sensor and an enclosure for trace gas measurements, soil heat flux plate, and soil temperature/moisture sensor (at 10 to 15 cm depth) provided by Quanterra Systems. Importantly, flux towers enable calculation of Fc, LE, H, based on EC technique. Forage biomass is sampled every 28 days during the growing season months of May, June, July, and August using 3 – 100 m transects with 2 – 0.5 m^2 quadrats clipped to ground level per transect. In addition, standing biomass is also measured every 10 m on the same transects using the non-destructive visual obstruction reading (VOR) technique modified but generally following Robel et al. (1970) where an observer observes a pole with 1 cm increment markings from a height of 1m and a distance of 4 m and records the plant species obstructing the lowest interval on the pole not completely obstructed as well as the highest interval where there was any obstruction. Forage samples will be assessed for forage quality metrics such as crude protein, energy, and digestibility. We are also using Ecological Outcome Verification (EOV) methods to assess water cycling, mineral cycling, energy flow, and community dynamics (Savory Institute 2024). Livestock variables measured included foraging behaviour using standardized observation techniques, animal movement using GPS-ear tags, and performance using calf weaning weights (to be initiated in 2025). In addition, grazing management data such as animal days per acre are also calculated. Wildlife are being measured using a network of infrared game cameras with a particular interest for large ungulates and carnivores. Bird communities are being measured using point count methods and in 2024 nest survival was being measured with nest searching techniques – and both techniques included additional habitat metrics being measured.

Results

Grazing treatments have been applied in 2023 and 2024 which were very different in terms of weather with 2023 being wetter through the growing season and 2024 drier early with late summer rains. The implementation of such a sampling system has been challenging the least. Cow days per acre have been higher in the AD treatment than the PR treatment both years (17% and 27% respectively) suggesting the realization of grazing management treatment different. We are in the process of integrating and summarizing our ecosystem service related data. Additional results at this point include lessons learned for establishing such networks in working rangeland landscapes. First, a diverse team of experts is required, and in our case, includes more than 40 individuals. Second, installation of such instrumentation takes time and financial resources that has to include trouble shooting and repair. Third, the streams of data will require dedicated personnel to build platforms that integrate and scaffold data into a useable interface. Fourth, measuring the response of the suite of ecosystem service responses will take time and likely 3 to 5 years.

Discussion

We are concurrently sampling multiple ecosystem services at the pasture scale including soil moisture and carbon, forage biomass and quality, wildlife habitat and populations (native rodents, predators, ungulates, and birds), cattle (movement and productivity), and CO_2 fluxes in a project that is the first of its kind in terms of scope. This adaptive multi-paddock grazing management in a North American semi-arid sagebrush steppe ranch experiment will have implications for western North America but also arid and semi-arid rangelands globally.

Acknowledgements

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Restoring biodiversity in a multi-use rangeland: mining, pastoral and Indigenous land users come together at Arid Recovery, South Australia

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Key words: arid ecosystems, extinction, conservation, invasive species, grazing, predation

Abstract

Australia's arid rangelands have suffered record losses in biodiversity since European colonisation, especially for mammalian fauna, principally driven by invasive species. The scale of the challenge to restore biodiversity requires long-term multi-stakeholder partnerships. Arid Recovery is an independent NGO in the dry rangelands of South Australia, and a unique partnership between the mining industry, government, Indigenous groups, rangeland communities and pastoralists. Work centres around a large predator-proof fenced reserve (12,300 ha) where rabbits, cats and foxes have been removed and six threatened native species have been reintroduced. The reserve supports a robust conservation science program that includes developing tools for management of introduced species, reintroduction of threatened species, and approaches to restore biodiversity at scale. We share lessons from 28 years of rangeland ecosystem restoration and research.

Introduction

While arid and semi-arid ecosystems have had less vegetation clearance than other habitats in Australia since European colonisation, the arid and semi-arid rangelands have suffered record losses in biodiversity due largely to invasive species (Dickman and Pavey 2023). The introduction of rabbits (Oryctolagus cuniculus), cats (Felis catus) and foxes (Vulpes vulpes) has transformed rangeland ecosystems. The spread of rabbits has caused long-term damage to rangeland vegetation (Finlayson et al. 2022), exacerbated by livestock grazing and feral herbivores (Silcock and Fensham 2013). Rabbit populations support the persistence of invasive predators (Read and Bowen 2001), which in turn are the primary cause of the loss of two thirds of the mammal fauna in the rangelands (Woinarski et al. 2019). Of these losses, around half the affected mammal species are now extinct, while another half suffered dramatic range contractions, many of them only surviving on islands free of cats and foxes (Legge et al. 2018). There have also been impacts to other fauna and flora, with some bird and reptile species made locally extinct or rare and vegetation communities altered by grazing (McLellan and Watson 2022; Read and Cunningham 2010). Here we report on a long-term collaboration by diverse land users, institutions and communities to restore biodiversity in Australia's arid rangelands. We highlight some of the challenges faced and knowledge generated over 28 years of applied research.

Methods

Arid Recovery is an independent partnership between the mining industry, government, academia and the conservation sector, in collaboration with Indigenous groups, pastoralists and rangeland communities. The initiative started in 1997 when co-founders sought to take advantage of the transformational reduction in rabbits, cats and foxes numbers caused by rabbit haemorrhagic disease (Pedler et al. 2016) to permanently exclude rabbits from an area of outback South Australia to allow native vegetation to recover, while also excluding cats and foxes to enable the return of vulnerable native animals (Moseby et al. 2018). A cost-effective exclusion fence was designed and tested (Moseby and Read 2006). The reserve grew to six paddocks over 12,300 hectares. Foxes are excluded from all, rabbits have been removed from four paddocks (6,000 ha) and cats have been removed from five (8,600 ha) but allowed to remain in the sixth for experimental purposes. Five locally extinct threatened native species have been successfully reintroduced: burrowing bettongs *Bettongia lesueur*, greater bilbies *Macrotis lagotis*, Shark Bay bandicoots *Perameles bougainville*, western quolls *Dasyurus geoffroii* and kowaris *Dasyuroides byrnei*. A further three threatened species reintroductions were trialled but one failed (greater stick-nest rat *Leporillus conditor*) and two did not progress to full translocations due to predation by native predators (numbat *Myrmecobius fasciatus* and woma python *Aspidites ramsayi*). Two locally rare threatened species colonised the reserve and have sustained populations since: plains mice *Pseudomys australis* and thick-billed grasswrens *Amytornis modestus*. The reserve layout provides experimental power with different experimental treatments across paddocks. A rigorous science program is supported by an advisory panel and collaborations with over 80 different institutions.

Results and discussion

Total grazing pressure must be managed

Arid Recovery's original focus of ecosystem recovery through removing introduced herbivores (rabbits and livestock) was challenged when a reintroduced native herbivore became overabundant. Burrowing bettongs are generalist herbivores that, from a founding population of 29 animals in 1999, increased to an estimated population of 8,000 by 2016. This resulted in reduced cover of more palatable plants and damage to sensitive perennial vegetation (Linley et al. 2017; Moseby et al. 2018). Competition with bettongs for food contributed to the local extinction of stick-nest rats, combined with increased predation pressure by goannas and reintroduced western quolls and an extended drought and record breaking hot summer (Moseby et al. 2024). Management of an overabundant threatened species within the reserve presented challenges. Unlike livestock, there was no market to sell animals and nor could they be translocated in sufficient numbers due to the very limited locations where they could be safe from predation (Radford et al. 2018). Lethal control was contemplated, but made difficult by the status of the species affording it legal protection and risks to the organisation of overstepping social licence. Contraceptive measures were trialled but were not feasible at the scale required. Some animals were allowed to self-disperse through one-way gates out of the reserve into the surrounding area where predators were controlled but not excluded (Butler et al. 2019). These animals had poor survival and persistence due to insufficient control of cats and foxes outside (Moyses et al. 2020). Ultimately, a severe drought in 2018-19 caused the collapse of the bettong population as food resources dwindled (Moseby et al. 2024). Arid Recovery now works to thresholds (50-100 bettong tracks per km) to trigger management actions such as translocation or control based on total grazing pressure measures from vegetation condition measures and interventions described in an adaptive management framework.

Ecosystems need predators

The lack of sufficient predation pressure was the main driver for overpopulation of native herbivores so western quolls were reintroduced in 2018. Quolls are marsupial predators that once occurred across 70% of mainland Australia. In the first reintroduction to an arid ecosystem, 12 adults were released in 2018 following a successful trial. One of the reserve's six paddocks was designated as a control area from which quolls were to be excluded to i) maintain insurance populations of threatened prey species, ii) measure the impact of quolls on the ecosystem, and iii) maintain prey populations naïve to mammalian predators for research (Moseby et al. 2023). Maintaining the control paddock presented a challenge, with at least one quoll incurring into the control paddock each year. Small quolls could gain access by squeezing through the 50mm aperture netting or exploit weak points at corners. However, with regular monitoring and response, quoll have consistently been removed and the control area's integrity maintained. Six years since the release of quolls, there is clear evidence of suppression of prey species and early evidence of trophic cascades (Stepkovitch et al. 2023). Bettong populations in quoll-occupied areas have been maintained below the acceptable thresholds, while bettongs in the quoll-free control paddock exceeded threshold in 2024, triggering translocation of animals out of the paddock. On a smaller scale, our experience reflects the major issue of overabundant kangaroos in the southern Australian rangelands, largely due to the absence of a predator, the dingo (Dawson et al. 2023).

Unique rangeland biodiversity must be preserved
Species restricted to arid ecosystems are dependent upon conservative rangeland management. An Australian example is the kowari, a small marsupial predator that occurs primarily on pastoral lease estate and exclusively so in South Australia. The species has a 20% risk of extinction within 20 years and was recently upgraded to the category of Endangered (Greenville et al. 2018). In 2022, 12 adult kowaris and their small dependent pouch young were translocated to Arid Recovery to establish an insurance population safe from predation by cats and foxes. The population has established and is being compared with remaining wild populations to understand causes for the kowari's decline and what management could be implemented on pastoral stations to improve its prospects. As climate change increases the frequency and intensity of droughts and heatwaves, arid species are in great need of large, interconnected protected areas under conservation management to buffer them against stochastic shocks.

Ecosystems operate across tenure
While using fencing to exclude threats is effective (Moseby et al. 2011), it is not a feasible tool for broadscale, sustained biodiversity recovery. This requires collaboration with diverse rangelands users because species and threats operate across property boundaries and tenures. The Arid Recovery Reserve presents an opportunity to seed the wider landscape with otherwise locally extinct species that have some tolerance to predation by introduced predators or may develop improved anti-predator traits through accelerated evolution (Ross et al. 2019). Effective control of cats and foxes will be necessary to elicit recovery beyond fences, especially as such reserves can attract predators like cats (McGregor et al. 2020). Another key challenge in recovering biodiversity in open landscapes is control of introduced predators in rangeland ecosystems where rabbits are present. We are pursuing the goal of leveraging the predator-free reserve to recover biodiversity in the wider Arid Recovery region in collaboration with Aboriginal communities, pastoral and mining partners. Feral predator control and monitoring of threatened species such as quolls has been coordinated with the Kokatha Aboriginal Corporation that manage three large pastoral leases around the reserve. Predator-proof safe havens like Arid Recovery are an essential bastion against extinction, but risk becoming a long-term holding pattern if efforts to recover biodiversity at scale in open landscapes are not pursued simultaneously (Read et al. 2023).

Conclusions
No rangeland system is immune to the risk of overgrazing. Earlier management of overpopulation could have prevented impacts to the Arid Recovery ecosystem from overpopulated bettongs. Native herbivores in reserves must be managed much as stocking rates for livestock during periods of scarcity in the rangelands. The return of the quoll is showing early signs of being an effective natural solution. Collaboration by different land users is essential to maintain and recover biodiversity in the rangelands as threats operate across tenures and protection of refugial areas for threatened species becomes more important under climate change. The broadscale coordinated control of feral predators required will only be possible through collaboration with a network of land managers over large areas. Equipping and energising rangeland communities for this work is essential, as is investing in research for 'beyond the fence' solutions and suitable policy for retaining the unique biodiversity of the Australian rangelands.

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Creating new foodscapes to enhance the sustainability of rangelands in the Western U.S.

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Key words: Biodiversity; Environmental impact, Plant secondary compounds, Grazing; Legumes

Abstract

Approximately eight million beef calves are produced annually in the western U.S., and ranchers must maintain profitable operations while addressing the growing number of consumers seeking environmentally, economically, and socially sustainable food. In response to such challenges, a diversity of deep-rooted perennial legumes and non-legume forbs high in nutrients and functional phytochemicals, are being grown and stockpiled in resource patches or “islands” across a “sea” of grass-dominated rangelands. These islands of multifunctional diversity are being tested across monotonous landscapes to be used as a low-cost and sustainable supplementation strategy for beef cattle with the aims of increasing biodiversity, animal productivity and health, while reducing environmental impacts. We are screening native and introduced plant species for their establishment and persistence in replicated studies at different ecosites in northern, central and southern Utah. Continuous culture fermenters are being used to evaluate how these forages and their combinations alter rumen fermentation, microbial growth, methane production, and nutrient digestibility. These forages are being strategically deployed in islands across the landscape aiming at higher probabilities for seedling success. This research is being integrated at the regional and local level through grazing schools, demonstration sites, and assessments of potential for adoption through online surveys and subsequent semi-structured in-depth interviews. This transdisciplinary project is progressing to create more sustainable beef production systems while engaging and educating a wide range of stakeholders including current and future land stewards, outreach personnel, and consumers.

Introduction

Approximately eight million beef calves are produced annually in the western U.S. alone (NASS 2024), and beef producers must maintain profitable operations while addressing growing consumer demands for environmentally, economically, and socially sustainable food (Villalba et al. 2019). Under this context, we are developing a transformative paradigm for western U.S. beef production systems through landscape interventions -smart foodscapes (SFS)- in order to increase American agricultural production with a reduction in environmental footprint. Our reasoning for this project stems from the idea that cattle evolved in the Mediterranean region grazing a diverse palette of broadleaf and grass species (Grove and Rackham 2001), but cowherds grazing U.S. rangelands today consume a diet dominated by a monotony of grasses like intermediate, tall and crested wheatgrass (Robins et al. 2020). The feeding value of these grasses plummets in mid-summer, disrupting nutrient cycles and necessitating costly supplementation (Putnam and DelCurto 2020). In turn, declines in the nutritional quality of grasses cause significant increments in the production of the greenhouse gas (GHG) methane by livestock (Lee et al. 2017). Legumes and some forbs are of greater nutritional value than grasses (Phelan et al. 2015), and, unlike grasses, many of these species also contain functional biochemicals or plant secondary compounds (PSC) (e.g., phenolics, terpenoids) that enhance cow-herd health and decrease nitrogen and GHG emissions to the atmosphere (Min et al. 2020). In addition, islands of diversity have the potential to increase landscape connectivity and structural complexity in rangelands, enhancing ecosystem biodiversity and resilience (Leroy et al. 2020). We are creating multifunctional alternative foodscapes using strategically selected legume and non-legume forb species (Objective 1), that synergize nutritionally (Objective 2), and are spatially distributed as resource patches or islands of diversity across the landscape (Objective 3), solving these key challenges to current and future food and agricultural production systems. This research is being integrated at the regional and local level through producer engagement and assessments of adoption (Objective 4).

Methods

Objective 1. The establishment and persistence of two dozen plant species with the potential to provide late-season supplemental protein when seeded as "resource islands" was assessed in strategic locations across semi-arid rangeland. The species include crested wheatgrass and native and introduced legumes and non-legume forbs, with excellent forage value, that are commonly included in rangeland grazing or restoration seed mixtures. Replicated monoculture plots were drilled at four rangeland locations from 1370-2000 m a.s.l. in northern, central and southern Utah in 2022. In July 2023, establishment was assessed as plants m^{-2}, although monoculture plots ranged from 11 to 74 m^2 depending on location. Average annual precipitation, primarily as snowfall, ranges between 247 and 457 mm $year^{-1}$.

Objective 2. Our objective was to evaluate the effect of potential forage candidates for the "islands" on rumen fermentation. The study was conducted as a 5 × 5 Latin square design using continuous-culture fermenters. All treatments contained 75% of crested wheatgrass plus (1) 25% alfalfa, (2) 25% sainfoin, (3) 25% small burnet, (4) 12.5% sainfoin + 12.5% small burnet, and (5) 8.3% sainfoin + 8.3% small burnet + 8.3% birdsfoot trefoil. The diets (60 g DM/day) were fed twice daily. The periods were 10 d long with 6 d of adaptation and 4 d of sampling. Data were analyzed using a mixed model including the fixed effect of treatment and the random effects of period and fermenter.

Objective 3. Nine 30x40 m (0.12 ha) islands were established in a 22-ha grass-dominated pasture (Meadow brome; *Bromus inermis*), with locations selected for higher probabilities of seedling success and a spatial arrangement that optimizes livestock distribution. The limiting resource for plant establishment in semi-arid regions is water availability (Zhang et al. 2020). Thus, areas within the pasture with a higher density of vegetation represented locales where moisture was greater. To identify these locations, temporal sequence of satellite imagery was analyzed utilizing the European Space Agency's Sentinel-2 platform to generate yearly maps of vegetation density via the normalized difference vegetation index (NDVI). Cloud-free Sentinel-2 images spanning the current and preceding 5 years for July and August were identified and NDVI values extracted for each pixel. Median July-August NDVI for each year was calculated for each pixel in the pasture and all pixels were reduced to the mean and standard deviation. These metrics were used to locate pixels within a pasture whose greenness consistently deviated in a positive direction (higher than average greenness) from average pasture greenness. Spatial groupings of these consistently greener pixels served as candidate locations for island establishment, with potential better access to water and nutrients. After spatial selection, islands were seeded with strips (8x30 m each) of: 1-Alfalfa (*Medicago sativa*, containing saponins), 2-Birdsfoot trefoil (*Lotus corniculatus*, containing condensed tannins-CT), 3-Sainfoin (*Onobrychis viciifolia*, containing a different array of CT, 4-Small burnet (*Sanguisorba minor*, containing hydrolizable tannins), and 5-Forage kochia (*Bassia prostrata*, containing phenolic compounds). The percentage establishment of the five-forage species was monitored using the frequency grid method (Vogel and Masters 2001).

Extension personnel is working with a group of livestock producers across the state of Utah to establish a series of demonstration plots using the same approach described above. Locations that represented some of the varied range types throughout the state were selected, as well as those sites with the greatest potential benefit from the intervention proposed, such as those dominated by crested wheatgrass. The team is taking measurements using the frequency grid method (Vogel and Masters 2001) to determine how sites establish and persist under the typical grazing regime of the different operations and speak with producers to understand what they perceive as the primary costs and benefits of the proposed landscape interventions.

Objective 4. During the first year of the project, we sought input from Utah ranchers who are currently grazing livestock by distributing a short online video about the project through team networks, relevant listservs, and social media groups, and to a sample purchased from a private vendor and subsequently asked the ranchers to fill out a brief online survey. Utilizing insights from the survey, we then conducted structured in-depth interviews with 14 Utah ranchers in 2023.

Results

Objective 1. The introduced species sainfoin, small burnet and alfalfa were able to establish in relatively dense stands at every location, and the native species showy goldeneye, Rocky Mountain penstemon, Utah sweetvetch, and prairie coneflower as well as falcata alfalfa all averaged more than 5 plants m^{-1} at some locations. Of the species that performed well at multiple locations, sainfoin accumulates condensed tannins (CT) while small burnet and Utah sweetvetch accumulate both CT and hydrolizable tannins (HT) and are of particular interest because of the synergies between the two types of tannins in improving ruminant health and reducing environmental impacts.

Table 1. Plant species ranked by number of locations with at least 1 plant m^2, and within location, by plant count. Values are final 2023 plant counts.

Genus species	Common name	#Locations	Plants m^{-2}
Onobrychis viciifolia Scop.	Sainfoin	4	36
Medicago sativa L.	Alfalfa, 'Ladak'	4	12
Sanguisorba minor Scop.	Small burnet	4	12
Lotus corniculatus L.	Birdsfoot trefoil	4	3
Heliomeris multiflora Nutt.	Showy goldeneye	3	11
Medicago sativa L. ssp. falcata (L.) Arcang.	Alfalfa, falcata	3	7
Penstemon strictus Benth.	Rocky Mtn. penstemon	2	13
Hedysarum boreale Nutt.	Utah sweetvetch	2	9
Astragalus cicer L.	Cicer milkvetch	2	4
Agropyron cristatum L. Gaertn.	Crested wheatgrass	2	4
Helianthus maximiliani Schrad.	Maximillian sunflower	2	3
Penstemon palmeri A. Gray	Palmer's penstemon	2	2
Ratibida columnifera (Nutt.) Wooton & Standl	Prairie coneflower	1	8
Securigera varia L. Lassen	Crownvetch	1	4
Dalea purpurea Vent.	Purple prairie clover	1	2
Linum lewisii Pursh	Lewis flax	1	1
Balsamorhiza sagittata (Pursh) Nutt.	Arrowleaf balsamroot	1	1

Objective 2. Fiber digestibility was affected by the treatments ($P < 0.01$). The NDF digestibility of Treatment 1 (75% crested wheatgrass and 25% alfalfa) was the highest followed by Treatment 2 (75% crested wheatgrass and 25% sainfoin) and 5 (75% crested wheatgrass, 8.3% sainfoin, 8.3% small burnet, and 8.3% birdsfoot trefoil), while Treatments 3 (75% crested wheatgrass and 25% small burnet) and 4 (75% crested wheatgrass and 12.5 sainfoin, and 12.5% small burnet) had the lowest NDF digestibility values. Among the short-chain fatty acid analyzed, acetate was the only one affected by treatments ($P = 0.04$). The highest acetate concentration was observed for Treatment 1, which was followed by Treatment 2 and 5. Treatments 3and 4had the lowest acetate concentration. The ammonia nitrogen produced from treatment 1 and 2 had greater values, followed by treatment 4 and 5, treatment 3 did not differ compared to treatment 4 and 5, but when compared to treatments 1 and 2, it had the lowest value. No treatment effects were observed for protozoa cell count and pH. Similarly, no treatment effect was observed for microbial growth.

Objective 3.

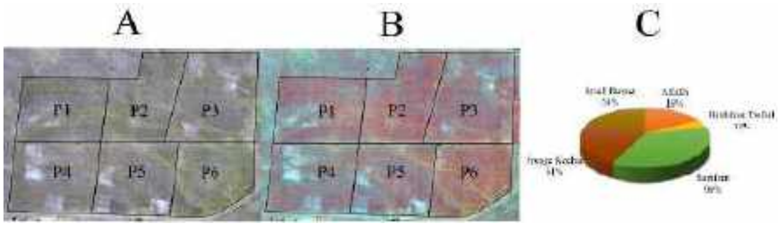

Figure 1. **A.** Natural color orthoimage generated from imagery collected on August 14, 2023, using a DJI Mavic 2 Pro unmanned aerial system (UAS). The 22-ha grass (Meadow brome; *Bromus inermis*)-dominated pasture in northern Utah (111° 48' 6" W, 41° 53' 22" N) shows the nine "islands" of 30x40 m (0.12 ha) each, distributed in three different fenced paddocks (P3, P4 and P5). Islands were seeded with strips (8x30 m each) of alfalfa, birdsfoot trefoil, sainfoin, small burnet, and forage kochia. Differences in color across the pasture represent variations in grass cover and species. **B.** Color infrared orthoimage generated from imagery collected by the same UAS filtered to the near infra-red of the same pasture taken on August 15, 2023. Differences in color across the pasture represent variations in grass cover and species. **C.** Overall percentage of frequency of forages in the islands shown in A and B.

Objective 4. The survey data indicates the participants are excited about the project, for gaining economic benefits, and in hopes of improved land management. Beyond themselves and the rangeland, they are also hopeful the project yields an outcome that will be beneficial and shared with the larger community in Utah such as increased environmental stewardship and enhancing plants and biodiversity. The ranchers who participated in the survey in Utah also stated several perceived potential challenges, largely centred around managing the smart foodscapes (SFS) within their existing ranching system, cost and time involved in comparison with future benefits, and external factors such as drought and weather change. Improved rangeland and optimistic perceptions about SFS are among the motivators for the ranchers for trying SFS in their operation in the future. Participants noted they still needed more information before trying SFS in their operation, particularly about the economics of making such transitions. Five key themes emerged, highlighting concerns about the time and resource intensity of SFS, management within existing operations, resistance to change, the need for more information, and the applicability of SFS to diverse landscapes. Economic considerations, water scarcity, and the reluctance to adopt new practices are key hurdles. These nuanced perspectives contribute valuable depth to the challenges identified in the survey, providing a comprehensive view of the complexities involved in the adoption of SFS in Utah's ranching community.

Discussion [Conclusions/Implications]

This project is filling the gap in knowledge about optimal synergistic/associative benefits for cattle and for the environment when animals graze a diversity of forage species with bioactive compounds. This research is devising diverse rangeland-based grazing systems aimed at optimizing ruminant production and health while reducing environmental impacts and enhancing biodiversity. This effort requires extensive analysis and synthesis of knowledge on the adaptability of plant species in the seeded islands, nutritional interactions among plant species, as well as a clear understanding of barriers to adoption. In turn, this new understanding is being communicated to producers and the public through demonstration plots and grazing schools. In summary, the transdisciplinary team assembled for this project is blending these variables into research, extension, and education programs to solve challenges to the sustainability of western rangelands. This project is improving natural resources quality through functional approaches that enhance livestock production and ecosystem diversity, while reducing the environmental footprint of beef production systems.

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State and transition modelling as a contextual framework for indicators of restoration in the Western Australian Mulga rangelands.

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Key words: ecological condition, grazing, management interventions

Abstract

Opportunities for ecological restoration are rapidly increasing and require consistent tools to assess outcomes. In Australia, state and transition models have been used as a communication tool for land managers, to support ecosystem condition assessment on pastoral leases, and more recently, in the federal Nature Repair Market. A three-day expert elicitation workshop was conducted with government rangelands officers, pastoralists and restoration practitioners to develop a state and transition model for shrub-grass mulga in the WA rangelands. A reference and nine modified states were described, including four regenerating states. Modified states reflect key differences in ecosystem condition along gradients of degradation and regeneration. The key drivers of degradation are overgrazing and associated hydrological dysfunction as grazing impacts worsen, while restoration and regeneration are largely implemented through grazing management and (where soil surface condition has been degraded) hydrological interventions to increase water infiltration. Overall, the state and transition model provides a synthesised, coherent model of WA shrub-grass mulga ecology that is accessible to both experts and non-experts. The model is targeted at supporting the development of rangelands monitoring and condition standards, and the planning and implementation of appropriate management interventions for restoration, enabling land manager access to emerging nature markets.

Introduction

Rangelands represent 81% of the Australian continent (DCCEEW 2005). Their long-term use for livestock production, combined with feral herbivores and introduction of exotic species, have led to widespread decline in ecosystem condition (Landsberg *et al.* 2003). Despite this, the rangelands are often overlooked in ecological restoration initiatives in favour of more intensively used agricultural landscapes (WWF 2021). Opportunities for ecological restoration are rapidly increasing, driven by global and national drivers such as the Nature Positive Initiative, UN Decade on Restoration, Kunming Montreal Agreement, and Australia's Nature Repair Market. These initiatives require consistent tools for ecosystem assessment and projection of outcomes. One approach emerging to facilitate this in Australia is the widespread application of state and transition models (STMs), for example, to underpin the Nature Repair Market, to support ecosystem condition assessment on pastoral leases (Richards *et al.* 2023), and more generally as a communication tool for land managers (Westoby *et al.* 1989).

State and transition models describe the integrity of different states in an ecosystem (including a historic and/or best-available reference state and current modified states) and the drivers of transitions between states (Westoby *et al.* 1989; Bestelmeyer *et al.* 2017; Richards *et al.* 2020). The application of STMs to ecological restoration requires ecosystem specific models that focus on restoration pathways. Although the concept was developed in Australian rangelands, STMs have only been patchily implemented in Australia (Bestelmeyer et al. 2017), and restoration pathways are often weakly developed. In this paper, we used an expert elicitation process to develop a STM for Australia's shrub-grass Mulga woodlands in the extensive production zones of Western Australia (WA), with a special emphasis on restoration pathways.

Methods

The WA mulga shrublands occur across the semi-arid zone of central WA, averaging 250-350 mm rainfall per annum (DCCEEW 2005). Mulga shrublands are areas where mulga (*Acacia aneura* species complex) are dominant in the tree or tall shrub stratum. This study focused on 'shrub-grass mulga' within the Murchison and Gascoyne IBRA regions, and the Hamersley (Pilbara) and Tallering (Yalgoo) IBRA subregions (Figure 1). Shrub-grass mulga include the range of *A. aneura* complexes found across the '*Acacia hardpan*' and '*Wanderrie grass'* pasture types (Waddell *et al.* 2023). Much of the area has been grazed by domestic livestock since the late 19th Century, first predominantly by sheep and more recently by cattle. Livestock numbers peaked in the 1930s before severe drought, while accumulated land degradation has prevented stock numbers from recovering and has a lasting and ongoing impact on ecosystem condition. During this period, total grazing pressure was also affected by feral goats, rabbits and changes in kangaroo numbers, potentially promoted by dingo culling and provision of water (Landsberg *et al.* 2003).

The model-building process took place through a series of meetings and a three-day in-person workshop held in Perth (13-14 August, 2024) with 30 experts in rangelands ecology participating, supported by an extensive literature of peer-reviewed science publications and rangeland management reports (e.g. Waddell *et al.* 2023). Experts included government rangelands officers, ecologists, pastoralists and restoration practitioners. The purpose of the workshop was to develop a STM for shrub-grass mulga (including identifying restoration-specific dynamics and interventions), following the methodology of Richards *et al.* (2023). At the workshop, experts were provided with an overview of the Australian Ecosystem Models Framework (Richards *et al.* 2020), state and transition modelling and key ecological information about shrub-grass mulga, including pasture types and maps. Starting from a preliminary model developed by the core project team, experts were asked to describe the key states for a 'reference' model (highest ecological integrity). This process was then repeated for the modified states. Finally, experts were asked to describe plausible transitions (including drivers, timeframes and conditions for transitions to occur) including both degradation and restoration drivers and to identify potential indicators for monitoring ecological recovery. Following the workshop, the models underwent further development by the authors.

Results

A reference and nine modified states were described for the shrub-grass mulga STM, including four regenerating states (Figure 2).

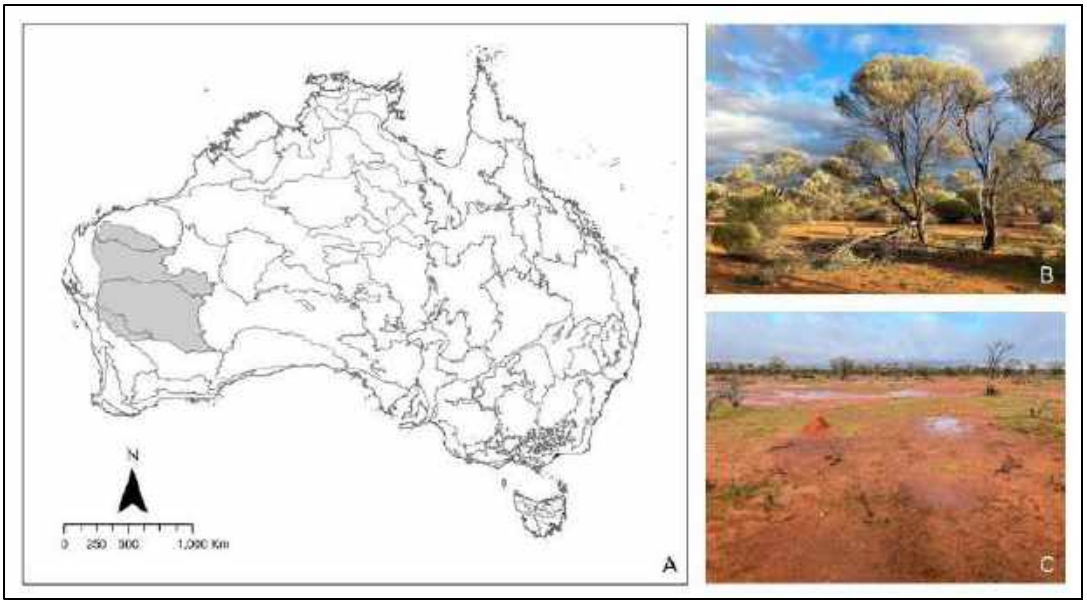

Figure 1. A) IBRA bioregion boundaries of Australia, showing the study region (grey shading): Murchison, Gascoyne, Hamersley and Tallering. Examples of mulga shrubland in B) fair, and C) collapsed condition. Source of IBRA data: DCCEEW (2023). Photo credits: S. Luxton.

Reference state: consists of a mosaic of mulga-dominated vegetation with grassy to shrubby understorey, with high grass richness and cover in more fertile parts of the landscape (including under trees). Uniform tree distribution may occur in the more productive environments, while banded or clustered groves become more pronounced in less productive areas. Reference fire regimes in shrub-grass mulga are inferred to be patchy and infrequent (>100 years based on mulga fire sensitivity, as it takes at least 50 years for mulga woodland to regain structure). Mulga is usually killed by even mild fire, and fire can lead to mulga shrublands moving temporarily to an expression where mulga are absent or sparse (i.e., grassland and/or sparse mulga expressions). The term ‘expression’ is used here in alignment with Richards et al. (2020) to recognise transient and reversible dynamics within states that differ substantially in one or more ecosystem attributes, relative to other expressions.

Modified states reflect key differences in ecosystem condition for biodiversity and pastoral value, along gradients of degradation and regeneration (Figure 2). The key drivers of degradation are overgrazing and associated hydrological dysfunction as grazing impacts worsen. Mulga harvesting, fire, drought and heatwaves, and isolated hail damage also contribute to ecosystem condition decline, leading to the removal and/or death of the mulga overstorey. As grazing pressures increase, the most palatable component of the flora declines (good to fair condition) and then disappears (fair-poor to poor condition). Less palatable grasses such as *Eriachne helmsii* become more common in grassy areas, and bare ground and exposed hardpan increase in cover. Unpalatable shrubs also increase in abundance (e.g., *Eremophila clarkei* and. *Acacia tetragonophylla*) and the overstorey shifts from healthy with good cover, to sparse with strong browse lines to collapsed (Figure 2). At the extreme, landscape hydrology becomes so dysfunctional that it can no longer support Mulga. This “collapsed” state (collapsed Mulga with collapsed understorey) is characterised by dying and dead trees and an understorey dominated by sparse annuals.

Recovering states with regenerating mulga overstorey (Figure 2, dashed boxes) were included to recognise the long timeframes for recovery of mulga overstoreys, including an approximately 50 year period from seedling establishment (defined at approximately 3 years since germination). Within this period, two distinct states of overstorey recovery we considered useful to recognise:0.3-2 m mulga and 2-3 m mulga. Given these long timeframes, understorey was considered to shift from collapsed to fair-poor and potentially to fair over this period, depending on management. The potential for the mulga understorey to recover to good condition was considered more likely over a 60-year timeframe, with the ongoing removal of grazing and natural recruitment.

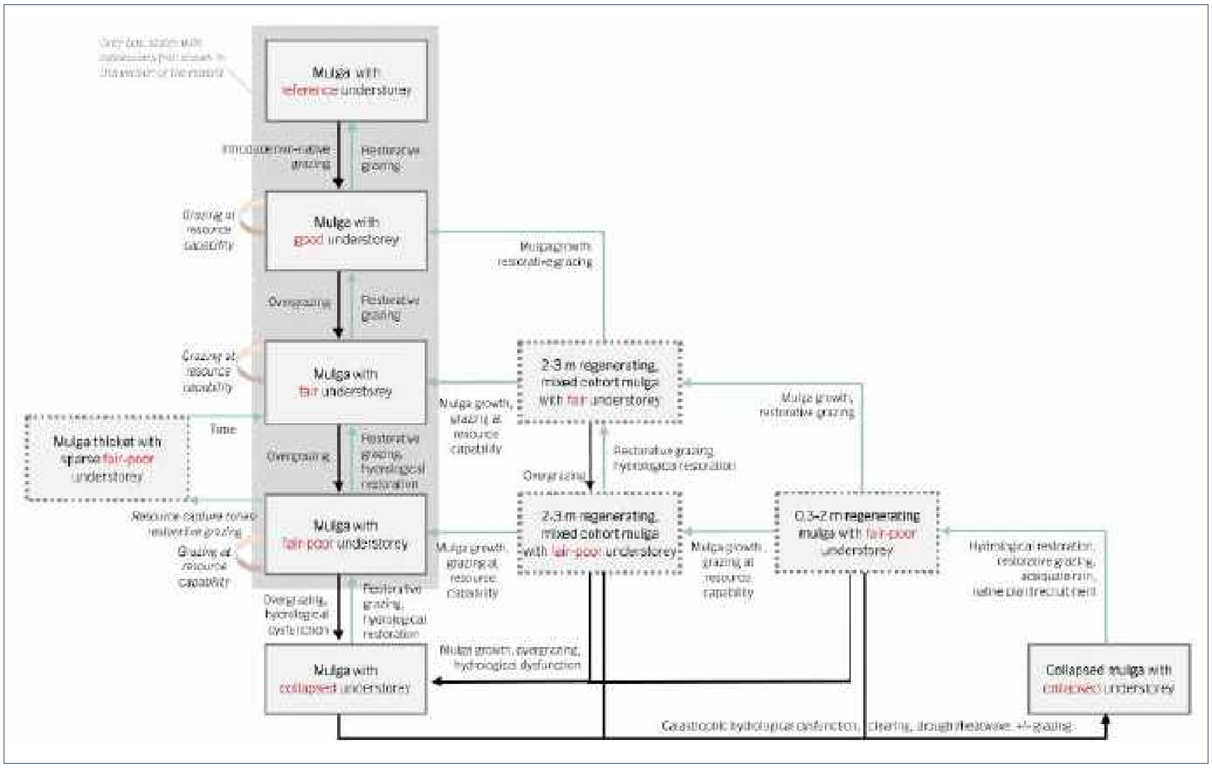

Figure 2. Simplified state and transition model for WA shrub-grass mulga showing degradation (black arrows) and restoration (teal arrows) transitions. Curved arrows (orange) indicate drivers that maintain a state in its current condition. Boxes with solid borders show reference and modified states, while boxes with dashed borders are regenerating (i.e. transitional) states. Text on arrows describe the drivers that are causing transitions between two states.

Restoration and regeneration in the mulga rangelands are largely implemented through grazing management and where soil surface condition has been degraded, through hydrological interventions to increase water infiltration. A range of restoration interventions were identified by the workshop participants, falling into two categories: tools to manage total grazing pressure (e.g., water point management, reduced dingo control, and rest-based grazing strategies), and tools to expedite recovery of landscape hydrology (e.g., water ponding with grader and bulldozer-built banks). Finally, a set of potential indicators for monitoring ecological recovery in the WA mulga rangelands were identified. They include indicators from Tongway and Hindley (2004) Landscape Functional Analysis procedure (e.g., soil cover, litter cover, cryptogam and perennial grass basal cover, and microtopography) and additional ecosystem attributes like the ratio of increaser:decreaser species, invertebrates and plant recruitment.

Discussion & Conclusions

The simplified STM presented above provides an expert-led synthesis of ecosystem dynamics for WA shrub-grass mulga (Figure 2). It integrates and organises information from experts and the current WA Department of Primary Industries and Regional Development (DPIRD) pasture condition assessment system (Waddell *et al.* 2023) to build a model of ecosystem function. This includes distilling the key drivers that either maintain the ecosystem in its current state, or lead to degradation or recovery - explicitly relating the intensity and/or duration of grazing pressure to different ecosystem condition states. While not presented here for brevity, each state includes a description of dominant species, and ground cover, hydrology and soil attributes alongside quantitative data where available. The STM provides a synthesised, coherent model of WA shrub-grass mulga ecology that is accessible to both experts and non-experts. General applications include supporting DPIRD to develop rangelands monitoring and condition standards. For restoration, the STM will assist with planning appropriate management interventions and their correct timing and scale. It also provides an estimate of recovery timeframes for regulatory purposes. These factors can support land managers to access emerging nature markets, including with the development of restoration plans and the measurement of outcomes using indicators.

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Local area intensification of rangelands

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Reviving the rangelands: Silvopasture approaches for profitable land restoration

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Key words: Silvopasture, Rangeland Restoration, Alternate Land Use, Income Diversification

Abstract

Rangelands cover more than half of the world's land area, providing vital support for around 500 million pastoralists and playing a key role in global livestock production and the livelihoods of pastoral communities. However, approximately half of these rangelands are degraded, negatively impacting both livestock production and pastoralist well-being. This underscores the urgent need for sustainable interventions to restore these ecosystems and improve global livestock production and pastoralist livelihoods. Transforming rangelands into more productive and climate-resilient systems, such as silvopasture (SPS) offer a promising solution. Research conducted by ICAR-IGFRI, Jhansi, India, in degraded semi-arid rangeland conditions of Bundelkhand converted to SPS via planting with native fodder trees, shrubs, and pasture species revealed significant findings. Under 12-years of evaluation, SPS was found to produce year-round fodder, with grasses yielding approximately 30–40 Mg ha^{-1} yr^{-1} green fodder and forage legumes yielding 10–12 Mg ha^{-1} yr^{-1} green fodder, supplying high-quality fodder from July to December. Trees produced 12–15 kg/tree of green top feed, and shrubs yielded around 7–8 kg/shrub of green top feed, ensuring supply of green fodder during lean months from December to June. These SPS systems were estimated to maintain 4–5 ACU ha^{-1} yr^{-1} and in addition to it sequestered 14.35 to 30.68 Mg C ha^{-1} in above and below-ground biomass, equivalent to 52.66 to 112.60 Mg ha^{-1} of atmospheric carbon dioxide equivalent storage. Furthermore, the SPS accumulated 31 to 48 Mg C ha^{-1} in the soil layer up to 60 cm and released around 38.31 to 81.92 Mg ha^{-1} of oxygen under various trees, shrubs, and grass/legumes combinations. The eco-restoration efficiency of these SPS systems was also found to be approximately 10 times greater than that of fallow land and also boosted TOC by 2–3 folds in soil over fallow land. The findings clearly demonstrate effectiveness of SPS as a climate-resilient approach for transforming degraded rangelands into profitable land use system ensuring diversified production and income generation to pastoral communities.

Introduction

Over half of the Earth's land area is occupied with the rangelands ecosystem which is very crucial for sustaining global livestock production and livelihoods of more than 500 million pastoralists. However, rangelands are currently facing degradation owing to overgrazing, developmental activities, fire, climate change etc. which is hampering livestock production, livelihood of pastoralists and ecosystem services negatively (UNCCD 2024). Thus, there is an urgent need to restore these ecosystems and sustain livestock production, pastoral livelihoods and ecosystem services in long run. Restoring degraded rangeland via transforming them to silvopasture systems offers a nature based solution to enhance productivity, carrying capacity, climate-resilience and ecosystem services in rangeland ecosystems. Considering this, a study for 12 years was conducted on silvopasture systems established on semi-arid central India's degraded landscapes with the aim to find out the fodder production potential, carrying capacity, carbon storage and oxygen release potential of SPS.

Methods

The silvopasture systems (SPS) consisting of indigenous high value fodder trees of semiarid zone *viz*. *Ficus infectoria*, *Morus alba*, *Acacia nilotica*, and a shrub *Leucaena leucocephala*; perennial grass species *Megathyrsus maximus* and *Chrysopogon fulvus* along with the perennial fodder legume *Stylosanthes seabrana* was studied for 12 years. The study receives average rainfall of 867 mm/annum; is prone to drought; and faces high temperature during summer (maximum: 47.4 °C in June); 4.1°C of minimum temperature in December with 60% mean annual relative humidity. Soil of the site is typical inceptisol having shallow depth, poor fertility, poor water holding capacity and low organic matter. Trees were planted at the spacing of 5 × 5 m; shrub at 5 m (row to row) × 2 m (plant to plant) and grasses as well as legumes at the spacing of 50 × 50 cm in rows between two trees/shrub rows.

The system was maintained in 4.32 ha area under rain-fed conditions and each treatment was replicated thrice under randomized complete block design. Green biomass yield of grasses and legume was measured by harvesting 1 × 1 m area at six random places in each plot and then calculated per hectare basis as Mg ha^{-1} (green fodder). For tree species, canopies were imposed to 30% pruning and shrub was pollarded at 1 m height and green pruned fodder biomass (leaves and soft twigs) per tree/shrub was recorded and was calculated per hectare basis as Mg ha^{-1}.

Total biomass carbon stock of trees, grasses and legume species under silvopasture system was calculated by adding their per hectare above ground biomass carbon (AGBC) and below ground biomass carbon (BGB) content. Above ground biomass carbon (AGBC) stock of trees/shrub, grasses and legume species was calculated by multiplying respective dry above ground biomass with a conversion factor of 0.50 and was expressed as Mg C ha^{-1} (IPCC 2006). Below ground biomass carbon (BGBC) stock of trees/shrub was calculated by multiplying AGBC with 0.26 (IPCC default value: IPCC 2006) and of grasses/legume by multiplying AGBC with their root: shoot ratio (*C. fulvus*: 0.59; *M. maximus*: 0.51; *S. seabrana*; 0.44). Finally total biomass carbon stock under each SPS was calculated by adding total biomass carbon stock of the respective trees/shrub with total biomass carbon stock of grasses/legume under each combination. This total carbon stock potential was converted to carbon-dioxide mitigation potential or carbon dioxide equivalent storage (CO_2e) (carbon stock × 3.67) as per IPCC (2006). Soil carbon stock in system was calculated as per the methodology of Ghosh et al. (2018) using fallow land as a reference. Total oxygen release in the system was calculated as Mg ha^{-1} using the formula (total oxygen release = total carbon stock (Mg ha^{-1}) × 32/12) (Nowak et al. 2007, Keerthika and Chavan 2022). Data were analyzed using analyses in online OPSTAT software, a statistical software package for agricultural research workers (Sheoran et al. 1998).

Results

Twelve years of evaluation of SPS revealed that the grass component have green fodder biomass production potential of around 30–40 Mg ha^{-1} yr^{-1} and forage legumes component have green fodder biomass production potential ranging between 10–12 Mg ha^{-1} yr^{-1}. Grasses and legume are capable of ensuring quality green fodder supply from July to December months. The trees have potential to produce 12–15 kg/tree of green top feed, and shrubs have potential to produce around 7–8 kg/shrub of green top feed during lean period from December to June months. These SPS can easily sustain 4–5 ACU (Adult Cattle Unit) ha^{-1} yr^{-1} along with ensuring round the year quality green fodder supply for livestock.

Biomass carbon storage studies revealed that these SPS have a huge capacity to store between 14.35 to 30.68 Mg C ha^{-1} in above and below-ground biomass under various trees/shrub and grasses/legume combinations. This carbon stored in biomass is equivalent to sequestration of 52.66 to 112.60 Mg ha^{-1} of CO_2e. In addition to this, these SPS can accumulate around 31 to 48 Mg C ha^{-1} in the 0-60 cm soil layer (Kumar et al. 2022). Further, the oxygen release capacity of these SPS is around 38.31 to 81.92 Mg ha^{-1} of oxygen under various trees, shrubs, and grass/legumes combinations. Moreover, these SPS have also been reported to have eco-restoration efficiency of approximately 10 times greater than that of fallow land and have capacity to enhance total organic carbon content by 2–3 times in soil over fallow land (Kumar et al. 2022).

Discussion

Thus, twelve years of evaluation of these SPS under semi-arid conditions at Jhansi, India demonstrated that establishing these systems on degraded landscapes including rangelands can sustain round the year quality fodder supply and thereby ensure pastoral livelihoods in the long run. Besides this, silvopasture systems can help in mitigating climate change via carbon storage in biomass, thus helping to offset the green house gases emission from grazing livestock. Huge oxygen release capacity of these SPS makes them viable option to help in oxygen shortage owing to rising pollution. Prioritizing the establishment of SPS on degraded rangelands, underutilized wastelands, permanent grasslands, and pastures across various agro–climatic regions in India as well as across globe can help to address the ongoing need for premium–quality fodder, enhance livestock productivity, bolster pastoral economies, and promote environmental sustainability.

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The manure value chain in the North of Senegal. What social, economic and environmental sustainability?

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Key words: manure; value chain; sustainability; pastoralists; rangelands

Abstract

In northern Senegal, due to the recent surge in the price of chemical inputs and the need to diversify the methods of fertilization and amendment of plots of agrobusinesses, manure has become in a few years the black gold of the region. The manure value chain is a relatively young sector; thus, it has not yet been the subject of research, despite its potential for expansion and impact on the territory. This study aims to assess its sustainability in social, economic and environmental terms, by considering and comparing different governance mechanisms in the value chain. Through semi-directive interviews with stakeholders all along the value chain, we identified three different sub-value chains based on what kind of stakeholder take the lead in manure processing. This can be made by specialized processors, manure producers (pastoralists), or consumers (agrobusinesses). The three sub-value chains have different impacts in terms of sustainability, depending mainly on job creation, the appropriation of added value, and rangeland degradation coming from manure grabbing. In any case, and depending on the governance mechanisms put in place to regulate the transactions, manure seems to have great potential for poverty reduction and crop soil fertilization. Indeed, it not only helps to strengthen the structure and fertility of soils; but also, its use for energy purposes allows more than 80 households to cook and reduce their expenses. Other rural households in the area use the sale, collection or transport of manure to supplement their income. Nonetheless, the manure value chain may have negative impact on family farming. Peasants struggle to obtain manure due to competition with manure collectors. Also, agribusinesses have diversified their manure supply strategies by switching to compost production, thus reducing the share of added value that other stakeholders – be they pastoralists or specialized processors – achieve to grab from the processing activity.

Introduction: a growing interest for manure

In northern Senegal, due to the recent surge in the price of chemical inputs and the need to diversify the methods of fertilizing and improving the plots cultivated by industrialists in the area, manure has become the region's black gold in just a few years. The methods of valorization are varied, as are the different supply chains (Belmin et al., 2022). Whether we are talking about raw manure or manure valorized into compost, the actors involved in the sector are multiple. The study area focuses on the Municipality of Mbane to the east of the Guiers Lake. This municipality has been prone, for several decades, to tensions over the resources it contains, due to its proximity to the lake. Irrigated and industrial agriculture is encroaching on pastoral territories and the removal of manure linked to the manure trade raises questions about the future of fertility in the bush and in pastures (Bourgoin et al. 2019).

This study aims to understand the value chain from the point of view of the actors who make it up, starting with the producers of manure, namely the livestock farmers. Whether from an economic, social or environmental point of view, this first study on the subject also aims to look further into the future, by understanding the sustainability of the governance mechanisms put in place within the value chain.

Methods: value chain approach and qualitative survey

The method used in this work is based on an analytical framework in terms of value chain (VC), that allows to understand the governance mechanisms and analyze the linkages, interdependences and unbalances between different stages of the life cycle of a product (Gereffi et al., 2005). Nowadays, literature has been focusing more and more on VC sustainability from multiple points of view. Several methods have been developed with this aim, such as FAO's Sustainability Assessment of Food and Agriculture Systems Guidelines (SAFA) (Scialabba, 2014), the Framework for Assessing the Sustainability of Natural Resource Management (MESMIS) (Lopez-Ridaura et al., 2002), the Value Chain Analysis for Development (VCA4D) (Fabre et al., 2012) and the Bellagio SusTainability Assessment and Measurement Principles (STAMP) (Pinter et al., 2011). Methods and studies mainly consider VC sustainability from a social, economic and environmental point of view (Duteurtre et al., 2020; Malak-Rawlikowska et al., 2019; Munasinghe et al., 2017; Muñoz López et al., 2020; Pacheco et al., 2017). Thus, starting for the existing frameworks, we built a set of social, economic and environmental indicators.

To collect information in the field, we conducted semi-directed interviews with all the actors involved in the manure value chain. These actors include: manure producers, i.e. local pastoralist households, who can be at the same time collectors and processors on a small scale; medium and large-scale collectors; manure processors into compost and/or digesta; consumers, i.e. agribusinesses. The study area is the Municipality of Mbane; however, the study also considers the regional scale, which represents the manure collection basin, and national, when the different national programs and policies come into play. The information collected was used to trace the value chain and its sub-chains (see governance mechanisms) and then compare them in terms of sustainability. By sustainability we mean the positive impact of the value chain on the area and we adopted the point of view of pastoralist households since the are the local inhabitants.

Results: a young and varied value chain

The manure value chain is relatively young. Before manure transporters set up, farmers and pastoralists used to exchange manure and crop residues, through the installation of animal pens as "common pastures" in the crop fields after the harvest. Some of these exchanges have persisted over time and the common pasture remains a widespread practice. Since the 2000's, as a result of the structural adjustment plans and several State programs to boost private investments, some huge agri-businesses were set up in the area, like the Indian *SenegIndia*. This led to the emergence of the first manure transporter, who travelled along the Senegal river valley to collect manure and sell it to those agri-businesses. From the 2010's, new methods of using manure were developed – that are composting and biomethanization – and some firms processing the manure into compost appeared. This raised awareness on the economic value of manure and led to its monetization. More manure transporters appeared, travelling up and down the silvopastoral area and collecting manure from pastoralist households, thus increasing the pressure on the resources of the rangelands. Nowadays, some agri-businesses are setting up internal compost platforms, so that they can buy raw manure and process it by themselves, thus bypassing intermediaries and contributing to a more vertical integration of the VC.

Three different sub-value chains

By identifying VC actors and activities, we distinguished three sub-VC (see Figure 1). The first one, that we call "producers-processors", involves pastoralist households who have set up small biomethanization platforms on their site, thank to loans granted by the *Building Successful Business* firm. This firm covers the installation costs and recover them over time through the supply of digesta (the by-products coming from processed manure). It then sells this digesta to the agri-businesses. Pastoralist households benefit from the payment of the digesta (once all the grants are recovered) and the production of biogas resulting from the process of biomethanization. The second sub-VC, called "consumers-processors", links households and agri-businesses via simple transporters. Indeed, the supplied agri-businesses have on-site compost platforms and prefer to buy cheaper raw manure. In this sub-VC, some household members (especially women and youth) collect manure from the bush and bring it to collection points that were previously agreed with transporters. In the third sub-VC, that we call "big processor", there is one firm (*Éléphant Vert*) which collect manure from pastoralist households and process it into compost to be sold to agri-businesses.

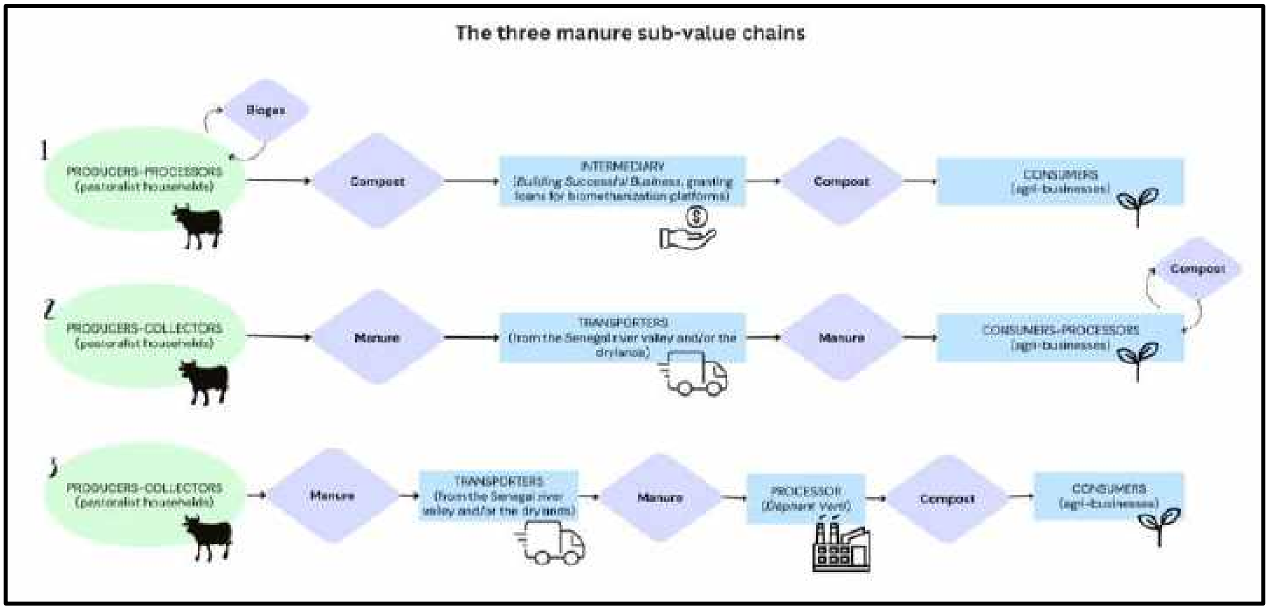

Figure 1 – The three manure sub-value chains: actors and products

The social, economic and environmental sustainability of the three sub-value chains

We compared the impacts of these three sub-VC on the area using a set of social, economic and environmental sustainability indicators. Based on the qualitative and quantitative data collected, we assigned plus (+) or minus (-) to each of the indicators according to the sub-VC, which made it possible to obtain an overall sustainability score for each of the sub-sectors (see Table 1).

Table 1 – Scores of social, economic and environmental sustainability of the three manure sub-value chains

Indicators	Sub-value chain 1 “producers-processors”	Sub-value chain 2 “consumers-processors”	Sub-value chain 3 “big processor”
Social			
Number of workers	+	++	++
Numer of jobs under contract	++	--	--
Access to accident coverage	+	--	-
Sub-total social sustainability	4	-2	-1
Economic			
Gross added value	+	0	++
Price payed to pastoralist households	++	--	-
% of added value to pastoralist households	++	+	-
Accessibility to a method of manure valorization	--	++	++
Sub-total economic sustainability	3	1	2
Environmental			
Distance traveled for collecting manure	++	--	-
Preferred collection area	++	-	0
Quantity of water used for composting	-	--	-
Sub-total environmental sustainability	3	-5	-2
Total	**10**	**-6**	**-1**

The scores show that it is sub-VC 1 (“producers-processors”) that presents the best social, economic and environmental impacts in favor of pastoralist households. Indeed, households are not only producers but also processors, thus grabbing a higher share of the added value coming from manure. This comes down to discussing the balance of power between actors: here households’ negotiating power is the strongest, which results in higher manure price. In sub-VC 2 (“consumers-processors”), it is the downstream actors who are favored in the balance of power: the monopolization of the processing activity, which resulted in the set-up of their own composting platform, leads to a vertical integration of processing and even transport intermediaries. Also, these giants are the sole buyers of some transporters and are therefore in an oligopoly position. In sub-VC 3 (“big processors”), the balance of power is exercised by the intermediaries, which creates a certain balance within the sub-VC. This sub-VC presents a high gross added value, however the percentage of added value which returns to pastoralist households is very low.

Discussion and conclusions: need to regulate the governance of the manure value chain

Through this work, we have noticed that the uses of raw manure are numerous and deployed on the study area. Whether through its uses in industrial or family agriculture, manure helps to strengthen the structure and fertility of soils. On the other hand, its use for energy purposes allows more than 80 households in the Northern zone to cook and supplement their income by selling processed manure. Other rural households in the zone use the sale, collection or transport of manure to supplement their income. At the same time, small crop producers struggle to obtain manure due to competition with manure collectors. We have also seen how agribusinesses have diversified their manure supply strategies by switching to compost production. This new production activity tends to threaten the activities of processors specializing in compost production in the zone. In general, it seems that interest in this black gold tends to increase in the coming years. Approaching the sector from a sustainability perspective would make it possible to perpetuate everyone's activities by changing practices.

In order to strengthen the basis for thinking about the sustainability of the manure sector and anticipate its potential impacts, other studies should be conducted to explore and deepen the three aspects of sustainability addressed – social, economic and environmental.

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Fertile Bajra-Napier Hybrids of *Pennisetum* are a potential candidate for "de-ranging" Indian rangelands to other food production systems

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Key words: de-ranging rangelands; Fertile BN Hybrid; *Pennisetum*; Seed producing

Abstract

Pennisetum Syn. *Cenchrus* is an important C4 genus of the family Poaceae, and comprises of more than 140 species. *P. glaucum* (L.) R. Br. (commonly known as Bajra or Pearl millet - diploid; 2n=2x=14) is one of the most important and well domesticated species utilized as a food and fodder crop in the arid and semi-arid tropics of the world. However, it is an annual crop, so Bajra needs to be grown every season/year. It also has less biomass than other species and so is not a suitable candidate for "de-ranging" rangelands. The *Pennisetum* genus contains other important species namely *P. purpureum* Schumach (commonly known as Napier or Elephant grass - allotetraploid; 2n=4x=28) widely known for its adaptability, high biomass, high tillering habit, fast regrowth capacity and tolerance to various biotic and abiotic stresses. However, it is cultivated vegetatively because of its very small seed size (1000-seed weight; 0.5-0.6 gm) along with high heterozygosity, poor seed setting and seed viability issues. It too is thus not a potential candidate for "de-ranging" rangelands. However, we have successfully developed an interspecific fertile cytotype (4x) of *P. glaucum* x *P. purpureum*, popularly known as fertile Bajra-Napier (BN) Hybrid by employing modified ploidy coupled with embryo rescue techniques. This fertile hybrid was selfed to produce a large F_2 population which was assessed for various agro-morphological and seed related traits, especially number of seeds per panicle (NSPP) and thousand-seed weight (TSW). All the F_2 lines are fertile and produce viable seeds in a differential pattern with NSPP varying between 13 and 550, and TSW from 0.62 to 4.77 gm. We now have fertile seed producing BN Hybrid in its F_6 generation through recurrent selfing. Having attributes of both *P. glaucum* (high palatability, grain type millet) and *P. purpureum* (wider adaptability, perenniality), these BN hybrids are a potential source of plant material for "de-ranging" rangelands to other food production systems as they can survive better under harsh climatic conditions and become an excellent source of food (grain type millet) and feed (green and dry biomass) to the pastoral communities depending on these rangelands.

Introduction

Bajra Napier (BN) hybrid, belongs to Pennisetum genus, is one of the most biomass producing plant with multiple benefits. It's a man-made hybrid popular among dairy farmers due to its high biomass and bioenergy potential. It is widely known as Bajra-Napier (BN) hybrid in India and King's grass & PMN hybrids worldwide (Dowling et al. 2014). It combines the unique features of both *P. glaucum* (Pearl millet; Bajra) and *P. purpureum* (Napier) species, which makes it more resilient to harsh environments with superior fodder quality (Burton 1944; Jauhar, 1981; Hanna et al. 1984). Since Napier (2n=4x=28) is an allotetraploid with A'A'BB genomes and Bajra is a diploid (2n=2x=14) species with AA genomes, the obtained interspecific BN hybrids with triploid genome AA'B

(2n=3x=21), is sterile due to irregular chromosomal segregation during meiosis and no fertile seed set (Techio et al. 2006). Several workers accomplished *in vitro* polyploidization with the perspective of restoring its fertility (Gildenhuys and Brix, 1964; Hanna, 1981; Hanna et al. 1984; Gonzalez and Hanna, 1984; Rajasekaran et al., 1986; Diz and Schank, 1993; Abreu et al. 2006; Barbosa et al. 2007; Campos et al. in 2009; Faleiro et al. 2016). However, till date no such seed producing hybrid is available and still these are propagated vegetatively either through rooted slips or stem cutting which is a major bottleneck and limitation in dissemination and widespread use of this highly potential fodder cum bioenergy crop. In India, ICAR-IGFRI being a premier research institute working on fodder crops, has developed the world's first fertile tetraploid seed producing BN hybrid (TBN-20-15) utilizing modified ploidy coupled with embryo rescue technique (Rana et al. 2023a,b). This fertile BN hybrid was subsequently selfed to produce F_2 population for studying traits segregation and again selfed for subsequent generations to make them homozygous and stable in F_6 generation. Overall objective of the study was to stabilize fertile Bajra Napier hybrid along with identification of potential candidates for "de-ranging" Indian rangelands to other food production systems.

Methods

Plant material and experimental site

Experimental material consisted of immortalized F_2 population of 250 individuals derived from an intraspecific cross of *P. glaucum* (Tetra Bajra) and *P. purpureum* (N27). For immortalized F_2 development, rooted slips from a single F_2 plant were harvested and transplanted through vegetative means. The immortalized F_2 were grown at Central Research Farm of ICAR-Indian Grassland and Fodder Research Institute, Jhansi, UP, India (latitude, 25.5114° N; longitude, 78.5337° E and 271 m altitude above sea level).

Morphological characterization of immortalized F_2 lines of Fertile Bajra Napier Hybrid

A population of 250 immortalized F_2 lines were characterized for 14 biomass related traits. The plants were grown in a single row having row to row distance of 1.5 meter and plant to plant distance of 1.0 meter in an augmented randomized complete block design (RCBD) in 8 blocks. The block-to-block distance was 2.0 meter. The recommended agronomic practices were followed during the cropping period. The list of traits recorded along with their description are as follows:

Trait	Trait wise description
AGRO-MORPHOLOGICAL TRAITS	
Plant Height (PH)	From ground level to the tip, 60 days after transplanting **(cm)**
Leaf length (LL)	Measured from ligule to tip of leaf (4th node from top on main tiller) at 60 days after transplanting **(cm)**
Leaf Width (LW)	Measured at the widest point of the leaf (4th node from top on main tiller) at 60 days after transplanting **(cm)**
No. of tillers per plant (NTPP)	No. of basal tillers were counted at 60 days after transplanting
Stem Thickness (ST)	The thickness of the stem (without leaf sheaths) between 3rd and 4th node from base at 60 days after transplanting **(mm)**
Inter Nodal Length (INL)	Distance between 3rd and 4th node from top at 60 days after transplanting **(cm)**
No. of Leaves Per Plant (NLPP)	Total number of leaves from base to panicle
Spike Length (SPL)	Calculated from the last leaf to the tip of the spike **(cm)**
Green Fodder Yield (GFY)	Recorded at 60 days after transplanting and continued for every 45 days interval upto 5 cuts for per plant basis **(kg)**
Dry Matter Yield (DMY)	Part/ fixed amount of green fodder harvested at 50% flowering, dried and weighed for per plant basis **(kg)**
SEED RELATED TRAITS	

No. of Seed Per Plant (NSPP)	Counted as total number of seeds produced from a plant from all their spikes **(Number)**
Seed Length (SL)	Measured with the help of measuring scale **(mm)**
Seed Breadth (SB)	Measured with the help of measuring scale **(mm)**
1000 seed weight (TSW)	Weight of 1000 seeds from each plant **(g)**

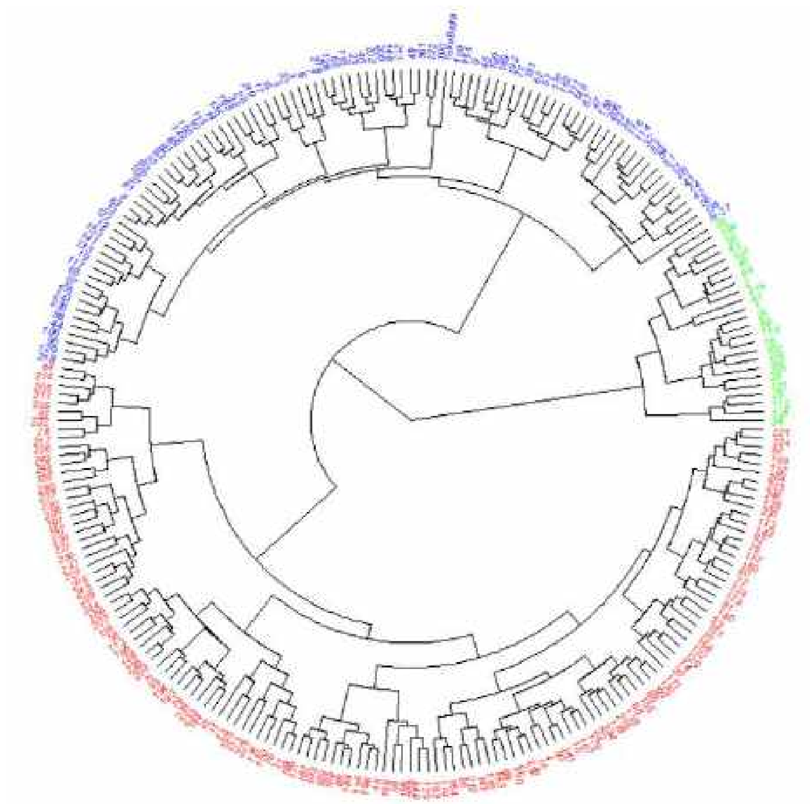
Statistical analysis

The experimental data collected in respect of various traits on 250 Fertile BN Hybrid immortalized F_2 lines along with two parental checks were compiled by taking the mean values of selected plants in each plot and subjected for statistical analysis. The data was statistically analyzed through R package and statistical software StatistiXL version 2.0.

Results and Discussion

Analysis of variance and trait correlations

Significant differences for all the 14 measured traits were observed among the population. Analysis of Variance (ANOVA) of 250 immortalized F_2 lines revealed significant differences for all the traits. In general, the mean values of F_2 lines were intermediate to that of parents. The values of F_2 lines outside the parental range were also observed for the traits under study. This indicated that the alleles that increased phenotypic values were dispersed in both parental lines, even when their values differed markedly, thus indicating transgressive segregation for all traits. The traits associated with biomass assessed in this study appeared to be quantitatively inherited as shown by the presence of nearly continuous distribution of mean phenotypic values of the traits. The ANOVA revealed the presence of non-significant differences between the blocks based on the parameters evaluated indicates that all the traits exhibiting variation (Gupta 2023). Mean for NSPP was 145.54 seeds which ranged from 11.50-546.00 seeds. Whereas, the maximum number of seed per plant was recorded for F_2-222 (550) and minimum number of seed per plant was recorded for F_2-135 (13). However, mean for TSW was 1.97 g which ranged from 0.59-10.31 g. Whereas, the maximum thousand seed weight was recorded for F_2-41 (4.77) and minimum thousand seed weight was recorded for F_2-133 (0.62 g).



Spherical dendrogram for 250 immortalized F2 lines of Fertile Bajra Napier Hybrid showing extent of variation present among the population

Range, mean and standard deviation for biomass related traits in Fertile Bajra Napier Hybrid

Trait	Mean	Std. Deviation	Range
PH	184.34	29.76	112.81-287.51
LL	40.81	6.51	22.06-66.03
LW	1.72	0.35	0.81-2.95
NTPP	7.24	2.53	2.83-17.03
ST	10.51	1.99	6.47-18.90
INL	12.32	1.73	7.81-20.30
NLPP	8.23	1.37	5.23-13.43
SPL	29.06	3.84	18.85-38.50
GFY	7.05	2.06	2.41-14.73
DMY	0.29	0.2	0.05-1.24
NSPP	145.54	73.72	11.50-546.00
SL	2.49	0.32	1.11-3.21
SB	1.28	0.24	0.82-2.25
TSW	1.97	0.92	0.59-10.31

Conclusions/Implications

Having attributes of both *P. glaucum* (high palatability, grain type millet) and *P. purpureum* (wider adaptability, perenniality), these fertile BN hybrids are a potential source of plant material for “de-ranging” rangelands to other food production systems as they can survive better under harsh climatic conditions and become an excellent source of food (grain type millet) and feed (green and dry biomass) to the pastoral communities depending on these rangelands.

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Nurturing communities and ecosystems: the power of community engagement and silvopastoralism in drylands

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Key words: arid and semi-arid regions, rangeland restoration, Al-Hima system, ecosystem services, socioeconomic benefits.

Abstract

This paper examines two case studies of ecosystem restoration in arid and semi-arid regions of the Near East and North Africa (NENA). The first study evaluates the economic benefits of rangeland restoration in Jordan using the traditional "Al-Hima" system, a community-based approach to sustainable grazing management. A cost-benefit analysis revealed that Al-Hima restoration increased forage production, groundwater infiltration, and carbon sequestration, resulting in a positive benefit-cost ratio of 2:1. The second study analyzes a silvopastoral restoration project in Tunisia, where the integration of trees and shrubs with livestock grazing led to increased biomass production, improved ground cover, and enhanced water use efficiency. This project also demonstrated socioeconomic benefits through reduced livestock feeding costs. Both case studies emphasize the importance of community engagement, sustainable land management practices, and the integration of ecological and socioeconomic considerations in successful ecosystem restoration initiatives.

Introduction

Drylands encompass a significant portion of the world's land area, supporting diverse ecosystems and communities such as rangelands and pastoralist communities. The Near East and North Africa (NENA) region is the world's driest area with Mediterranean zones, large swaths of arid and hyper-arid deserts, and a diverse array of ecosystems and barren deserts with almost no vegetation (UNCCD, 2024). Rangelands are a vital ecosystem, essential for the livelihoods of millions of people in the NENA region. They provide critical ecosystem services like livestock grazing, water regulation, and carbon sequestration. This region, however, faces substantial environmental challenges, including desertification and soil degradation, primarily driven by unsustainable land management practices and climate change. Rangelands are important socioeconomic drivers, e.g., Morocco's rangelands deliver 1.5 foraging units/year (FAO, 2022). This paper examines two case studies of ecosystem restoration in arid and semi-arid regions, highlighting the potential for ecological and socioeconomic benefits. The first explores rangeland restoration in Jordan using the traditional "Al-Hima" system, while the second analyses a silvopastoral restoration project in Tunisia.

1. **Jordan**

Methods
An ex-ante cost-benefit analysis was conducted to demonstrate the value of large-scale restoration through the Al-Hima[12] system implemented by the Ministry of Agriculture and IUCN in the Zarqa River of Jordan (Myint and Westerberg, 2014). The project involved establishing a community-managed Hima area, where sustainable grazing practices were implemented, and access to grazing resources was regulated.

The economic valuation study by Myint and Westerberg (2014) used a combination of valuation methods (stated preference, avoided cost, replacement cost, and market price), the study compared a baseline scenario (no change in land-use management) with a Hima restoration scenario (large-scale adoption of the Hima system). High-resolution remote sensing, GIS, and biophysical soil and water assessment tools were used to calibrate the impact of land-use changes on ecosystem services. The study compared two scenarios:

- Baseline Scenario: This scenario assumes no change in current land-use management schemes.

- Hima Restoration Scenario: This scenario assumes large-scale adoption of the Hima system where each plot of land was divided into four units, with three under the Hima system and one kept as open access. A rotational grazing system was adopted where one of the Hima units would be open for grazing in any given year and closed the year after.

Results
The study revealed significant economic benefits from Hima restoration. Firstly, by substantially increasing forage production and reducing the reliance on livestock feed purchases, the Hima system ***enhanced rangeland productivity***. Over a 25-year period, the total discounted value of avoided fodder costs was estimated at 23 million USD. The study concluded that in rangeland units with open-access (unrestricted grazing), productivity decreased by 2 kg of dry biomass per year. Another key benefit of Hima restoration was ***increased groundwater infiltration.*** GIS modelling showed that large-scale restoration through the Hima model led to an annual increase of 14% in the yield of the Zarqa River Basin and valued at approximately 19 million USD per year. Additionally, there was a notable ***reduction in sedimentation.*** The avoided cost of replacing lost storage capacity due to sedimentation and maintenance was estimated at 3.4 USD/m3. Finally, the value of ***sequestered carbon*** over 25 years in the restored rangeland was estimated at 30.5 USD/ha. The study also identified costs associated with Hima restoration, including implementation (community engagement, equipment purchase, surveillance infrastructure), management, and opportunity (forgone benefits of current grazing practices). Despite these costs, the net present value of Hima restoration was calculated at 17 million USD with a benefit-cost ratio of 2.1; meaning for every 1 USD invested in Hima restoration, pastoral communities would receive 2 USD in benefits.

2. Tunisia

A pilot project implemented by the FAO, the International Center for Agricultural Research in the Dry Areas,, and the Tunisian Forestry Directorate in the Sbaihia community, Tunisia, showcased the benefits of silvopastoralism (FAO and ICARDA, 2020) in enhancing community resilience to drought, increasing income, and restoring rangelands.

Methods
The project adopted a participatory/multidisciplinary approach, engaging the local community, national institutions, and researchers. A series of activities were implemented to demonstrate the feasibility of silvopastoralism and grazing with trees. One of the main interventions was the ***restoration using native species.***

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[12] Traditional communal rangeland management practice in the Levant and the Arabian Peninsula dating back to ancient times that governs resource allocation through a community-based decision mechanism .

Drought-tolerant and palatable shrub and tree species (e.g., Opuntia ficus-indica), along with the native forage legume Hedysarum coronarium (sulla), were planted on slopes to reduce erosion and increase biomass and fodder availability. Another main intervention was the ***reseeding of degraded lands with sulla***, a native and highly palatable shrub, to evaluate its performance under different treatments. These treatments included assessing the adaptation of sulla to tillage under three conditions: sulla with soil scarification, scarification alone, and an untreated control. The primary field measurements for this evaluation were dry matter yield (DMY), rain use efficiency (RUE), and pastoral value (PV). Additionally, the effects of the interventions on biodiversity, biomass, and vegetation cover were examined using three treatment types: plots reseeded with sulla, plots protected from grazing for two years, and plots subjected to grazing. Finally, rotational grazing schemes were established to prevent overgrazing.

Results

The restoration activities were highly successful as illustrated in Table 1, with all species demonstrating good survival rates. *Ceratonia siliqua* had the lowest survival rate at 78 percent, while *Opuntia* had a 100 percent survival rate. The selected species provided local communities with increased fodder biomass for their livestock.

Table1: Focus on key results (the project had several experiments; in the paper we focused on the main ones listed below).

Experiment One	Scarified Sulla Plots	Scarified Only	Control
Biomass Production (tDM/ha)	7	2.5	3
Rain Use Efficiency (DM/ha/m³)	0.8	0.38	0.5
Pastoral Value (%)	42.5	20	20
Experiment Two	**Reseeded**	**Protected**	**Grazing**
Ground Cover (%)	100	100	59
Species Composition (No. of Species)	30	77	20
Biomass production (tDM/ha)	10	2.2	1

Figure 1 shows that the biomass production was significantly higher in the scarified sulla plots (>7 tDM/ha) than in the scarified (around 2.5 tDM/ha) and control plots (3 t DM/ha). RUE was also highest in the scarified sulla plots (0.8 DM/ha/m3), followed by control (0.5 DM/ha/m3) and scarified plots without sulla (0.38 DM/ha/m3). PV was 42.5 percent in the sulla plots and less than 20 percent for the other two. Reseeding with sulla and protecting the land from grazing both resulted in complete (100 percent) ground cover, primarily consisting of protective plant litter. In contrast as illustrated in Figure 2, land open to grazing had much sparser plant cover (only 59 percent), with most of the ground consisting of bare earth (69 percent). Protected rangelands had the richest species composition (77), followed by sulla reseeded plots (30) and grazed plots (20). In terms of biomass production, reseeded plots achieved the highest yield (10 tDM/ha), compared to protected plots (2.2 tDM/ha) and control plots (1 tDM/ha). The socioeconomic benefits of reseeding integrated with rotational grazing were also evident, as managed grazing reduced the cost of livestock feeding by about $0.13/day/head.

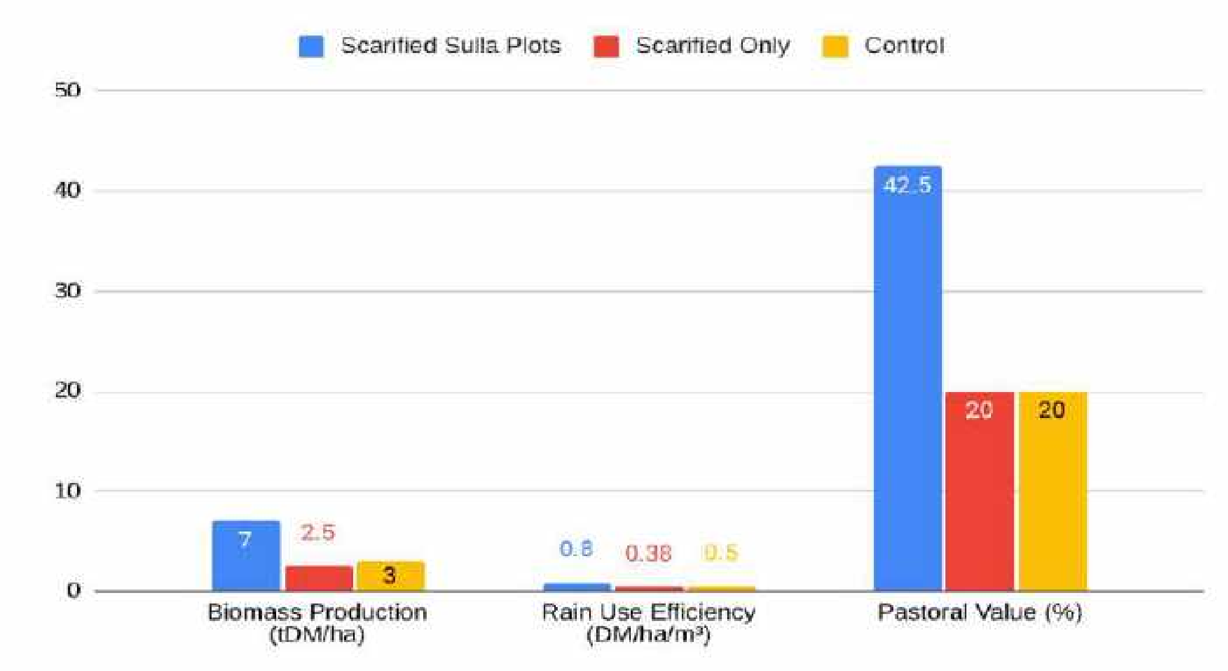

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Figure 1 illustrate the findings from experiment 1 on restoration using native species

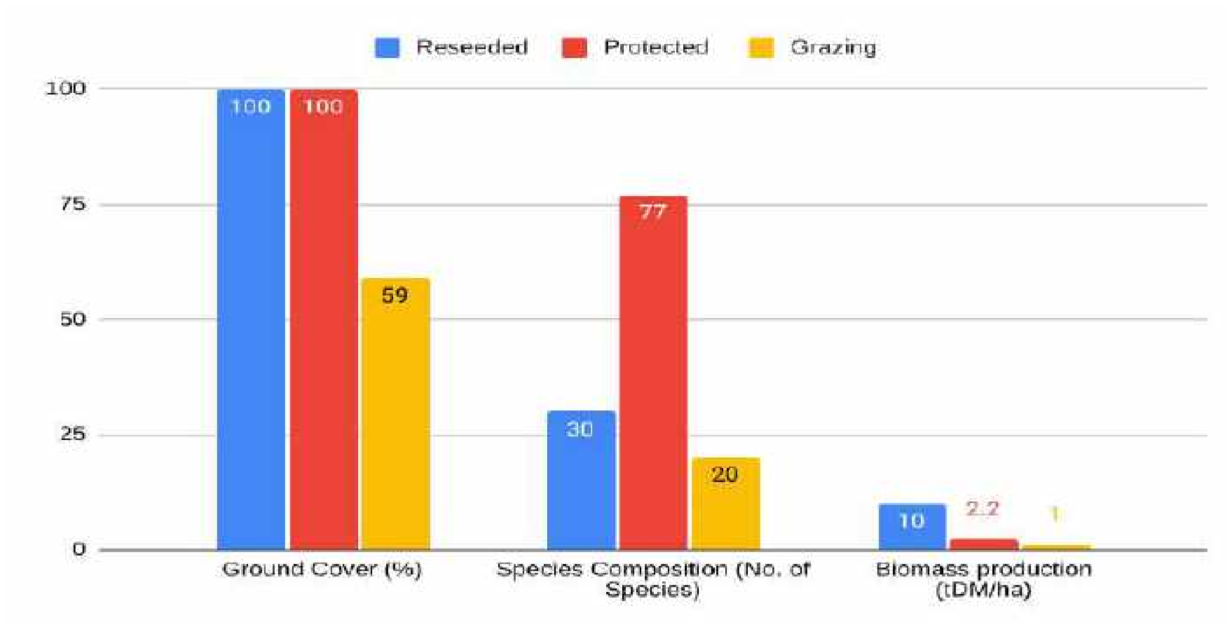

Figure 2 illustrate the findings from experiment 1 on reseeding of degraded lands with sulla

Discussion

Both the Jordanian and Tunisian projects highlight the importance of enhanced rangeland management and restoration through better community engagement and rangeland enrichment via reseeding and planting native species. These results highlight the critical role of reseeding with native species such as sulla in enhancing biomass production, protecting soil from erosion, and enhancing water infiltration and use efficiency. However, it is also important to consider potential drawbacks related to biodiversity. The importance of community involvement for the successful restoration of rangelands is gaining traction globally. For instance, in Kenya, the inclusion of Maasai tribes in rangeland management proved beneficial (Nyongesa et al., 2023). Similarly, research in Mongolia demonstrated the benefits of community inclusion in restoration and management (Ulambayar and Fernandez-Gimenez, 2019). Adopting a silvopastoral approach within the broader framework of landscape restoration can lead to more effective outcomes, delivering enhanced socioeconomic and environmental benefits (Vetter, 2020). The promising results from Tunisia reflect this paradigm shift, advocating for the integration of silvopastoralism in restoring both forests and rangelands.

Conclusion

The case studies from Jordan and Tunisia demonstrate the effectiveness of integrated approaches in combating land degradation and promoting sustainable land management. By combining ecological restoration with socioeconomic considerations and community engagement, these projects successfully enhanced ecosystem services, improved livelihoods, and built local capacity. Their success highlights the potential for replicating and scaling up similar initiatives in other regions facing desertification and land degradation.

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Using the Australian tropical forages collection to develop new pasture legumes for Australian rangelands

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Key words: genetic resources, regeneration, Queensland

Abstract

Beef cattle production is the key agricultural industry in the seasonally-dry and moderate rainfall zones of northern Australia. Uncleared natural woodlands are the key feed resource in the northern monsoonal zone, whereas sown pastures dominate the moderate rainfall zone further south. In additional to seasonal feed gaps, beef producers face emerging challenges from declining land condition, a warming and more variable climate and pasture dieback associated with mealy bugs. Sown deep-rooted legumes (*Desmanthus, Leucaena, Macroptilium, Stylosanthes*) can improve productivity on these pastures by improving nitrogen cycling and improving diet quality. The development of tropical pasture cultivars in Australia is underpinned by the Australian Tropical Forages Collection (ATFC), now held in the Australian Pastures Genebank supported by state and federal governments and primary industry research and development corporations. The ATFC comprises ~10100 warm season grasses and 7300 legumes sourced from other tropical countries and within Australia over 40+ years, including over 4000 legumes from genera with potential in permanent or semi-permanent pastures in the dry zone. Comprehensive plant evaluation and release activities by federal and state governments saw the development of a network of on-property plant evaluation sites and the release of useful legume cultivars for key beef production land-types. However, some environments have no well-adapted pasture legumes. The evaluation site network has recently been exploited to develop legumes for frost-prone areas on light-textured soils and clay soils in the monsoonal zone. A Queensland government regeneration and characterisation program has also prioritised the development of legumes for the seasonally dry and moderate rainfall zones to enable access to seeds and plant traits to breeders both in Australia and overseas.

Challenges faced by north Australian beef producers to manage their feedbase

The production of beef cattle is the dominant primary industry and land use in northern Australia. The total Australian cattle herd was 29.9 M head in June 2023, with over half in the 'North' (44.5% in Queensland and 6.4% in the Northern Territory) (Meat and Livestock Australia 2024). Most of the lower rainfall sub-coastal and inland zones comprise native grasslands within extensive savannah woodlands (*Bothriochloa, Dichanthium, Heteropogon*) and naturally treeless (*Astrebla*) plains (Tothill and Gillies, 1992). The northern range of this zone is characterised by a 7-9 month dry-season, and businesses mostly target feeder steer and live export markets. Key profit drivers in the northern dry zone are breeder productivity (weaning and death rates) and heavier sale weights (McLean et al., 2014). Cattle production further south in central and southern Queensland and extending into northern New South Wales is supported by a greater proportion of sown tropical grass (*Cenchrus, Chloris*) pastures on previously cleared woodland. This is the principal area of beef production in northern Australia, where a more even rainfall distribution combined with many relatively fertile soils enables additional marketing options including backgrounding cattle for slaughter.

Limitations to cattle production on native and grass pastures relate to the amount and quality of feed produced over the year. In the northern monsoonal zone, the short summer growing period results in a few months of high quality feed before native grasses seed, senesce and become dormant. This presents the greatest challenge to graziers seeking to raise young cattle over the dry season and maintain reproductive females (Rolfe et al 2016). Management of the dry-season 'feed gap' is exacerbated by a significant decline in land condition on many soils within the seasonally dry zone (Shaw et al. 2024). This includes declines in useful perennial grasses and increases in herbaceous and woody weeds, resulting in decreased sustainable carrying capacities. The productivity of sown grass pastures is compromised by a decline in nitrogen cycling which limits grass growth. This limits both the productivity of the grazing business and the capacity to sequester carbon within the pasture system, an emerging consideration for beef producers. Peck et al. (2011) tested a range of methods to overcome this problem in southern and central Queensland and concluded the adoption of legumes as the best long-term economic solution. A recent challenge to graziers using sown grasses has been damage or death of plants due to 'pasture dieback', a condition associated with mealy bugs and which can significantly affect profitability at a beef business level (Buck et al. 2022). Legumes seem unaffected, so can potentially act as a temporary source of feed and competition for weeds while grass pastures recover. Finally, the omnipresent trend in increasing temperatures and recently measured increases in rainfall and temperature anomalies (CSIRO, 2024), all which can influence pasture growth in extensive grazing systems, presents a new and perhaps greatest challenge to beef graziers managing their feed-base.

Historical development of pasture legumes using the Australian Tropical Forages Collection (pre-2000s)

The use of legumes to lift the productivity of grass pastures through nitrogen fixation and improving the quality of the ruminant diet is well understood and has been applied for over 150 years throughout the world. The development of sown grass pastures in northern Australia was initiated by acclimatisation societies and individuals, including a small number of legumes (Clements and Henzell, 2010). However, it was not until federal and state programs from the 1960s, championed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), that development began *en masse*. Targeted plant collecting trips were conducted for promising taxa, with most legumes originating from south and central America. Seeds of up to 29,000 accessions were held by CSIRO in the Australian Tropical Forages Collection (ATFC) by the 1990s (Hacker et al, 1997). Refer to Smith *et al*. (2021) for a detailed description of the development of the ATFC.

Seed increase and plant evaluation programs were conducted by federal and state government agencies from the 1960s to the mid-1990s. Co-funded by the Beef Industry, the well-resourced and world-leading evaluation programs targeted a wide range of land-types with a particular focus on Queensland and the Northern Territory. Some involved assessment of a wide range of grasses and legumes across land types (Pengelley and Staples 1996), while others targeted legume development (Bishop and Hilder 2005; Clem and Jones 1996). Tropical pasture plant development was highly successful and supported by an effective pasture seed industry. By 1997 72 tropical grass and 65 tropical legume cultivars had been released in Australia, mostly in Queensland (Hacker et al., 1997), with approximately 220 t of legume seed (half stylos for light textured soils) being produced in Queensland (Walker and Weston 1990). There were still major gaps, however, particularly on clay soils where *Desmanthus* spp. and *Stylosanthes seabrana* cultivars had recently been developed (Walker et al. 1997).

Disinvestment in tropical sown pastures research from the 2000s saw the dismantling of research teams and reduction of the ATFC to priority taxa for development in Australia before transfer to the Queensland Government. The tropical forages database (www.tropicalforages.info) was developed to preserve 50 years of data and experience from international teams (Cook et al. 2020). A range of methods were used to progress promising international legume cultivars, but only one species (S. guianensis) has some application to the seasonally dry tropics (Cox 2014). A review of seed viability and stocks found approximately 25% of the collection required regeneration (Lawrence 2002). A Queensland Government regeneration program in north Queensland regenerated 380 grass and 609 legume accessions over 3.5 years from 2005 (Cox et al 2009).

New legume development using the Australian Pastures Genebank
Uncertainty over the funding of genetic resources to support forage and pasture development resulted in the formation of the Australian Pastures Genebank (APG) in 2014, an amalgamation of 11 genebanks from across the country (Hughes et al 2017). The APG includes ~10100 warm season grasses and ~7350 legumes selected by an expert panel as having potential for development in Australia. The regeneration program resumed in 2014. Priority was placed on legumes for seasonally dry areas, multi-purpose legumes and high-quality grasses (Cox and Dayes 2019). The new program better accounted for genetic diversity within accessions and 170 grasses and 318 legumes were regenerated over 4 years. Traits useful for plant breeders were measured and the data transferred to a public access website for breeders to assess and request seeds for evaluation (https://pir.sa.gov.au/research/services/australian_pastures_genebank).

A specialist panel review and meta-analysis of 40 years of plant evaluation data (persistence and herbage yield) covering 950 species across 567 sites collected was used to identify priorities for future sown pastures development in northern Australia (Bell et al. 2015). The analyses identified large potential for legume adoption broadly to improve beef productivity and profitability across northern Australia. Priority areas for investment in new legumes for the dry zone included legumes for sandy soils in cooler (frost prone) areas of the subtropics and legumes for clay (grey and black) soils in northern areas. The ATFC contains a wide range of legume taxa with application to the dry zones of the tropics and sub-tropics (Table 1). The accessions represent a wide range of growing environments so have the potential to address current and emerging needs.

The operation of the APG continued in 2023 under a new funding arrangement facilitated by Meat and Livestock Australia. The regeneration and characterisation program resumed, with a focus on legume taxa for the dry zones of northern Australia (Table 1). The 2024 regeneration included 40 *Desmanthus* accessions identified (APG website) by James Cook University (JCU) researchers. Expanded plots were grown to supply seed for evaluation over the next few years (in addition to the 5000 seeds for the APG), principally on heavy clay soils in the seasonally dry zone. This complements recent activities (Queensland Government/Tropical Dairy) in north Queensland to assess 17 *Vigna parkeri* APG accessions (entire collection) for herbage and seed production performance to improve supply to beef and dairy farmers (Gorman 2021), plus progressing the development of *Macroptilium atropurpureum, M. gracile* and *Centrosema brasilianum* accessions (one of each) considered by researchers to have application for the seasonally dry tropics (Cox *pers. comm.* 2024).

Table 1. Number of APG accessions of key taxa with potential in the dry zones of the tropics and subtropics. Genera marked with * included in the 2024 Queensland Government regeneration program.

Taxon	Habit	Number	Key genera (in decreasing order of accessions in APG)
Alysicarpus	Herbaceous	311	*vaginalis*, rugossus*, monilifer*
Centrosema	Herbaceous	928	*molle*, pascuorum*, brasilianum*, schottii, pubescens**
Chamaecrista	Herbaceous	155	*rotundifolia*
Clitoria	Herbaceous	157	*ternatea**
Desmanthus	Shrub	490	*virgatus*, leptophyllus+, bicornutus*, pernambucanus*, pubescens**
Leucaena	Small tree	627	*leucocephala*, hybrid
Macroptilium	Herbaceous	691	*atropurpureum*, lathyroides*, bracteatum*, gracile**
Stylosanthes	Shrub	2050	*scabra*, hamata*, guianensis*, viscosa*, seabrana*

Developing new cultivars using old plant evaluation sites

The historical plant evaluation activities saw the establishment of a large network of sites over some 40+ years, particularly in Queensland. Records of many of these sites, the plants sown and plant performance data are held in the Queensland Government QPastures database. Although active work at these sites has been long completed and fences removed, the sites provide an opportunity to identify material originally sourced from the ATFC which has persisted under grazing over decades. Used in combination with data from the various final reports and scientific papers and senior researcher experience, this can be used to identify new legumes where there are perceived shortages. Critically, this addresses the need for long term assessment of pasture plants to identify those persistent under long-term climate cycles (droughts), changes in soil fertility and the capacity to coexist with pasture grasses. Two recent examples include:

Desmanthus* spp. *for heavy clay soils in the tropics

Desmanthus is a diverse genus of sub-shrubs and shrubs, many originating from dry areas on clay soils in central and southern America, and a large collection was introduced from the 1950s (Smith et al, 2021). Plant evaluation included six sites established in the 1980s across the semi-arid, cracking clay region of north and western Queensland. JCU researchers revisited the sites and collected seeds of the best survivors at sites in the Mitchell Grass Downs Bioregion (Gardiner et al 2016). Queensland Government seed increase and further plant evaluation was conducted on these, and other, accessions from other abandoned sites (Gardiner et al. 2017). Further development and selection resulted in the release of 'Progardes', a blend of *D. bicornutus, D. leptophyllus* and *D. virgatus* accessions with a range of growth habits and flowering times. Another five lines were selected and similarly commercialised, including high-biomass types better suited to higher rainfall areas. There are currently reliable supplies of commercial seed and adoption has steadily increased since release.

Stylosanthes for cold (frost-prone) areas within the sub-tropics and tropics

Pasture legumes are sought to address pasture productivity decline associated with nitrogen rundown but there are no reliable options for light-textured soils in the frost-prone sub-tropics (Peck et al. 2011). Observations by pasture researchers that legumes, mostly stylos, were persisting in old evaluation sites in frost-prone areas of southern Queensland resulted in a Queensland Government-Beef Industry program to collect, test and release new stylo varieties (Peck et al. 2022). Forty lines, mostly *Stylosanthes scabra* and *S. seabrana*, were collected and seed increase conducted in north Queensland before field testing over 3 years against current cultivars on two soil types in three frost-prone districts. The capacity to produce commercially viable amounts of seeds and susceptibility to diseases of historical significance (*Colletotrichum* spp.) was assessed at this time. Three *S. seabrana* and two *S. scabra* lines which out-yielded commercial legume varieties were identified for release and seed increase undertaken to progress commercialisation. Although the stylo lines have immediate application to frost prone areas in the dry sub-tropics, stylo persistence is also poor on productive alluvial soils in the tropics where cold air is concentrated along waterways (Cox pers. comm. 2024), and the new stylos might therefore have broader application.

Conclusions

The legacy of fifty years of (mostly) government investment in sown pastures in northern Australia presents on-going opportunities to develop new pasture plants for the dryer zone of northern Australia. Decades-old plantings of thousands of accessions of pasture legumes across land types can yield useful cultivars but only while records are maintained and there are pasture researchers to exploit them. Similarly, the APG contains a wealth of useful germplasm collected from a wide range of environments for developing new pasture legumes to address current productivity gaps and respond to emerging needs such as climate adaptation. Current funding and regeneration and characterisation programs are focussed on ensuring these resources are accessible for plant breeding programs.

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Poster presentations – Theme 7

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Suitability of biomass from riparian areas of the Noteć River Valley for renewable energy production

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Key words: biomass; IFBB technology; renewable energy; riparian areas; storable biofuel

Abstract

In the Wielkopolskie region (western-central Poland), the largest protected area under the Natura 2000 network is located along the Noteć River Valley. The problem of these riparian areas is lack of utilisation and abandonment of grass communities. The production of storable biofuel from harvested biomass using the IFBB (Integrated generation of solid Fuel and Biogas from Biomass) technology of such communities should be a suitable strategy for conservation and maintenance of semi-natural grassland in this region. Analysis of natural conditions and harvesting tests showed that the middle and lower parts of the Noteć River Valley – an area of 770–790 km^2 covering the 180 km-long and 2–13 km-wide floodplain – are the most appropriate areas for the implementation of the IFBB technology. The dominant species were *Phalaris arundinacea*, *Carex acutiformis* and *Carex gracilis*. The briquettes from this biomass after IFBB processing had a high heating value (on average 17.54 MJ/kg) and high level of combustion. The concentration of nitrogen in the biomass was very low, on average 1.23% in DM. The biomass after IFBB processing had a low level of ash in comparison to typical grassland used for forage purposes. The average yield of harvested grass communities was ca. 5 t DM/ha. A plant in Osów village was proposed for applying the IFBB technology in the Noteć River Valley. This was considered profitable with an Internal Rate of Return of 11.05%. Economies of scale apply since, with an IFBB plant of that size, investment costs disproportionately decrease relative to the large amount of output (grass briquettes, power). Cash flow calculations show a positive result from Year 1. With an annuity of 68.814 €/annum, the entrepreneurial risk of investing in a new technology such as IFBB might not be covered entirely. However, potentially reducing investment costs – e.g. by making use of regional investment subsidy programmes for investments in new renewable energy technologies – should make this investment attractive.

Introduction

Floodplain grass communities are frequently characterised as high-nature-value areas and, furthermore, fulfil various ecological services (Verhoeven & Setter 2010). Considering flood protection, they play an important role as riparian areas to reduce the risk of flooding by increasing the infiltration capacity. In addition, the year-round plant cover minimises soil erosion and loss of nutrients. However, the management of these grass- and/or rangeland sites is comparatively challenging due to particular soil conditions and, in many cases, the low nutritive value of the vegetation. Hence, these areas are becoming increasingly abandoned in many European regions. Many farmers managing these grass communities are looking to diversify their activities. Therefore, agri-environmental programmes have been established that are focused on protection of endangered bird species, habitats and natural sites. Farmers receive financial support for fulfilment of special management of these grass communities. One of the main conditions is late harvest time – typically in the middle of July or beginning of August. Because the harvested biomass can be used for bioenergy purposes, we evaluated the quantity and quality of the biomass from selected grass communities.

The aim of the study was to analyse the suitability of biomass from riparian areas of Noteć River Valley for renewable energy production in the form of storable biofuel using the IFBB technology.

Methods

The study was carried out in the years 2014–2016. We focused on the Noteć River Valley (Wielkopolska region, western-central Poland), where the largest riparian grass- and/or rangeland sites are located. This area contains high-nature-value riparian semi-natural grasslands and rangelands that are included in the European network Natura 2000 as areas of special bird and habitat protection. The area is a second largest peatland in Poland. It is a part of one of the most important ecological corridors between the Odra and Vistula Rivers and a refuge for wild birds at a European scale. For possible use of those areas towards their conservation and maintenance, we analysed the suitability of biomass for renewable energy production using the IFBB (Integrated generation of solid Fuel and Biogas from Biomass) technology (Wachendorf et al. 2009, Blumenstein et al. 2012). Preliminary analysis of natural conditions and harvesting tests showed that the best potential for the IFBB technology was in the middle and lower parts of the Noteć River Valley from Nakło nad Notecią town in the east to Santok village in the west, an area of 770–790 km^2 covering the 180 km-long and 2–13 km-wide floodplain. The botanical composition using the phytosociological method and the yield (quadrat frame method) of harvested biomass from 20 grass communities located in the valley were estimated and samples of biomass for chemical analyses were collected. In the samples, the crude protein (XP), NDF, ADF and ash (XA) using commonly accepted methods were determined. The economic calculations were based on the annuity method according to the guidelines for economy calculation systems for capital goods and plants (VDI 2002). The annuity displays the average yearly net operating result as calculated over the life span of 20 years. If the annuity is > 0, the investment is profitable. The Internal Rate of Return (IRR) is a key profitability measure. If the IRR exceeds the target rate, the investment is profitable.

Results

A majority of the vegetation was classified as *Arrhenatherion*, *Calthion* and *Filipendulion* as well as *Phragmition* and *Magnocaricion* alliances. The dominant species in the sward of the grass communities were *Phalaris arundinacea*, *Carex acutiformis* and *Carex gracilis*. The average yield of harvested grass communities was ca. 5 t DM/ha with huge deviation depending on site and type of plant vegetation. Therefore, the technical production potential for the IFBB technology was estimated to be on the level of 316.5 thousand tons.

In Table 1, the results (average values) of chemical composition of biomass after ensiling and after hydrothermal conditioning from raw materials harvested in the Noteć River Valley are presented. It turned out that the biomass after IFBB processing (press cake) had a low level of ash in comparison to typical grassland used for forage purposes. In particular, the most detrimental minerals Cl, K, N and S were leached into the press fluid resulting in concentrations in the press cake, which were for K and S close to wood from beech including bark. The concentration of nitrogen in the biomass was very low, on average 1.23% in DM. In general, the analysed biomass is a promising substrate for solid fuel (briquette or pellet) produced in the IFBB technology. The briquettes from this biomass after IFBB processing had a high heating value (on average 17.54 MJ/kg) and high level of combustion.

Table 1. Chemical composition of biomass before (silage) and after (press cake) hydrothermal conditioning from raw materials harvested in the Noteć River Valley

Parameter	Biomass silage	Press cake from IFBB	Difference (%)
Dry matter (%)	39.5	31.7	-20
Ash (g/kg DM)	72.2	35.4	-51
N (g/kg DM)	12.3	7.0	-43
Cl (g/kg DM)	6.1	0.8	-87
S (g/kg DM)	2.8	0.9	-68
K (g/kg DM)	8.2	1.1	-87
Ca (g/kg DM)	11.7	4.1	-65
Mg (g/kg DM)	2.4	0.5	-79
P (g/kg DM)	1.8	0.4	-78
Na (g/kg DM)	0.8	0.4	-50

A plant in Osów village (52°49′04″N 15°48′03″E) in the Drezdenko Commune was proposed by the research team for applying the IFBB technology in Noteć River Valley. Assuming that the average distance between the harvesting site and the potential plant location is 15 km, more than 1000 ha of extensive grassland and rangeland are available for bioenergy production. The average size of a riparian grass community plot is 100 ha per single site. Harvesting in many cases takes place after 1 August, due to agri-environmental schemes, mainly 'Protection of endangered bird species and natural habitats in Natura 2000 areas'. For this reason, harvesting is done once a year. There are possibilities to deliver biomass from Noteć River Valley located further away from the biogas plant by river transport, which could create an additional advantage concerning sustainability of a locally feasible processing mode.

After many analyses and much research, the best solution suitable for Noteć River Valley was identified as the IFBB technology as an add-on option (conventional biogas plant with IFBB module). The two main products of the IFBB technology are solid fuel (briquette or pellet) and electricity from biogas. Electricity from cogenerated biogas combustion is used to provide energy for the installation. Surpluses of electric energy could be sold through the Polish Power Grid Company, manager of the public grid network. Solid fuel could be offered in retail locally, but the main target market should be the wholesale one for large combined heat and power (CHP) operators.

Considering an average yield of 5 t DM/ha and an extensive grassland and rangeland area of 1000 ha, a total of 5000 t DM biomass are provided (or approximately 16,100 t FM, respectively), available for energy generation with the IFBB process. Based on the substrate available, a total of 4686 t (85% dry matter) of grass briquettes for heating purposes are produced per year. All of these can be sold, since the internal heat demand of 4,882,835 kWh_{therm} per annum is more than covered by the adjacent biogas plant, which provides approximately 6.3 Mio. kWh_{therm} per annum. In addition, about 1.35 Mio. kWh_{el} per annum electricity are generated from the IFBB press fluids by the CHP of the biogas plant. The proposed IFBB add-on plant in Osów can be considered profitable under the given circumstances. The IRR of 11.05% is close to being considered appropriate regarding the volume of investment. Here, economies of scale apply since, with an IFBB plant of that size, investment costs disproportionately decrease related to the large amount of output (grass briquettes, power). Cash flow calculations show a positive result from Year 1 on. With an annuity of 68,814 €/annum, the entrepreneurial risk of investing in a new technology such as IFBB might not be covered entirely. However, potentially reducing investment costs – e.g. by making use of regional investment subsidy programmes for investments in new renewable energy technologies – should make this investment attractive.

Discussion

Riparian areas of Noteć River Valley in western Poland are high-nature-value areas, mainly in terms of biodiversity. The semi-natural grasslands and rangelands are mostly covered by Natura 2000 network and included in agri-environmental schemes. In a previous study, we already indicated that, because of late cutting, the harvested biomass is fibre-rich and can be used for bioenergy production (Goliński & Goliński 2013). The study of Wachendorf et al. (2009) and other authors shows that the IFBB technology helps to improve the process of bioenergy conversion from riparian grassland biomass.

Biomass obtained from riparian areas of Noteć River Valley is a potential feedstock for renewable energy production. As reported by Hensgen et al. (2012), technical and environmental limitations exist in using this biomass for combustion, due to the presence of harmful elements. Converting biomass using the IFBB technology produces a press cake with lower concentrations of harmful elements and a press fluid usable for biogas generation. The concentration of harmful elements such as N, S, Cl and K in the solid fuel was significantly reduced compared to the original biomass silage. Comparatively high heating value (on average 17.54 MJ/kg) of received briquettes indicates a high performance of this material for combustion. This result was similar to the findings presented by Blumenstein et al. (2012) and Bühle et al. (2014).

The proposed IFBB add-on plant in Osów, Poland, can be considered profitable with an IRR of 11.05% under the given circumstances considered in the investment plan. Economies of scale apply, since with an IFBB plant of that size, investment costs disproportionately decrease relative to the large amount of output (grass briquettes, power). Cash flow calculations show a positive result from Year 1. It can be concluded that the production of storable biofuel from biomass harvested from riparian areas of Noteć River Valley using the IFBB technology should be a suitable strategy for conservation and maintenance of semi-natural grassland and/or rangeland in this region and other central European floodplains.

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The territorial land planning in consideration of natural belt and zones' features

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Key words: natural belt; zone; territory; development plan

Abstract

The study shows possibilities to improve land quality by researching ways to implement proper policy of protecting and using land that is suitable to the features of the local land by carefully integrating it into the soum[13] development plan using participatory approach. The study looked into the causes of land degradation beyond the overuse of land carrying capacity, improper land use activities and climate change that has become evident in almost all the natural belt and zones in Mongolia.

The study includes nationwide collection of data on natural zones and belts and transferring it into a digital mapping system. The database provides key meanings of the factors affecting the natural zones, individual features and characteristics of each zone. The livelihood activities of the local people residing in these areas, and the use of the land, the types of existing land use of these areas were identified as well as forms of land uses in these zones and belts.

We discovered that the land is currently used for 130 different types purposes. It is evident that as the purpose and types of land use increase natural yield, service and capacity are decreasing. Thus, a rational plan that includes the appropriate type of land use in line with the features of the natural zones and belts in which it locates is necessary. By allowing the forms of land use in consideration of features of zones and belts of Mongolia, our study shows that we can keep the negative impacts of excess use of land, overgrazing, and degradation of the land at minimum as well as avoiding any reduction in the natural yields.

Introduction

In the recent years, the negative impact like degradation and overuse of land carrying capacity has become evident in almost all the natural belt and zones in Mongolia due to the improper activities of land use and climate change. Therefore, it is absolutely necessary to develop a rational plan suitable to the features of natural belt and zones in order to reduce the negative impact. As the purpose and types of land use increase natural yield, service and capacity are decreasing. Thus, it shows that it is possible to improve land quality by researching ways to implement proper policy of protecting and using land that is suitable to the features of the local land. One of such possible

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[13] Small administrative unit of a province.

ways is developing soum development plan based on the local land resources and the participation of the local residents.

Methods

In the study we have use the methodology outlined in the soum territorial development plan, approved by the order no.A/139 (2019) of the Head of ALAGAC, which proposes a holistic approach that consists of 3 main parts: (i) analysis on the condition and resources of nature, (ii) socioeconomic data relevant to the whole territory of the soum and the types of land use, and (iii) creation of database and processing the data. A study on natural resources and conditions is done based on the 11 core data types, that is topographic, climatic, demographic, geological and hydrological data, and data on above-ground natural resources, flora and fauna, soil, and forestry. Socioeconomic study is conducted using data on demography, employment status, and information pertaining to economic growth like animal husbandry, agriculture, light industry, service industry, and mining.

Based on the principles of development, that is ecologically sustainable, environmentally friendly, economically beneficial, and various suitable solutions of land use types, the secondary information was compared with the primary data, which is collected from the total of 16,450 local residents representing different zones – 1,560 residents from high mountain zone, 878 from mountain taiga zone, 8,710 from forest steppe zone, 4,560 from steppe zone and 2,302 from Gobi zones.

Results

The tendency of dividing Mongolian territory into zones and belts was practiced by scholars in their respective field of studies, namely Yunatov.A.A, 1968; Tsegmid.Sh, 1962; Avaadorj.D, 2003; and Dash.B, 2005. They have divided the Mongolian territory into natural zones based on the characteristics: the amount of heat decreases due to the reduction of solar radiation that forms the climate in the Northern hemisphere; natural conditions are different in each latitude; temperature and humidity regimes; air flow characteristics; unique surface conditions; elevation; and composition of flora and fauna in differentiating one area from another.

Such natural zone information is collected nationwide and transferred into the digital mapping system. The database provides key meanings of the factors affecting the natural zones as well as the individual features and characteristics of each zone. We have determined the mapping of the natural zones based on these information and database.

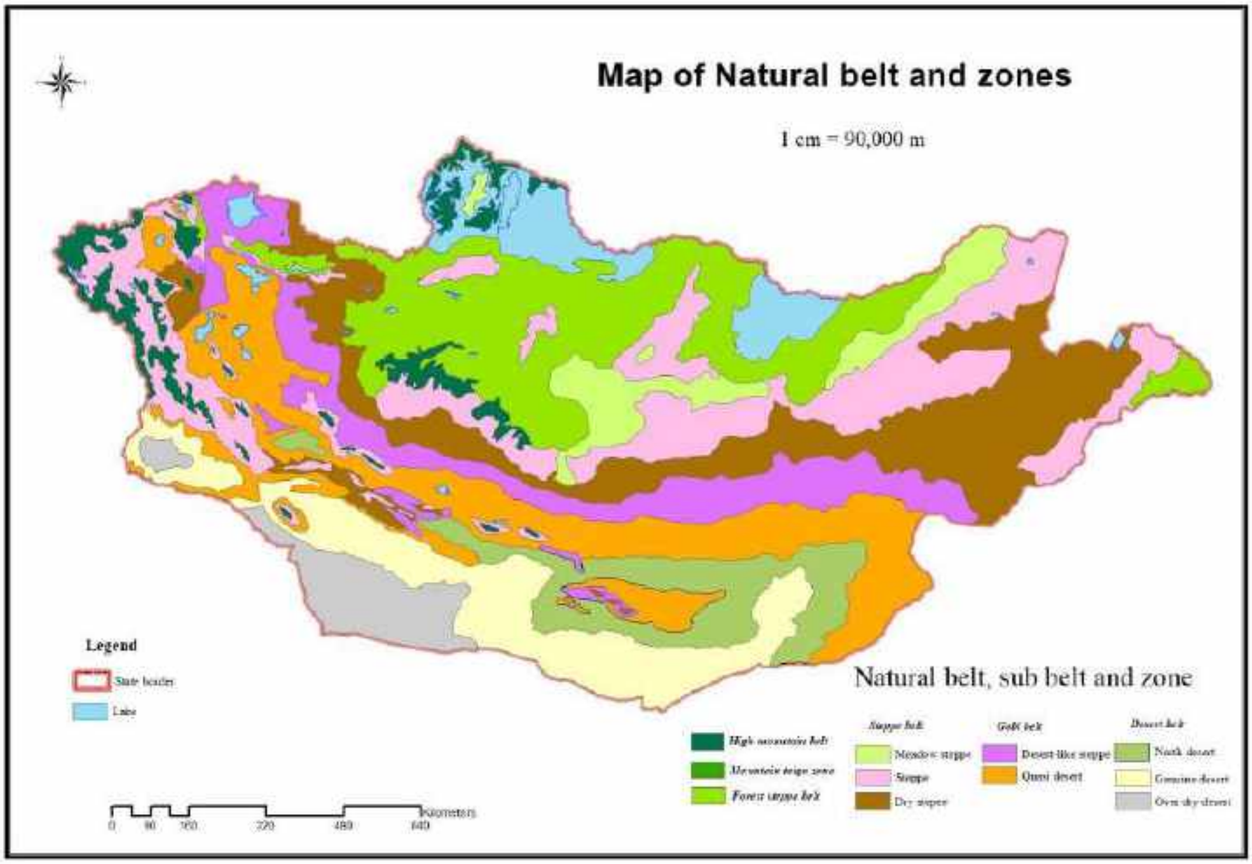

Figure 1. Map of Natural Belt and Zones of Mongolia

When mapping and determining the area covered by natural zones and belts in Mongolia with appropriate factors, high mountain belt that is 3.6 percent or 5,711,628.3 hectares that is the lowest, mountain taiga zone 4.3% or 6,725,556.7 ha, forest steppe 15.1% or 23,813,912.9 ha, and great steppe zone is 34.3% or 59,979,158.7 ha, the highest land covering zone. From that, 22.8% or 35,980,610.5 ha is Gobi zone, 19.0% or 30,082,860.1 ha is desert zone.

Upon determining the features of the area, livelihood activities of the local people residing in these areas, and the use of the land, the types of existing land use of these areas were identified as well as forms of land uses in these zones and belts.

According to the land use types in these zones, currently the land is used for 130 different types purposes. At minimum in the high mountain zones land is used for about 60 different purposes, and at maximum in the forest steppe zones the land is used for about 130 different types of purposes and are included in the territorial land use planning. The study result indicates that there are 60 types of land use in the desert zone, 70 in gobi zone, 80 in high mountain zone, 90 in mountain taiga zone, 110 in steppe zone, and 130 in forest steppe zone.

Therefore, when developing land use planning, first it needs to be defined in which zone the soum territory belongs to and determine the most appropriate uses suitable to the features of the zones and belts.

Discussion

There are total of 130 different forms of land use in the country. Soum development plan shall be developed based on the features of these belts and natural zones to which it belongs to. For example, Bayangol soum of Selenge province belongs to the forest steppe zone, and there are 20 planning measures included for the soum. Out of that, 5 forms of land protection measures, 8 forms of measures of proper land usage, 5 measures for proper usage and protection of land, and 2 measures of rehabilitation of land.

The result of the study shows that the forms of land use in consideration of features of zones and belts of Mongolia have the minimum impact on soum land use. The key here is to have appropriate development plan considering the natural zones and belts and the features of the area and implement it thoroughly.

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Transitioning meat goat production systems in western NSW - Learnings from the Going Ahead with Goats project

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Key words: Meat Goats; Rangelands; Extension Program

Abstract

Historically, meat goats were considered a niche industry in Australia. However, goats are now viewed as a viable addition to livestock production systems in western New South Wales (NSW) rangelands, providing valuable income diversification. In the 2021-22 financial year, Australian goat exports were valued at $298.6 million, with 55% of these goats produced in western NSW. The sector saw rapid growth following an 83% goat carcass price rise between 2018 and 2019, prompting landholders to invest in infrastructure and genetics, transitioning from opportunistic harvesting of rangeland goats to managed production systems. The Going Ahead with Goats (GAWG) project commenced in 2022, facilitating this transition by providing targeted extension support to landholders and the broader industry. Through extensive consultation with industry, the project delivers a suite of research, development, and extension activities aimed at improving the sustainability, productivity and profitability of the meat goat industry. The GAWG project combines traditional extension methods of knowledge dissemination such as producer groups, workshops, and field days with innovative digital platforms, including podcasts, video case studies and online discussion groups. To create landholder engagement and enhance on-farm decision-making, the project integrates advanced agricultural technologies, including satellite tracking tags, GPS collars, and satellite pasture monitoring systems, capturing real-time data on managed goat production. Despite adoption barriers such as market volatility, limited infrastructure and capacity to implement controlled mating programs, as well as labour shortages, the GAWG project has seen significant industry engagement, with over 65 western NSW goat businesses involved. These businesses are either transitioning to managed goat production enterprises or have identified an intent to transition, as well as adopt recommended management practices including; resting pastures, rotational grazing, weaning, infrastructure improvements and genetic selection decisions. This transition to managed goat production enables landholders to include goats in their overall grazing strategy, incorporating landscape management objectives such as recruitment of perennial pasture species and the control of invasive native scrub.

Introduction

Unmanaged rangeland goats are a common feature of western NSW landscapes, originating from a combination of dairy and Angora goats that were either released or escaped from domestication and have survived in a wild state for decades (Hacker and Alemseged 2013). Approximately 90% of goats slaughtered annually in Australia are rangeland goats, with Australia being the largest exporter of goat meat globally, valued at $298.6 million in the 2021-22 financial year (Meat and Livestock Australia 2024). Historically, the sale of goats from rangeland properties has been seen as an opportunistic enterprise to supplement alternative income streams, relying on harvesting unmanaged goats through self-mustering trap yards as well as land-based and aerial mustering (Robertson et al. 2020). The opportunistic harvest of goats is heavily dependent on seasonal conditions, population density, sale price and processor capacity, leading to limited continuity of supply. The low labour requirements of goats in comparison to Merino sheep and the ability of goats to survive on diets containing high browse and shrub contents have seen goats increase in popularity in western NSW rangelands (Hacker and Alemseged 2013). However, inadequate fencing and handling infrastructure as well as a lack of knowledge and skills associated with goat management have limited the development of managed meat goat enterprises in NSW rangelands.

The Australian goat industry experienced a major transition following an 83% Over The Hook (OTH) carcass price rise from 2018 to 2019, with goat export carcass prices exceeding lamb and mutton prices from 2019 to 2022 (Meat and Livestock Australia 2024). Many producers used cashflow from goat sales to invest in fencing, watering point and yard infrastructure improvements enabling the management of goats, contributing to an estimated 82% increase in managed goat production from 2015-16 to 2020-21 (Meat and Livestock Australia 2023). Significant investments were also made in purchasing Boer and Kalahari meat goat genetics to improve growth rates. There is currently a spectrum of managed goat enterprises in western NSW, from producers who have one securely fenced goat paddock that is being used to hold goats and grow out smaller harvested goats, through to multiple paddocks and managed breeding programs (Robertson et al. 2020). The management of goats allows for greater control over total grazing pressure and more predictable turnover and forecasting of goat sales. The GAWG project, delivered by Western Local Land Services, is a three-year extension program that aims to support and upskill goat producers in western NSW (40% of the state, covering 314,500 km²) and enhance the goat industry more broadly through a suite of research, development and extension activities.

Extension Methodology

The methodology used for the GAWG project incorporates multiple extension activities in combination with the creation of accessible digital resources. Extension activities were designed to be regionally specific and use a whole-of-systems approach, delivering information that meets the needs and interests of producers and stakeholders in the western NSW rangelands. Prior to the delivery of educational activities, project staff undertook industry consultation activities including one-on-one interactions, group discussion sessions and a literature review to identify knowledge gaps and areas of interest for future research, development and adoption activities. Extension activities used in this project include the formation of two producer groups, promoting ongoing peer-to-peer learning, as well as workshops and field days for the broader goat industry. In addition, a core component of the extension project has included on-farm agricultural demonstrations and data collection including the use of Ceres Tags, GPS tracking collars, satellite pasture monitoring technologies and electronic eartags (eID tags) for individual animal data collection. Digital resource creation was another key aspect of the project, creating legacy documents in readily accessible formats including podcasts and video case studies.

Project Outcomes

Two goat producer groups comprising of 20 businesses were formed, which meet quarterly to partake in customised workshops and engage in peer-to-peer learning. These producers currently have managed goat enterprises or have identified an intent to transition to managed goat enterprises, and are seeking to improve their knowledge and skills, with approximately 150,000 goats managed across these businesses. Knowledge and experience levels vary in these groups, with a combination of producers who have been managing goats for less than 3 years, to over 25 years. Producer group members identified and ranked their top three categorised topics and areas of interest for further learning as part of the GAWG project. There was a mix of responses (Table 1) with the top three topics being labour saving technologies and goat infrastructure, genetic improvements and goat nutrition. This trend was also shared with wider industry when assessed by one-on-one producer consultations, provided direction for extension activities and resource creation.

Table 1. Ranking of topics of interest for further knowledge and skills development amongst western NSW goat producers.

Western NSW Goat industry producer topic of interest	Ranking (1 = Highest, 6 = Lowest)
Labour saving technologies and goat infrastructure	1
Genetic selection and improvement	2
Goat nutrition and supplementation	3
Marketing and sales	4
Pastures, species identification and feed budgeting	5
Goat health and disease	6

The GAWG project has also supported several industry research and data collection projects in collaboration with producer group members to further increase goat production data in western NSW including genetics, growth rates, grazing behaviours of goats and management factors affecting reproductive outcomes in goats. In addition to producer group events, broader goat production field days and workshops have been run across western NSW, including; goat infrastructure tours, along with workshops focusing on drone mustering, genetics, marketing options, as well as business, pasture and herd management. Ten podcast episodes were produced, focused on; genetic selection, target markets, pasture management, transition to managed goat production and weaning. Several episodes captured methods of "re-domesticating" harvested rangeland does to establish a core breeding herd, including segregating offspring by age and sex, and increased movement of animals to new paddocks and watering points to control grazing distribution and educate animals. Video case studies and resources created include goat infrastructure and trapping, as well as performing condition score and udder assessments on goats. To date, podcast episodes have received a total of 1600 downloads and two video case studies have received over 70000 views. There have been over 275 attendees at 20 events across western NSW, highlighting the significant ongoing interest in meat goat production in rangeland environments. Producers have identified an intent to change management practices including; spelling pastures, rotational grazing, weaning, infrastructure improvements, genetic selection decisions, as well as gastrointestinal worm control. Factors influencing intent to change and adoption of management practices presented at workshops include; inability to control mating regimes, limited infrastructure and number of goat paddocks and limited confidence in price and knowledge of target markets.

Project Challenges

Designing and delivering an extension program for an emerging industry transitioning to more managed production systems has highlighted several ongoing industry challenges. Some of these have been overcome through the project, with other challenges requiring further research and development. Firstly, extension programs for developed livestock industries including sheep, beef and dairy sectors focus on the adoption of demonstrated best management practices (BMPs) supported by relevant literature and research (Nelson and Robinson 2009; Bell 2019). While there are now several multi-year goat research projects being undertaken in the genetics, methane and reproduction space in Australia, there is currently very little scientific data on many aspects of goat production in Australian rangelands (Hacker and Alemseged 2013; Alemseged and Atkinson 2015). Hence, there is a reliance on information from international studies, often with exotic breeds in vastly different production systems. Thus, providing specific herd management advice based on peer reviewed literature and evaluated BMPs has been challenging in this extension project, with reliance on anecdotal evidence and small field trial data for some aspects of goat production in Australian rangelands. The depth of experience within the goat producer groups has been a major benefit, with early innovators and adopters of managed goat practices being able to share their experiences and observations of managed goats in rangeland environments. However, these experiences and observations sometimes contrast between producers. To create a complete BMP framework for goat production in Australian rangelands, further research and economic evaluations are needed for management practices such as weaning, sex separation, castration, as well as joining time and age to validate the anecdotal evidence of production benefits.

Controlled mating programs have been demonstrated as a key tool to optimise stocking rate, sales timing and manage pasture demands (Reeve and Sharkey 1980). A major limitation to the transition and further management of goats highlighted throughout the GAWG project is the difficulty in implementing controlled mating programs. This is due to multiple factors including the incursion of unmanaged rangeland goats disrupting breeding programs and slowing genetic progress, combined with maiden does reaching sexual maturity as young as 5 months of age, resulting in year-round kidding (Robertson et al. 2020). In addition, continuous mating adds challenges to timing of livestock movements and resting pastures, as well as performing business benchmarking due, to constantly changing livestock inventories and difficulties in calculating cost of production. Additional fencing improvements are needed for many properties to have greater livestock control.

A further challenge identified during the project was a lack of clarity on the ideal carcass specification requirements and the ideal breed composition, weight and sex of goats at a processor level, with limited feedback on goat consignments, consistent with the findings of Tesse et al (2023). Some producers were hesitant to introduce meat goat breeds into their managed rangeland goat herds due to reservations of potentially being penalised for breed composition in future, despite most processor carcass grids only including carcass weight as price differentiation criteria. Part of the GAWG project involved interviewing processors and sharing their ideal carcass specifications with producers to overcome this barrier to adoption. Further research is still needed into the effects of breed composition on yield and meat quality attributes.

Moreover, industry confidence associated with short term market price, which went from the highest average OTH price on record in Australia prior to the commencement of the project to the lowest average OTH price on record since prior to 2003 (Meat and Livestock Australia 2024b), was another challenge identified during the project. Several producers who had begun to transition from opportunistic harvest systems to managed goat production systems began to question their decisions and look into alternative livestock enterprises that suited existing infrastructure improvements such as Dorper sheep. Explaining the factors that influenced this price shift as well as delivering data on comparative long term average enterprise profitability was a key part of maintaining project engagement from these participants.

Learnings from the Going Ahead with Goats Project

There have been several key learnings through the delivery of the GAWG project. These include:

1. Drawing on the knowledge and experience of early adopters and innovators in the industry is critical when there is limited relevant production data. However, these experiences and observations can often be conflicting and require further validation through production research and economic evaluation.
2. Agricultural technologies and on-farm data collection has been a useful median for ongoing and real time engagement with project activities, as well as the delivery of extension messages.
3. There is the capacity for a number of new research projects in the goat industry, particularly in the nutrition space, as well as economic analysis of best practice goat management methods.
4. Short term market price is a limiter to extension program engagement and adoption of new practices for emerging industries. Many participants in the project began infrastructure improvements to run more managed goats during periods of high prices. These investments have slowed and stalled in some cases with participants focusing their time on alternative enterprises that are perceived to be more profitable or spending more time pursuing off-farm employment as an alternative income stream.
5. Barriers to adoption are enterprise specific. The transition from harvested goat production to managed goat production systems has its own unique set of challenges, with infrastructure limitations, labour and property scale remaining as ongoing challenges.

In summary, the GAWG project has identified and delivered a range of extension events to meet the needs of producers transitioning from harvested rangeland production systems to managed production systems, as well as assisted producers who are currently managing goats. This extension project has faced some unique industry challenges with several key learnings. On-ground, locally relevant information and data collection have enabled ongoing industry engagement. With further research, coupled with the experiences and knowledge of early adopters and innovators within the industry, the goat industry is set to continue to advance into the future.

Acknowledgements

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Land systems, soils and vegetation survey of the southern Goldfields and Great Western Woodlands of Western Australia

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Key words: Ecology; Erosion; Geomorphology; Habitat; Soil science; Nature markets

Abstract

The southern Goldfields region is ecologically significant as it closely aligns with the Great Western Woodlands– the world's largest intact Mediterranean-climate woodland ecosystem, dominated by *Eucalyptus* species and encompassing diverse mosaics of woodlands, mallee, shrubland, and grassland. The region has been subjected to significant ecological perturbations since European colonisation. Despite multiple land-use pressures on a unique environment, the region is the last large area in Western Australia (WA) to be comprehensively surveyed for biophysical resource condition to promote sustainable use.

This survey presents a comprehensive assessment of the biophysical environment of WA's southern Goldfields region, covering 151,753 km². The survey maps land systems and refines soil-landscape zones at 1:250,000 scale. The accompanying report describes the geomorphology, soils and vegetation, offering new insights and revisions to existing physiographic data.

The survey advances prior studies by refining mapping in alignment with WA and national standards, thereby providing consistency in data presentation and analysis across regional and national scales and complementing the Interim Biogeographic Regionalisation for Australia. This survey's integration into WA's hierarchical soil-landscape mapping system enables data describing the southern Goldfields to be interpreted within broader regional, statewide, and national contexts. Key contributions are:

- complete biophysical mapping that meets national and state standards
- a multidisciplinary explanation of key aspects of landscape evolution
- revised physiographic mapping that reveals patterns of erosion, deposition, and landscape maturity
- defining 101 land systems and 88 habitat types that summarise key elements of landform, geology, geomorphology, soil and vegetation characteristics.

The survey's hierarchical mapping framework and associated biophysical information provides comprehensive baseline data and improves understanding of the region's ecological processes and environmental pressures. It thus constitutes a valuable resource for agencies, companies, and individuals involved in strategic land-use planning,

land management, monitoring, conservation and rehabilitation, and the sustainable use of rangeland habitats across the southern Goldfields region.

Introduction

The southern Goldfields region of Western Australia (WA) is ecologically significant as it closely aligns with the Great Western Woodlands–the world's largest intact Mediterranean-climate woodland ecosystem, dominated by *Eucalyptus* species and encompassing diverse mosaics of woodlands, mallee, shrubland, and grassland (Watson et al. 2008). The vegetation evolved over the Cenozoic from rainforest with a significant proteaceous element to become increasingly scleromorphic and then xeromorphic as southern WA aridified from the Late Miocene to present. The long history of isolation in a progressively drying climate resulted in a megadiverse vegetation suite adapted to fire (Martin 2006).

Prior to European colonisation the area was populated by indigenous inhabitants who used fire in patchwork mosaics to secure food and manage the vegetation and landscapes. Since then, the region has been subjected to significant ecological perturbations. Early European settlers extracted sandalwood. Gold was discovered in the region in the 1890's. Mining required structural wood and firewood to power steam engines for transport and water supply. Extensive areas were temporarily cleared for wood production until the late 1960's, and the wood-fired steam power increased the incidence of wildfire from ember strike. The combination of both pressures changed structural characteristics of vegetation. Pastoralism, based initially on wool production and more recently on cattle and opportunistic harvesting of feral species, has skewed vegetation composition by the preferential grazing habits of introduced herbivores. This highly mineralised region has extensive open pit mining and mineral exploration, because it contains world class deposits of gold, nickel, lithium and iron ore. Both mining and pastoralism require access, and the vehicular track network affects overland water flows, affecting vegetation growth and altering geomorphic processes (Raiter et al. 2018).

Since the 1950's, rangeland areas of WA have been progressively surveyed to document resources, identify condition, and promote sustainable use. Despite multiple land-use pressures on a unique environment, this southern Goldfields region is the penultimate WA pastoral area to be surveyed, with the final area still pending.

This communication summarises key findings of a recently completed comprehensive assessment of the biophysical environment of the southern Goldfields region. The survey covers 151,753 km² and extends from latitude 30°00'S to 33°00'S and from longitude 118°00'E to 124°00'E. The survey maps the region's land systems and characterises the geomorphology, soils and vegetation, offering new insights and revisions to existing physiographic data. This survey, together with adjacent rangeland surveys (see 'Methods' chapter in Waddell and Galloway 2023), provides mapping at a land system scale of 1:250,000. Together these surveys describe the biophysical features of the Great Western Woodlands, except their southernmost extremities.

The bulletin and accompanying land systems maps provide a reference for land managers, advisers and administrators, the people most involved in planning and implementing land management practices. They also provide a baseline reference on landscape resources of the region. Land system surveys also enable recognition and location of land systems and landforms with particular habitat or conservation values for land use planning.

The survey advances prior studies by refining vegetation, soil, and physiographic mapping in alignment with WA and national standards, thereby providing consistency in data presentation and analysis across regional and national scales and complementing the Interim Biogeographic Regionalisation for Australia. This survey's integration into the State's hierarchical soil-landscape mapping system enables data describing the southern Goldfields to be interpreted within broader regional, statewide, and national contexts (Schoknecht et al 2004). A notable contribution is the revision of physiographic descriptions and soil-landscape zones of Tille (2006). These zones are based on geological and geomorphic criteria that reveal patterns of erosion, deposition, and landscape maturity, facilitating understanding of the region's evolution and environmental processes.

Accompanying the land system map is a report in two volumes. The climate chapter provides a synopsis of past and present climates with reference to the vegetation and geomorphic evolution. The landscape evolution chapter describes the region's geology, relevant tectonic processes and geomorphology, then discusses how the landforms formed and are distributed. These chapters contextualise evolution of landscape and vegetation.

The remaining chapters detail the region's biophysical features relating to soils, vegetation and ecology, and land systems. They provide information on landforms, soil and vegetation and, used in conjunction with the maps, provide a comprehensive description of biophysical resources. Included within these chapters are references to the impacts of certain management practices on the soils and vegetation, which are directed towards land managers to provide general information to assist in land use planning.

Methods

A detailed description of the methods and the types of data collected during the survey is provided in the 'Methods' chapter in Waddell and Galloway (2023).

Results

Our investigations at 606 inventory sites sampled during the survey and data from another 57 inventory sites from previous work in the area augmented knowledge of the region's biophysical features. Using this data, we were able to assimilate our comprehensive literature review of the geology (petrology and tectonics), geomorphology, and paleoclimate to interpret the landscape in an interdisciplinary manner.

At inventory sites we identified 69 WA Soil Groups and 88 habitat types. This great diversity reflects the complexity and diversity of the landscapes and vegetation associations present. The 88 habitat types, being combinations of landforms, soil types and plant communities, were clustered into 13 broader groups to aggregate ecologically similar types in topographically comparable positions. Forty-nine habitat types were described for the first time.

We identified 101 land systems in the survey area: 62 are described for the first time and the other 39 were previously described in adjacent surveys. The descriptions of some land systems identified in the adjacent rangeland surveys were modified to account for vegetation changes associated with the southerly transition from the Great Victoria Desert, Murchison, Nullarbor and Yalgoo bioregions into the Coolgardie bioregion.

We grouped the land systems into soil-landscape zones defined by geomorphologic or geological criteria, suitable for regional perspectives. Where existing physiographic mapping was inadequate (see discussion in Tille 2006), we identified and mapped 4 new zones and modified 6 others using the 'bottom-up' hierarchical approach of Schoknecht et al. (2004). We described zones using a combination of Pain et al. (2011), Tille (2006) and new information from this survey. Our new physiographic zones correlate to all prior mapping.

Discussion

The addition of the southern Goldfields rangeland survey to the long-running program of describing WA's rangeland biophysical features, with accompanying land system and zone mapping, has many benefits. Primarily this is through detailed information on landforms, soil and vegetation with references to the impacts of certain land use practices on the soils, surface hydrology and vegetation.

Implications for unified data

Inventory site data, land system maps and descriptions of their unmapped components meet State and National standards (and is the first WA Rangeland survey to do so). The data can be transferred to the publicly available

Australian National Soil Information System, and it therefore contributes to current and future research efforts to improve the resolution of soil, physiographic and other environmental mapping using 'big data'. A particularly promising research use for the baseline data generated during this survey is the estimation of carbon stocks for better modelling of global carbon storage to assess greenhouse induced climate cascades.

Adhering to standards enabled correlation of the southern Goldfields maps to soil-landscape maps of the adjoining agricultural region and existing mapping for the rest of WA (Schoknecht et al. 2004; Tille 2006). Such correlation simplifies the generation of derivative land suitability, land capability and land degradation maps that are seamless and comparable across WA's agricultural and southern Goldfields areas. These derivative products are invaluable for the land use and management implications described below.

The hierarchical nature and standardisation of our mapping permits application across scales for regional and property perspectives. The land zone mapping provides the spatial context for our explanations of regional scale geomorphic features that are present due to the interlinked evolutionary history of geology, paleoclimate, vegetation, weathering, erosion and deposition, and tectonic processes at continental, regional and local scales.

Implications for land use

Information curated enables government to administer pastoral leases and prevent or minimise land degradation. In WA, the Valuer General's Office sets pastoral lease annual rental charges based on potential carrying capacities. Carrying capacity figures derive from land system mapping in conjunction with habitat type analysis. Baseline information from rangeland survey informs rangeland assessment staff about the resource condition of habitats, enabling them to report on land degradation on pastoral leases and administer actions under the Soil and Land Conservation Act (1945; Waddell et al. 2023).

Some areas within the pastoral estate may be suited to alternative land uses. The ability to apply standard land evaluation criteria permits a regional scale 'first pass' mapping that allows a like-for-like comparison, even across diverse land uses. For example, maps could be created to identify areas best suited to sandalwood re-establishment, native animal re-introductions, or potential water supply.

Though assessments of vegetation condition are primarily relevant to a pastoral context, evaluation of community composition and physiognomy is determined in intact, ungrazed states (where possible), so they do not preclude condition assessment from an ecological context and are useful in determining (or as surrogates for determining) conservation value of vegetation and habitat (Pringle and Tinley 2001; Brandis 2008), state and transition modelling, status of carbon stocks and identifying the potential for carbon sequestration in rangeland landscapes (Williams et al. 2023).

The survey identified areas subjected to increased land use pressure. A pertinent example is the identification of stressed vegetation surrounding a gold roasting plant. Soil characterisation at an affected inventory site identified an acidic soil profile under vegetation that traditionally inhabits alkaline soil types. In other respects, the soil had morphological characteristics of the alkaline soil. The regional nature of the survey precluded a detailed study, but it identifies a potential problem and provides the basis for future research. Elsewhere a common observation was where tracks and fencelines disrupt natural water flow, altering moisture levels across the landscapes. Some areas pond water while others are water-starved and contribute to degradation.

The survey identified vegetation suites that indicate a change in state to lower production. Some locations affected by historic overgrazing have undergone a step-change in ecological state due to altered species composition, soil loss or both stressors combined. The introduction of non-native herbivores has resulted in some areas becoming degraded with reduced vegetation cover, decreased species diversity, encroachment by unpalatable perennial shrubs, weed proliferation and erosion. The condition of some habitats preferred for grazing has declined – the extent of palatable species has been reduced or totally lost. Survey data provides a baseline description of habitats facilitating the strategic location of monitoring sites (Pringle et al. 2006), restoration strategies (Tinley and Pringle 2014), and mapping supports the placement of infrastructure (e.g. tracks, fencing, watering points) and facilitate weed control programs to economically target priorities.

The inclusion of the land zone hierarchy in our southern Goldfields mapping provided a spatial context for our explanations of regional geomorphology, which enhanced our explanations of general distribution of ecological communities, plants and soil characteristics. These broad geomorphic patterns are responsible for environmental processes that exert a significant influence on all land uses. While the aspects of landscape evolution discussed are provided with evidence, where possible, the paucity of paleo-information means some ideas remain speculative and are ripe for further study. We hope the new information and mapping presented will assist and support management strategies and future management of the southern Goldfields region.

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Grazing-induced impacts on woody regeneration of palatable and unpalatable species for carbon sequestration

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Key words: grazing management, trees and shrubs, carbon farming

Abstract

Australian rangelands are currently contributing to climate mitigation through nature-based solutions which include land management changes to facilitate forest [14]growth. Currently, >42 million ha of rangelands are being incentivised through the Australian Carbon Credit Unit Scheme to promote native woody forest regeneration through adoption of new grazing management regimes and removal of past suppression activities which have prevented the establishment of forest cover. These activities include the management of domestic animals by controlling the frequency, timing and intensity of grazing; control of feral animals; cessation of clearing activities; management of fire; and changes to infrastructure which allow enhanced control of grazing pressure to achieve native forest regeneration. The legitimacy of grazing management to influence woody regeneration in these arid and semi-arid environments has recently been challenged, sparking debate over the use of grazing management as a credible land management activity to underpin carbon market mechanisms.

Contrasting palatable *Acacia aneura* (mulga) and unpalatable *Eremophila sturtii* (turpentine) species are used to illustrate how grazing management activities can influence opportunities for recruitment, establishment and growth. Key biological features are identified for each species and used to guide reported or expected responses to grazing management interventions and influence the temporal patterns of carbon accumulation either directly or indirectly. The importance of initial landscape conditions to support the preconditions for grazing management to influence rates of regeneration as well as land management skills and capacity are identified as potentially important factors in determining successful use of grazing management in native forest regeneration.

Introduction

Australian rangelands are currently contributing to climate mitigation through land management which includes facilitation of forest[1] growth. Currently, >42 million ha of rangelands are being incentivised through the Australian

[14] An area of at least 0.2 hectares, dominated by trees and shrubs that are at least 2 m tall and provide crown cover of at least 20% (Australian Government 2024)

Carbon Credit Unit Scheme. Across many projects, these land managers are undertaking native forest regeneration by removing past forest suppression activities under the Human-induced Regeneration (HIR) method. Grazing land management activities include the management of domestic livestock to control the frequency, timing and intensity of grazing, control of feral animals, cessation of clearing activities, management of fire and changes to infrastructure which allow enhanced control of grazing pressure to achieve native forest regeneration.

Criticisms challenging the ability for grazing management to influence woody regeneration are largely based on studies of woody plant encroachment. Here, over-grazing which persistently removes grasses, alters the competitive balance between trees and grass in favour of woody regeneration. This has led to conclusions that reduction or removal of herbivores will not result in increased woody regeneration or an increase in tree/shrub growth (Eldridge and Sala 2023). However, a recent study employing remote sensing showed that long-term removal of livestock does increase woody biomass, albeit small changes over long timeframes (Retallack *et al.* 2024). Other remotely sensed approaches examining more adaptive grazing management strategies have shown variation in ground cover response across multiple sites (McDonald et al. 2024). This variation in findings highlights the complexities associated with heterogeneous rangeland landscapes and management histories which may lead to complex local site characteristics providing multiple barriers, and drivers, to regeneration.

There are few studies which have directly examined the influences of grazing management on woody regeneration in the context of carbon farming. However, the circumstances under which grazing management can influence patterns of woody regeneration has been recently reviewed (Waters et al. 2025). Here, the primary driver of regeneration was identified as climate, with grazing playing a moderating role enabling the potential regeneration set by rainfall to be achieved. Further, a set of broad, evidence-based grazing principles were developed within a framework that considered three critical stages in regeneration (site condition, germination and establishment and growth and mortality) based on the biological characteristics of widely studied, palatable woody species mulga (*Acacia aneura*). Here, we compare the responses of *A. aneura* (palatable) outlined in Waters et al. 2025) with *Eremophila sturtii* (unpalatable) and predict how grazing management regime (removal of all herbivores, manipulation of herbivore type and management of grazing intensity) may influence regeneration outcomes, outlining the importance of understanding local landscape and socio-economic factors which may modify responses.

Grazing management activities

Unpalatable species are unlikely to be directly influenced by grazing unless alternative feed is unavailable during extremely dry conditions or when safe carrying capacity of livestock and/or total grazing pressure is exceeded for a protracted period (Figure 1). For both palatable and unpalatable species, grazing management may also indirectly influence regeneration by moderating the incidence of fire which will be particularly important for fire sensitive species.

Figure 1. Impact on unpalatable species, *Acacia sclerosperma* with a clear browse line (left) and browse line and re-sprouting *Eremophila mitchelli* (right) following dry periods and little alternative forage availability.

Under all management regimes, and at all growth stages, maintaining adequate levels of ground cover is a central management outcome (Table 1). It is likely to be important in creating enhanced seedbed conditions for germination and establishment by improving landscape function through the retention of resources (water and nutrients). In the case of turpentine (*E. sturtii*), disturbance from grazing may enhance seedling germination (Robson 1995, Table 1). In the context of a carbon project, and given the infrequent rainfall driven opportunities to initiate a germination event, management aimed at enhancing seedbed would be most beneficial early in a HIR project, not just to set the trajectory of long-term plant community dynamics, but to ensure forest cover is achieved within 15 years of project commencement as required under the HIR method. Maintaining landscape function is also likely to be important later in the project to mitigate occurrence of hard setting, more compacted soils, reduced soil nutrient status/biological activities which have been reported under dense woody growth (e.g. Tighe et al. 2009). Improved landscape function can be achieved through total grazing pressure management which increases perennial ground cover through fencing and/or waterpoint management (Waters et al. 2019).

What is less clear is whether the removal of all herbivores (destocking) will constrain or increase rates of woody regeneration and result in the occurrence of high stem density cohorts. In this situation, the ability to manipulate competition between perennial grasses and seedling growth during germination and establishment phases will have been removed. A lack of herbivory may limit the capacity to achieve maximum attainable carbon carrying capacity by creating high stem density vegetation patches which may slow rates of woody biomass accumulation compared to more open vegetation (Waters et al. 2017, Table 1). Finally, a lack of herbivory may also reduce the ability to manage fuel loads and wildfires which can reduce or preserve accumulated biomass. While destocking may be an option for conservation land use, maintaining pastoral land use as well as the delivery of carbon sequestration has been shown to benefit pastoral enterprises and regional communities (Baumber et al. 2020). The management of herbivore type and grazing intensity will create opportunities for multi-use, integrated landscapes. Here, focusing on woody regeneration at the germination and establishment stages to incorporate periods of rest to promote recovery from grazing (controlling forage utilization and retaining ground cover) will enable seedlings to achieve heights above browse height (1.2 to 1.5 m) for palatable species.

Waters et al. (2025) outline the importance of land manager capacity (knowledge, skills and resources) in effective implementation of grazing management. However, local landscape features such as terrain will influence the stability of infrastructure in managing total grazing pressure. Drainage channels pose a risk of fence breaches in high rainfall events. Examples of alternative practices include fence alignment to high terrain, avoiding watercourses, adoption of low impact earth works, or minimising disruptions to natural movement to soil surface hydrology from linear surface disturbances such as vehicle tracks, fence line clearing and animal pads (Pringle 2019).

Conclusions

In areas where management can improve land condition for seedbed enhancement (soil condition and water availability), management has been shown to indirectly influence regeneration (Waters et al. 2025). In those areas, management aimed at improving site condition and germination appears critical for both palatable and unpalatable species. It is proposed that ensuring that pasture utilization does not negatively impact establishment and growth stages of unpalatable species during periods of protracted drought and limited forage availability is critical.

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Table 1. The potential influence of different grazing regimes on site condition and growth stages of woody regeneration for palatable and unpalatable species. [1.] References within Waters et al. 2025.

Growth stage	Palatable species (mulga, *Acacia aneura*)[1.]	Unpalatable species (turpentine, *Eremophila sturtii*)
Removal of all herbivores		
Site condition	Maintain or improve levels of perennial ground cover and improve landscape function. Increased ground cover, soil water infiltration, nutrient retention potential to create ideal seedbed conditions.	Seedling germination enhanced with soil disturbance such as blade ploughing (Robson 1995); Maintain or improve levels of perennial ground cover and improve landscape function. Increased ground cover, soil water infiltration, nutrient retention potential to create ideal seedbed conditions.
Germination & Establishment	May remove the ability to manipulate competition between perennial grasses and seedling growth which may result in slower rates of regeneration.	Greater seedling emergence occurs under high shrub densities (approx. 32 to 6% higher) compared to open landscapes (Booth et al. 1996).
Growth & mortality	Areas of high stem density cohorts may limit capacity to achieve maximum attainable carbon carrying capacity.	Areas of high stem density cohorts may limit capacity to achieve maximum attainable carbon carrying capacity. (Waters et al. 2017).
Manipulation of herbivore type		
Site condition	Management of total grazing pressure plays a critical role in maintaining or restoring landscape function through maintaining or improvement of ground cover.	Management of total grazing pressure plays a critical role in maintaining or restoring landscape function through maintaining or improvement of ground cover (Hacker, McDonald 2021).
Germination & Establishment	Sheep, Dorpers and goats may prevent recruitment directly through herbivory. Under deteriorating seasonal conditions and lack of alternative available forage, kangaroos as well as sheep, Dorpers and goats may impact germination and recruitment. Cattle less likely to impact regenerating Mulga.	Sheep and goats will not reduce establishment unless extremely heavy goat grazing pressure (Harrington 1979). Under protracted drought, when alternative forage unavailable Dorpers and goats may impact seedling establishment.
Growth & mortality	Sheep, Dorpers and goats can prevent growth (density and height). Cattle are less likely to impact regenerating mulga, Kangaroos little impact on mature trees.	Sheep, Dorpers, goats and cattle are unlikely to impact growth (density and height) of mature turpentine unless under extreme grazing pressure by goats or when feed demand outweighs feed supply (little alternative available forage) during periods of drought.
Managing grazing intensity		
Site condition	Management of total grazing pressure plays a critical role in maintaining or restoring landscape function through maintaining or improvement of ground cover.	Management of total grazing pressure plays a critical role in maintaining or restoring landscape function through maintaining or improvement of ground cover (Hacker, McDonald 2021)
Germination & Establishment	Direct impact of herbivory from sheep, Dorpers and goats may result in higher levels of seedling mortality. Overgrazing will reduce seedling growth rates and expose cohorts to a greater susceptibility to drought, potentially amplifying mortality events.	Regulate the level of competition between perennial grasses and seedlings in the first summer after germination to increase regeneration (Waters et al. 2025)
Growth & mortality	Direct impact of herbivory from cattle, sheep, Dorpers and goats may result in reducing plant height as well as removal of branches above browse height, lowering potential carbon accumulation. This may be amplified when alternative forage unavailable.	Sheep, Dorpers, goats and cattle are very unlikely to directly impact growth (density and height) of mature Turpentine unless under extreme grazing pressure by goats or when feed demand outweighs feed supply (little alternative available forage) during periods of drought.

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HOSTED SESSIONS

Strategies and tools to navigate global change in non-equilibrium rangelands

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Non-equilibrium then and now

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Key words: climate change, equilibrium, precision ranching, state-and-transition models

Abstract

Non-equilibrium is a fundamental characteristic of rangelands and pastoralism. The non-equilibrium (NE) paradigm emerged primarily in response to problems in management, especially in the context of pastoral development. Aiming their arguments at the World Bank and other multilateral organizations, anthropologists and development professionals demonstrated that the use of equilibrium ideas – such as climax to evaluate range conditions, carrying capacities to set stocking rates, and succession to remedy degradation – had backfired repeatedly. Such shortcomings were familiar in the scientific community, but an alternative paradigm remained elusive until after the 2nd International Rangeland Congress in Adelaide in 1984. Following seminal publications on the topic (Ellis and Swift 1988; Westoby et al. 1989; Behnke et al. 1993), the NE paradigm was widely analyzed, debated, and largely adopted by global scholars, especially for drier, more variable rangelands (Illius and O'Connor 1999; Vetter 2005). Tools reflecting NE, such as state-and-transition models and satellite-based assessments of rangeland productivity, are now widely produced (Allred et al. 2022, Bestelmeyer et al. 2017). Widespread acceptance among scientists has not translated readily into the practices of pastoral development, however. In this paper we reflect on how the NE paradigm has shaped global rangeland management and governance over the past 30 years. Are rangeland systems better managed because of it? What are the prospects for the NE paradigm to support adaptation to global change in rangelands in the years ahead? We argue that while debates about NE concepts have faded into the background, the implications of NE are more important than ever.

Introduction: Is rangeland management better because of NE concepts?

In contrast to the equilibrium paradigm, the NE paradigm posited that 1) rangeland condition is determined primarily by abiotic drivers and non-linear (or threshold) responses to those drivers, 2) rangelands exist as alternative stable states best described by state-and-transition models rather than simple succession models, and 3) the high degree of spatial and interannual variability in rangelands requires careful attention to pastoralist mobility and flexibility, alongside governance structures that ensure access to land at needed spatial extents (Scoones 1995). NE characteristics are especially relevant to the most arid, variable, and extensive rangelands (von Wehrden et al. 2012) which have been least likely to be converted to cropland or intensified pasture systems.

While many organizations now advocate for pastoralism and mobility to conserve imperiled rangelands, and technology is providing increasingly effective solutions for perceiving and reacting to NE rangeland behavior, policies continue to limit pastoralists' ability to implement those solutions. Pejorative narratives about pastoralism and limited societal valuation of extensive rangelands continue to drive policy prescriptions irrespective of the scientific advances (Davis 2016). Especially in the Global South, governments are pressured to convert land and livestock into financial opportunities and reliable revenue streams by connecting rangelands with urban and international markets. Exclusive land tenure, capital investments (e.g., in livestock breeds), consistent output, and optimized rates of return-on-investment are viewed as necessary to meet these goals. In short, the core management requirements of NE – flexibility, mobility, and reciprocity at multiple scales – suffer not from a lack of scientific support but from incompatibility with neoliberal globalization.

Pastoralists continue to experience political and economic marginalization, compromised management autonomy, diminished access to land, and sedentarization (UNCCD 2024), reducing the spatial scale and sustainability of livestock management. With powerful outside interests seeking to appropriate land and water resources for more lucrative land uses, policies and development efforts often reduce options for livestock movements and flexibility by encouraging the conversion of rangeland to cropland to increase economic returns, afforestation to 'restore' ecosystem functions, and intensification/modernization of livestock production (via fencing, wells, and harvested forages) to increase production efficiency (Nori and Scoones 2023). And as climate change advances, the variability of precipitation on rangelands is increasing (Sloat et al. 2018). The complications associated with NE are expanding and intensifying with losses in forage productivity, amplified abiotic extremes, and widening scalar mismatches in rangeland administration. Thus, NE is becoming both more relevant and more challenging than ever.

Prospects for improved application of the NE paradigm

For practical, management purposes, the core challenge of NE is the combination of spatio-temporal variability and unpredictability. Technological advances now allow pastoralists and policymakers to perceive and react to NE in ways that were unimaginable decades ago. First, the recognition of NE behavior in rangelands catalyzed the global development of state-and-transition models (STMs) that emphasize the potential for threshold responses in different rangeland types (Bestelmeyer et al. 2017). These models provide indicators and, more importantly, have expanded the mental models of managers to include the possibility of abrupt and persistent changes in natural resources. Operationally, STMs have guided grazing strategies and the selection of restoration practices that account for spatial heterogeneity in resilience due to climate, soils, and history, and the role of climatic variability. Where STM-based thinking has been adopted, managers are more attuned to variability, risk, and opportunity (Knapp et al. 2011).

Second, the fusion of satellite-based remote sensing, standardized databases of ground-based measurements, and user-friendly web and mobile applications has produced a revolution in information about rangeland conditions (Allred et al. 2022). A manager can now detect short-term changes and long-term trends in vegetation at the scale of patches that are a few hundred square meters in size and across thousands of hectares. While this technology is recent and most advanced in the United States, progress is underway in rangelands across the world and is improving rapidly with the use of artificial intelligence.

Third, sensor technologies under the umbrella term of 'precision ranching' are also becoming more effective and attainable, including Global Positioning Systems (GPS)-based tracking collars, water-level sensors, and automated rain gauges (Spiegal et al. 2024). These sensors allow managers to track variable resource conditions and animal movements (particularly in the Global North where herding is seldom practiced; McIntosh et al. 2022). Virtual fencing combines GPS with stimuli on collars that control livestock movements. Thus, virtual fencing allows for adaptive rotational grazing and rest that does not depend on expensive physical infrastructure and fixed pasture locations and dimensions. When combined with remote sensing-based production maps and analytics, GPS collars and virtual fencing can allow grazing pressure to adapt to NE behavior of rangelands (Bestelmeyer et al. 2024).

Conclusion

NE calls for flexible access to land, variable output (including wide swings in herd sizes), traditional ecological knowledge and bottom-up decision making to cope with inherent uncertainty (Scoones 1995). How do we overcome the policy barriers to supporting NE rangeland social-ecological systems, with assistance from technological advances? In practical terms, this question remains open and will be addressed by participants in our symposium. Several approaches, however, will be essential. First, rangeland and pastoralist advocates need to reinforce the broad societal benefits of rangeland social-ecological systems and their right to exist. Society and policymakers should treat the loss of rangelands with the same sense of urgency that they treat the loss of wilderness and forests. Second, development strategies should be designed from a deep understanding of local context, communities, and livelihoods (Allington et al. 2024). Third, policies should reflect careful consideration of the heterogeneity, connectivity, and scale needed to preserve those livelihoods and the natural resources on which they depend, taking advantage of technology. Carefully crafted socio-technical solutions may at last harness the insights of NE thinking to improve rangeland sustainability and pastoral livelihoods.

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Developing and maintaining productive and profitable pastures in the tropics and subtropics of Queensland, Australia

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2025 situational analysis of pasture dieback in eastern Australia

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Key words: Pasture dieback; Eastern Australia; Tropical grasses

Abstract

Pasture dieback affects millions of hectares of highly productive grazing land in eastern Australia, specifically north, central and south-eastern Queensland, and north-eastern New South Wales. The impact to grazing industries, including beef, dairy and sheep, is significant. Improved (or sown) tropical and sub-tropical grass species are predominately affected; very few native grasses are impacted. Affected plants initially exhibit leaf discolouration, which culminates in a mosaic of patches of dead grass across a pasture. Temperate grasses and broadleaf plants including annual and perennial legumes are not affected.

Dieback has occurred previously in tropical pastures across Queensland. A large dieback event happened in central Queensland during the 1990s and a much smaller and shorter event occurred in the mid-1920s in south-eastern Queensland. The leading cause of the current situation is the pasture mealybug bug (*Heliococcus summervillei*), whereas the cause of the 1990s event remains unknown despite research at that time. This indicates potential for a disease complex. Dieback has also been recently reported in tropical pastures across multiple south American countries where varied causes have been purported.

The Department of Primary Industries (DPI) initiated research activities into this condition in 2015 which included: characterising symptom progression, factors affecting disease occurrence, diagnostic pathology, and management options for affected areas. This research has been complimented by similar activities undertaken by other organisations. Research activities were accompanied by an industry engagement program including peer-to-peer learning activities such as group workshops and field days; and published resources including online and print factsheets, articles, videos, podcasts and social media posts. All are available in an online hub (www.futurebeef.com.au/resources/pasture-dieback/).

Background to Pasture Dieback

Pasture dieback is a condition killing productive tropical and sub-tropical pasture grasses in grazed and non-grazed situations. Improved (or sown) grass species are affected, whereas very few native grasses are impacted and temperate grasses and broadleaf plants including legumes are unaffected (Buck 2017; DPI 2024). Currently, pasture dieback is affecting millions of hectares of pastures (AgForce 2021; DPI 2024) resulting in significant productivity impacts to beef, dairy and sheep industries. The concern for pastoralists and agricultural industries is pasture dieback affects the most productive pastures in moderate-high rainfall locations that support most of the beef and dairy cattle herd in Queensland.

Dieback has occurred previously in tropical pastures across Queensland. A large dieback event happened in central Queensland during the 1990s where buffel grass (*Cenchrus ciliaris* cvv. American and Gayndah) was predominantly affected (Graham and Conway 1998; Makiela and Harrower 2008). A much smaller, and shorter duration, event occurred in mid-1920s in south-eastern Queensland where paspalum grass (*Paspalum dilatatum*) was affected (Summerville 1928).

Pasture dieback is reported in other countries. A similar pasture condition was reported in multiple tropical and sub-tropical grasses in New Caledonia during 1998 (Brinon et al. 2004). In south American countries including Brazil, Argentina and Paraguay, pasture dieback has been affecting tropical grass species, namely Panic grasses (*Megathyrus* spp.) (Ribeiro-Junior et al. 2017; A. Radrizzani, pers. comm. 2018). Pathogenic soil fungi are implied in Brazil due to stress from waterlogging (Dias-Filho, 2006), whereas in Argentina or Paraguay there is uncertainty of the cause of dieback (A. Radrizzani pers. comm. 2018).

Where does pasture dieback occur in Australia?
Pasture dieback is currently affecting perennial sown grass pastures in eastern parts of southern, central and northern Queensland, and north-eastern New South Wales (Figure 1). Rainfall in these locations is summer dominated with average annual totals around or above 500mm. The total area affected by pasture dieback is difficult to estimate due to dieback spreading over time and the episodic nature of the condition.

The current outbreak of pasture dieback was first reported during 2014-15 in buffel grass (*Cenchrus ciliaris*) dominated pastures in the Dawson valley area of central Queensland, and in creeping bluegrass (*Bothriochloa insculpta*) dominated pastures in the north-western Burnett region (Buck 2017). Dieback was reported some years later in southern and northern Queensland. Pasture dieback was first reported in north-eastern New South Wales in 2020 and has continued to spread south and south-west (N. Jennings pers. comm.).

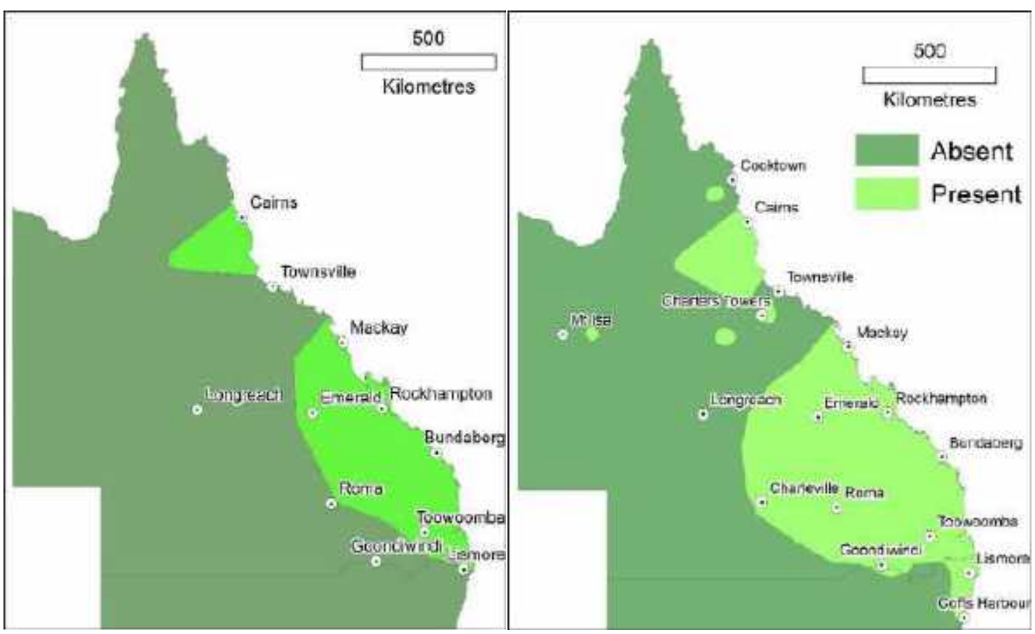

Fig. 1. Pasture dieback location (light green coloured areas). Left: observed 2021. Right: observed 2024.

What does pasture dieback look like?
Plants affected by pasture dieback typically occur in patches but larger areas or whole paddocks can be impacted. Pasture dieback can be challenging to identify. Diagnosis is easiest during the summer growing season where sick or dead patches are obvious amongst green healthy grass. However, similarities occur between dieback and other

plant disorders, for example water or nutrient stress, and so environmental conditions, landscape, soil and pasture management factors need to be considered prior to a positive diagnosis.

Affected plants progress through four stages. 1. Initial leaf discolouration. Depending on the species, leaves can turn yellow/orange, or a combination of red and yellow, or red/purple. 2. Whole plant discolouration, unthrifty growth and sick appearance. 3. Dead patches of grass plants that are characterised by a grey appearance and are easily uprooted. 4. Broadleaf plants colonising and growing in patches/whole paddocks of dead grass.

Fig. 2. Pasture dieback symptom progression. Photos left to right: Stages 1, 2, 3, 4.

What causes pasture dieback?
Over the last ten years, research has been undertaken by multiple organisations to determine the cause of pasture dieback. On-farm characterisation of affected paddocks and properties across Queensland was conducted by DPI between 2015 and 2020. Paddock observations and management, climatic conditions prior to noticing dieback, and other factors were investigated. While results demonstrated pasture dieback was more common in moderate-high yielding pastures, no factors consistently indicated a potential cause (Brazier and Buck 2021).

Research conducted since this time by DPI, Queensland University of Technology and University of Queensland, with financial support of the Australian government through Meat and Livestock Australia (MLA) Donor Company, demonstrate the cause of the current outbreak of dieback as the pasture mealybug (*Heliococcus summervillei)* (Buck et al. 2022; Hauxwell 2022). The pasture mealybug is a sap sucking insect that typically feeds on growing plants between spring and autumn. They over-winter below the ground or around the crown of the plant, under stubble/trash or manure pats and logs. Warmer than average winter night-time temperature and rainfall are potential pre-curser conditions for pasture mealybug populations the following summer (McKenna et al. 2024). Multiple other abiotic (e.g., soil nutrient and chemistry) and biotic (e.g., insects including ground pearl, and nematodes, fungi, viruses, bacteria) factors were also investigated including the potential of secondary infections killing the plant once the pasture mealybug compromises the plants natural defence mechanisms. While results indicate there are some interactions with these organisms, laboratory, glasshouse and field trials demonstrate the pasture mealybug as the main cause.

What can be done about pasture dieback?
There are three options to consider when dealing with pasture dieback, the first is whether dieback can be prevented. Currently there are no known methods to reliably prevent pasture dieback if the pasture contains susceptible grass(es) under conductive conditions with the pasture mealybug present in the local district. Conceivably, graziers could remove susceptible grasses and re-seed with more tolerant types prior to the potential infection. However, this is highly unlikely due to the cost, effort, and unwillingness to remove a healthy and productive pasture on the *potential* of infection. Due to dieback being more prevalent and severe in pastures with moderate-high biomass, another concept is to heavily graze the pasture prior to or when dieback is initially seen. Experience in commercially-grazed paddocks demonstrate this is an unreliable method. Also, there is high risk of significantly reducing pasture biomass which is needed to support stock during the subsequent dry season if sufficient follow-up rainfall does not occur. Appropriate use of biosecurity techniques such as controlling property access, careful movement of people and stock, and diligent farm hygiene (e.g., come clean, go clean) could reduce

the potential of initial infection and subsequent spread on-farm. However, graziers commonly report dieback initially occurring in pastures where stock or humans have not accessed for some time (months) indicating pasture dieback can spread through wind or other environmental factors. Ultimately, implementing biosecurity measures may only delay an inevitable occurrence.

The second option is to eradicate the pasture mealybug once the pasture is affected. Fire has been used in research trials and commercial situations with mixed results. Most graziers report dieback returns, suggesting a positive outcome is temporary at best. To eradicate the pasture mealybug with insecticides the land manager needs to first determine presence in a pasture. Plant damage and death is only caused by juveniles therefore control needs to occur before or at this lifecycle stage. However, finding juveniles without a hand-lens or magnifying glass is problematic due to their minute size. Further, gaining a thorough understanding of location across tens, or hundreds of hectares in some cases, is impractical. Other constraints occur regarding insecticide application: lack of registered products for tropical pastures in Queensland and New South Wales; cost of these, grazing withholding periods, and the impracticalities of application across extensive pastureland; inability to effectively kill all mealybugs with one spray; negative impacts on beneficial insects such as lady-beetles, lacewings and wasps. Due to these reasons the current recommendation is not to use fire or insecticides to eradicate the pasture mealybug.

The third option is to manage pasture dieback. Perennial pasture systems persist through regeneration of new plants from the soil-seedbank. Under dieback conditions, specific practices can assist this process: spraying broadleaf weeds if present in high numbers; regularly assessing pasture growth to match grazing periods to allow seedling survival. Managing for recovery is commonly how graziers are dealing with pasture dieback due to the low direct costs, and the cost, effort and outcome uncertainty of other options. However, risks include not knowing when the pasture will fully recover (may take longer than 12 months), and the potential for noxious weed incursions. For example, African love grass, Giant rats tail grass, or broadleaf weeds such as parthenium have colonised some areas affected by pasture dieback. Another method is through improving the pasture. Effective practices include renovating the paddock through cultivation, and or applying fertiliser. Planting an annual grain or forage crop to provide a disease break and produce short-term feed to transition from the old pasture into the new, is another. However, the most effective long-term option is to re-seed a new pasture with tolerant grasses and resistant perennial legumes and fertilise if required. While this mainly suits arable landscapes and graziers need to source the required machinery, productivity gains are substantial and the likelihood of pasture dieback fully impacting the new pasture into the future is low. Therefore, this option is currently recommended where feasible.

To summarise, Table 1 outlines current knowledge on options and responses to pasture dieback.

Table 1. Options for pasture dieback, likelihood of success, and management practices.

Option	Likelihood of success	Management practice(s)
Prevent	Unlikely	Biosecurity measures slow the spread at best
Eradicate	Unlikely	No insecticide registrations; variable outcomes from fire
Manage	Highly likely	Manage for recovery; or sow new pasture with tolerant grasses and resistant legumes suitable to situation, fertilise

Where to find more information?

Research activities undertaken by DPI are accompanied by industry engagement including peer-to-peer learning activities such as group workshops and field days, and published resources including on-line and print factsheets, articles, videos, podcasts and social media posts. All are available in an on-line hub at www.futurebeef.com.au/resources/pasture-dieback/. MLA also have on-line resources at www.mla.com.au.

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Legume production paddocks to improve beef enterprise productivity and grassland management

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Key words: tropical pastures; Queensland

Abstract

Weaner or steer production of tropical cattle breeds for feeder or live export markets is the dominant primary industry in the seasonally-dry zone of northern Australia. Uncleared savannah woodlands and natural grasslands are key feed resources, with smaller cleared areas used for pasture development or cropping. Extended dry-seasons, soils of mostly low to moderate fertility and the maturation characteristics of native grasses limit animal growth and market options for producers. Land condition decline and the associated increase in early maturing introduced grasses (*Bothriochloa pertusa* and *Themeda quadrivalvis*) are emerging issues for beef producers. Recent research in north Queensland by the Queensland Government, with support from the Australian Government and Meat and Livestock Australia, has focussed on the development and promotion of ‘production paddocks’ using deep-rooted and productive legumes (*Clitoria, Desmanthus, Macroptilium, Stylosanthes*). These relatively intensively-managed paddocks target the nutrition of weaners and steers during the early to mid dry season to (1) enable earlier sale or higher sale weights of cattle, and (2) encourage sustainable grazing practices through spelling other areas on the property enabled by improved animal productivity. Small-plot studies of grass x legume combinations on commercial beef properties resulted in pasture yields 2-3 times those achieved on native pastures on fertile and infertile soils. Critically, the legume component contributed leaf with high feed value (15-20% crude protein and 8-10 MJ/kg metabolisable energy) when companion grasses had low feed value. The high quality of the dry season feed provided by legumes was confirmed using faecal sample testing.

Introduction

Beef cattle production is the principal land use in the monsoonal zone of northern Australia which includes the seasonally dry zone (600-900 mm AAR) in north Queensland north and west of Bowen. The area contains ~30% of the total Queensland herd which in turn approximates 45% of the 2024 national Australian herd of ~29.9 M head (Meat and Livestock Australia 2024). Weaners and steers of tropical cattle breeds for feeder (store) and live export markets are the key products in this zone. Key determinants of profit are breeder productivity (weaning and death rates) and sale weights (McLean et al., 2014). Native grass pastures in woodlands and natural treeless plains are the key feedbase for cattle in the seasonally dry zone, with the type of forage depending on geological soil development processes and rainfall (~600-900 mm average annual rainfall). Most (geologically older) soils are considered infertile, with low levels of plant available phosphorous and sulphur, but younger soils (basalt and alluvial) are considered more fertile and therefore productive overall.

The growth of native pastures is highly seasonal due to a brief (3-4 months) monsoonal summer growing period (December-March), followed by an extended dry season. For cattle producers, this results in deficits in feed volume and quality (digestible energy and protein) when they need to feed weaners and steers or maintain cow condition for reconception and during pregnancy. Management of the dry-season 'feed gap' in a variable climate and where pasture yields are inherently low is the greatest challenge to beef producers, requiring careful management to not damage native pastures (Rolfe et al 2016). Long-term declines in land condition, including declines in useful perennial grasses and increases in herbaceous and woody weeds presents an additional challenge and ultimately decreases the number of cattle which can be sustainably grazed on a property (Shaw et al. 2024).

A historical strategy to increase pasture productivity was to either sow introduced grasses considered to have desirable production characteristics (e.g. *Cenchrus ciliaris, Urochloa mosambicensis*) in small areas on better soils with or without legumes, or to integrate introduced hardy legumes (*Chamaecrista rotundifolia, Stylosanthes* spp.,) into native pastures by broadcasting during the wet season (Walker and Weston, 1990). In the 1990s, the potential to increase stocking rates and improve weaner and steer growth and potentially target new markets by incorporating *Stylosanthes* spp. and increasing legume growth by applying fertiliser phosphorous and sulphur was demonstrated on low fertility soils (Anon 1994a; 1994b). Development of this 'production paddock' concept stalled during the 1990s and 2000s due to disinvestment in sown pastures research and extension, but in 2014 the Queensland Government, collaborating with the Australian Beef Industry, began to assess new and historical grass and legume cultivars under management suitable for production paddocks. The results reported below relate to the second phase of the research, after which suitable grasses and legumes had been identified from single-taxa replicated plot experiments on a range of land-types (Cox et al. 2019). The specific objectives were to assess how combinations of promising grasses and legumes, exhibiting a range of growth habits, perform under grazing on soils of high or low fertility and gain insight into the potential for improving animal performance.

Methods

Two experiment sites were developed representing fertile (red basalt soil) and infertile (red earth soil) landtypes (Table 1). A complete factorial design of one grass and one legume in each plot was used: legumes were randomly allocated within grass strips laid out in a replicated (x3) complete block and seed sown into sites prepared by combinations of cultivation and herbicide to control previously established and emerging weeds. Fertiliser was applied prior to the final cultivation and sowing completed by broadcasting seeds onto a rolled seedbed and rolling again after broadcasting. Sowing rates were based on recommendations (www.tropicalforages.info) for each species and adjusted based on seed tests (top of paper, 35/20°C:16/8 hr).

The plots were not grazed in the first dry season (to allow complete establishment) and wet season spelled thereafter. Biomass accumulated over the growing season was measured before dry-season grazing (target residual of 1000 kg DM/ha). Herbage yield was estimated at the end of the growing period over 3 (red earth) or 4 (red basalt) years by cutting a minimum of two 0.5 m^2 quadrats per plot (360+/site), separating species while fresh, drying at 65°C until constant weight and separating legumes into leaf and stem components before weighing. Sub-samples were ground and submitted to an accredited laboratory (Dairy One™) for feed value analysis (presented) using wet chemistry. Once the legumes had spread from the plots into the surrounding native pastures, fresh faecal samples were collected from at least six grazing weaner heifers. The samples were submitted to an accredited laboratory to estimate feed value (eaten) using NIRS (Dixon and Coates 2010).

Table 1. Characteristics and management of sites used to test production paddocks in north Queensland.

Site feature/management	**Fertile site**	**Infertile site**
Location (°S/°E)	Mt Surprise (18.14/144.64)	Charters Towers (19.49/145.69)
Mean annual rainfall (median)[1]	791 (806)	556 (509)
Soil type	red basalt	red earth
pH_{water}; $P_{Colwell}$; PBI; S_{MCP}	6.6; 240; 220; 5	6.2; <5; 19; 7
Dominant vegetation (few)[2]	BP, HC (SH, SS) (uncleared)	BP, HC, SH, SS, UM (cleared)
Fenced site dimensions	6 ha	4 ha
Grass and legume treatments	7 grasses (1 failed) x 8 legumes	7 grasses x 9 legumes
Plot sizes; replicates (plots)	63 m^2; 3 reps (192 plots)	152 m^2; 3 reps (189 plots)
Site preparation methods	No fallow period; cultivation x 2; glyphosate x1; roll	One year fallow; cultivation x 2; glyphosate, roll
Pre-plant fertiliser (kg/ha)	120 ammonium sulphate	120 single superphosphate
Sowing date	27 Feb. 2019	5 Feb. 2020
Sowing methods	Broadcast and roll	Broadcast and roll
Sowing rates (kg/ha) and target viability	Grasses: (3): *Panicum/Urochloa* 80%, *Digitaria* 70%, *Bothriochloa* 50% Legumes: *Clitoria* (8, 80%), *Macroptilium (*6, 80%), *Desmanthus/Stylosanthes* (3, 60%)	
Rainfall after sowing (mm)	28 first 4 weeks + 20 (6 months)	201 first 4 weeks+173 (6 months)

[1] Bureau of Meteorology (BoM) records: Mt Surprise (BoM station 30036) 1873-2022; Charters Towers (30137) 1993-2018

[2] BP = Bothriochloa pertusa, CR = Chamaecrista rotundifolia, CC = Cenchrus ciliaris, HC = Heteropogon contortus, SH = Stylosanthes hamata, SS = Stylosanthes scabra, UM = Urochloa mosambicensis.

Results

Plant establishment was successful for all grasses and legumes except for one grass (*Urochloa* hybrid) at the red basalt site (poor quality of available seed). Grasses dominated at the red earth site under higher than usual rainfall, whereas exceptionally dry conditions in first dry season suppressed grasses at the red basalt site (data not presented). Plant growth was rapid at both sites thereafter and the sites were considered to be suitable for full grazing by April in the year after sowing. Once established, rainfall was at, or above, long-term means.

Herbage yields averaged across the grass treatments and for a well-adapted competitive grass (*Bothriochloa insculpta*) are presented for 2021 and 2023 growing seasons along with legume percentage leaf and key feed value indices for samples collected in 2021 (Table 2). Yields increased from 2021 to 2023 at both sites and were higher overall on the red basalt site. The highest yields on both land-types were achieved in the plots containing *Stylosanthes seabrana*, with *Clitoria ternatea, Macroptilium atropurpureum* and *Stylosanthes scabra* also performing well on the red basalt site, and *S. scabra* on the red earth. In general, plots with higher legume yields tended to have higher overall pasture yield.

Table 2. Total pasture and legume herbage yields, legume leaf content and feed quality from small-plot testing of grass x legume combinations. Means with different letters were considered different (95% level).

				Clitoria ternatea Milgarra	*Desmanthus spp.* Progardes	*Macroptilium atropurpureum* TGS84989	*Macroptilium gracile* TGS849	*Stylosanthes hamata* Amiga	*Stylosanthes guianensis* ATF3308	*Stylosanthes scabra* Seca	*Stylosanthes seabrana* Unica
Fertile soil (red basalt)											
2021	Total pasture yield (t DM/ha)	Across all grasses[1]		6.89 de	4.47 abc	5.75 cd	5.94 d	4.03 a	4.17 ab	5.56 bcd	7.94 e
		B. insculpta		5.40 a	4.53 a	5.55 a	4.76 a	6.07 ab	5.11 a	6.46 ab	9.79 b
	Legume yield (t DM/ha)	Across all grasses[1]		2.28 b	0.75 a	0.65 a	0.01 a	0.23 a	0.01 a	2.66 b	5.76 c
		B. insculpta		0.96 a	0.00 a	0.41 a	0.41 a	0.23 a	0.15 a	0.94 a	5.33 b
	Percentage legume leaf (%)			43.5 a	36.7 ab	61.1 c	37.6 ab	66.2 c	33.6 a	44.6 b	31.3 a
2023	Total pasture yield (t DM/ha)	Across all grasses[1]		9.91 b	4.92 d	8.46 bc	4.83 d	5.29 d	5.38 d	7.48 c	14.07 a
		B. insculpta		12.75	4.61	7.67	4.96	7.45	6.37	9.38	14.58
	Legume yield (t DM/ha)	Across all grasses[1]		3.01 b	0.19 e	1.21 c	0.06 f	0.39 d	0.04 f	2.13 b	7.79 a
		B. insculpta		2.78	0.21	1.25	0.02	0.41	0.15	2.66	5.38
Infertile soil (red earth)											
2021	Total pasture yield (t DM/ha)	Across all grasses[1]		3.18	3.21	3.40	3.34	3.17		3.43	3.98
		B. insculpta		2.17	2.14	3.00	2.85	2.17		3.02	3.87
	Legume yield (t DM/ha)	Across all grasses[1]		0.02 ab	0.01 a	0.08 b	0.01 a	0.18 c		0.35 d	0.63 e
		B. insculpta		0.03	0	0.01	0.04	0.17		1.01	1.28
	Percentage legume leaf (%)			42.6 b	38 b	60.4 c	54.3 c	40.7 b		39.9 b	26.1 a
2023	Total pasture yield (t DM/ha)	Across all grasses[1]		4.62 bcd	4.48 cd	5.16 bc	4.45 cd	5.08 bcd		5.20 ab	5.89 a
		B. insculpta		4.82	3.81	3.14	3.97	3.16		4.53	7.14
	Legume yield (t DM/ha)	Across all grasses[1]		0.43 d	0.04 e	0.91 c	0.10 e	1.31 b		2.32 a	2.60 a
		B. insculpta		0.7	0.19	0.47	0.05	0.62		1.93	3.47
Feed quality indices (pooled across sites)[2]											
2021	Crude protein (%)	wet season	Leaf	18.6	14.1	17.3	19.71*	16.9	10.2*	16.0	16.5
			Stem	12.4	7.10	12.6		11.8		8.00	7.80
		dry season	Leaf	20.3	16.5	15.7	14.7	17.4	6.49*	13.9	15.7
			Stem	10.1	6.00	9.30	8.00	9.70		6.50	6.20
	Metabolisable energy (MJ/kg DM)	wet season	Leaf	8.92	10.4	8.15	9.37*	8.83	13.8	9.20	8.68
			Stem	5.38	5.87	5.34		6.81	6.80	4.99	4.87
		dry season	Leaf	9.04	9.76	8.51	8.94	9.30	8.00	8.53	8.51
			Stem	5.67	5.57	6.59	7.93	7.07	5.23	5.21	5.10

[1] grasses tested at both sites: *Bothriochloa insculpta* 'CPI125652B, *Digitaria milanjiana* 'Jarra', *Panicum* hybrid 'Massai', *P. coloratum* 'ATF714', *P. maximum* 'Gatton', *Urochloa brizantha* 'Mekong' *U. mosambicensis* 'Manzini'.

[2] feed quality indices marked with a '*' represent a whole plant sample.

The legumes varied considerably in the proportion of leaf and stem and key feed value indices. The shrub legumes (*Desmanthus, Stylosanthes*) tended to have lower (~30-40%) leaf content than the twining legumes (*Clitoria, Macroptilium*) (50-60%) when sampled at the end of the growing season (at both sites). Crude protein (15-20%) and metabolisable energy (8-10 MJ/kg) contents were substantially higher in leaf than stem in the wet and dry seasons with values of both tending to decline over the growing season. Dry season values for legume stem were similar to the higher values of companion grasses (3-6% crude protein and 5-7% MJ/kg)(data not presented). Faecal NIRS testing of fresh dung from animals introduced into the red basalt site in September 2024 had higher crude protein (7.3%) and metabolisable energy (7.7 MJ/kg) than for cattle grazing in a similarly spelled adjacent native grass paddock (4.3% and 7.1 MJ/kg), presumably due to grazing *S. seabrana* and *C. ternatea* which have spread from plots.

Discussion

The small plot experiments indicate good potential for grass-legume 'production paddocks' to increase cattle productivity (stocking rate and growth rates) through improving the diet particularly in the dry season on fertile and infertile land types. The herbage yields achieved were in the order of 2-3 X those of undeveloped native pastures in good land condition (Queensland Government, 2024a; 2024b) and were sustained 3-4 years after sowing without the application of additional fertiliser (although additional application of S or S and P fertiliser is expected to maintain productivity in the longer term). Nitrogen fixation by the legumes would also likely contribute to improved forage yields through increased nitrogen cycling but this was not measured directly. Queensland Government analyses based on the findings of the experiments found gross margins per hectare after interest were 4-7 times those on native pastures when cattle prices and costs were averaged over 5 years, being higher on the fertile red basalt site due to higher herbage production and less fertiliser costs (Finlay and Cox 2022). These support the findings of Bowen et al (2019) whereupon the introduction and fertilising of stylos were found to be the most profitable interventions for beef producers in the northern Gulf region. An additional benefit of the competitive grass/legume systems was the suppression of *Bothriochloa pertusa* and *Chamaecrista rotundifolia* at the fertile and unfertile sites, respectively, providing a means to lift or restore productivity where these relatively unproductive species have become dominant (Cox et al., 2023a; 2023b). The adoption of production paddocks should enable cattle producers to spell pastures elsewhere on the property enabling grass recovery and more sustainable long-term management of native grasslands. It is recommended studies and demonstrations be completed at paddock-scale to refine methods for the establishment and management of production paddocks and confirm the economic benefits to assist decision making by graziers.

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Legacy pasture evaluation trials delivering new persistent legume varieties

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Key words: legume; pasture evaluation; persistence.

Abstract

Pasture legumes are the best long-term option to increase productivity and profitability from grass-dominated pastures in the sub-humid, sub-tropics and tropics of Australia through improving pasture yield, diet quality and performance of livestock. However, finding legume varieties that are persistent and productive in the long-term for the climatic zone and grazing systems has been challenging.

Queensland graziers report that long-term persistence (20 to 50 years) of legumes is their highest priority trait for selecting new varieties. Legume and livestock productivity was a second order priority; other traits such as seasonality of growth, ease of establishment, seed production, and methane reduction potential were considered important but of lower priority.

Research funding cycles are typically 3 to 5 years, which means long-term persistence of legume accessions cannot be directly measured before release as new varieties. However, there is a network of old pasture evaluation trial sites in the study area which provides an important opportunity for selecting persistent varieties.

Forty-eight pasture evaluation trial sites that were sown between 1978 and 2008 were inspected across southern and central Queensland to identify legumes that persisted in the long-term. Most of the sites had been 'abandoned' as research trials for >10 years and generally incorporated back into the grazing property. The two outstanding genera for long-term persistence were *Stylosanthes* and *Desmanthus* with some accessions demonstrating long-term persistence across broad geographic locations.

Legume persistence at these legacy trial sites has supported new research. Accessions of legumes were described and collected from old trial sites and evaluated across six new sites in southern Queensland. Five new *Stylosanthes* varieties have recently been released for commercial production demonstrating better persistence and 40 to 70% higher yields (averaged across trial sites) than the best performing commercially available legume stylo varieties. On-going research is identifying persistent and productive *Desmanthus* accessions for potential commercialisation as new varieties.

Introduction

Pasture legumes have been identified as the best long-term option to improve the productivity of both native and sown grass pastures across large areas of the tropics and sub-tropics in Australia, where there are suitably adapted and productive cultivars available (Peck *et al.* 2011). Finding legumes that are suitable for the Brigalow Belt bioregion of Queensland and New South Wales (NSW) has been particularly challenging due to its unique climate characterised by a sub-tropical climate with moisture deficits in all months of the year but is not arid (Hutchinson *et al.* 1992). The Brigalow Belt is important for the beef industry because it carries approximately 40% of Queensland's (10.6 million head) and 30% of northern Australia's beef cattle (13.3 million head) herd (ABS 2022).

Graziers advised that most of the legume cultivars that were previously commercially released for use in the Brigalow Belt were not persistent with competitive sown buffel grass (*Cenchrus ciliaris*) pastures typical in the region (Peck *et al.* 2011). The highest priority trait identified by graziers for new legume varieties was long-term persistence described as >20 to 50 years (i.e., graziers only want to sow legumes once). Research funding cycles are typically 3 to 5 years, which means that long-term persistence cannot be directly measured before legume accessions are shortlisted and selected for release as new cultivars. Fortunately, there is a network of old trial sites that were established between 1978 and 2008 that enables direct measurement and assessment of long-term persistence under grazing of legumes across a broad geographic area. This paper describes research conducted over the last 15 years that has utilised the old trial sites to identify legume species, cultivars and experimental accessions that have persisted and are productive in the long-term. This research provided better recommendations on which varieties to sow and identified accessions for further evaluation and release as new cultivars that are more productive in the long-term than existing, commercially available varieties.

Methods

Investigation of legume performance in southern and central Queensland

Forty-eight old pasture evaluation trials located across the Brigalow Belt bioregion were inspected to identify which legume species had persisted in the long-term. Re-visiting and describing these trial sites relied on the interest and input of multiple retired pasture scientists that were former employees of the Queensland Department of Primary Industries (DPI) or Commonwealth Scientific and Industrial Research Organisation (CSIRO) that had established the trials.

The old trial sites were sown between 1978 and 2008. Trial sites were inspected for long-term legume persistence between 2011 and 2023; 36 trials were inspected in 2011, 4 in 2013, 4 in 2016 and 4 in 2023. At the time of first inspection for long-term legume persistence, the trials ranged in age from 5 to 33 years post sowing with the average age being 18 years post sowing. Some of the trials have been inspected for legume persistence over multiple years. All the trial sites had been discontinued as research trials at the time of inspection, with most of the sites reverting to commercial grazier management for >10 years. If still fenced, most of the sites either had the gates open or fences were no longer stock proof, therefore the condition of the sites generally reflected the surrounding paddock. Due to the presence of pasture legumes, many of the sites were preferentially (and therefore heavily) grazed compared to surrounding paddocks. A full description of the methodology used to assess long-term persistence of legumes at trial sites is described in Peck *et al.* (2017).

The old trial sites were initially inspected to describe long-term persistence of commercially available legume varieties; however, these sites also enabled the identification of persistent and productive, non-released accessions for further evaluation and potential release as new cultivars. The activities to identify high-performing accessions for release as new varieties are described in the following sections.

Evaluating promising stylo lines for southern Queensland

A summary of the evaluation methodology is provided in this paper. A full description is available in Peck *et al.* (2022).

Multiple accessions of stylo from multiple species persisted and spread at old pasture evaluation trial sites at more southerly latitudes, with greater frost frequency, than considered suitable for commercial varieties. Forty legume accessions were described and seed re-collected from 8 sites (36 accessions of stylo, 3 desmanthus and 1 *Neptunia* sp.); however, the seed crop of one of the stylo accessions was severely damaged by disease, resulting in 39 accessions for sowing in new evaluation trials.

The 39 accessions, plus 3 experimental accessions shortlisted from other projects and 10 commercial legume varieties were sown in 2016 at six evaluation trial sites across southern Queensland. One of these trial sites failed to establish with adequate plant density due to soil crusting. The remaining five trial sites were assessed over nine growing seasons.

Evaluating promising shrubby stylo accessions in central and northern Queensland
Two accessions of coastal biotype shrubby stylo (*S. scabra*) have been shortlisted from the "evaluating promising stylo lines in southern Queensland" project for further evaluation across central and northern Queensland. Seven evaluation trials are planned for sowing in the 2024/25 growing season to test their performance relative to commercial cultivars.

Investigating desmanthus persistence and performance in southern Queensland
Following the success of the stylo selection project, an investigation of desmanthus persistence and performance at 12 evaluation trials in southern inland Queensland has commenced. Each of the sites had a wide range of desmanthus accessions from multiple species sown. Sites are >20 years post sowing. Sites have been inspected for legume persistence, with trials that warrant further investigation reinstated (e.g., fences repaired, or new fences erected). Identification of persisting accessions at trials that had large plots (>50 m^2) was completed in 2023 and 2024. One of the large plot trial sites was harvested to estimate yield in 2024. Investigation of persisting accessions at old small plot (approximately 6m^2) trial sites commenced in 2024/25.

Results
Performance of commercially available legume varieties in southern and central Queensland
Observations from the network of old pasture evaluation trial sites demonstrated that some commercially available legume varieties persisted across broad geographical areas of southern and central Queensland; however other legume species and varieties commonly recommended to graziers were not widely persistent. A summary of legume persistence and productivity results for commercially available legume species and varieties across the Brigalow Belt is provided below:

- *Stylosanthes* spp.: Caatinga stylo (*S. seabrana*) was widely persistent and productive on a wide range of soil types, but its productivity was impacted by high death rates of the population in southern districts on clay soils during wet winters. Shrubby and Caribbean (*S. hamata*) stylo are persistent on light textured (loamy and sandy) soils in central and northern Queensland but not in southern Queensland.
- *Desmanthus* spp.: *D. virgatus* was widely persistent on clay soils; however, in many locations, it had a very high population density of small plants with poor leaf retention. Other *Desmanthus* species (e.g., *D. leptophyllus*, *D. bicornutus*, *D. pernambucanus*) maintained an adequate plant density that contributed to animal production in a small percentage of trial sites where they were sown, but did have high dry matter production at some sites.
- *Leucaena leucocephala*: Leucaena persisted on fertile soils with high water holding capacity with good grazing management. Leucaena did not maintain adequate plant populations at multiple sites that had one or more of the following traits: sub-soil constraints, low fertility, heavy frost, and heavy continuous grazing.
- Legume species persisting in niches: Annual medics (*Medicago* spp.) are widely persistent on clay soils with regular frosts in southern Queensland. Butterfly pea (*Clitoria ternatea*) persisted on deeper, basalt derived black earth soils in central Queensland; but has not persisted on other clay soils. Round-leaf cassia (*Chamaecrista rotundifolia*) persisted on very sandy soils in central Queensland and on a wider range of soils in north and southeastern Queensland.

- Legume species that have not persisted on grazed trial sites include: Lucerne (*Medicago sativa*), burgundy bean (*Macroptilium bracteatum*), Atro (*Macroptilium atropurpureum*), fine-stem stylo (*Stylosanthes guianensis* var. *intermedia*). These legumes species should not be recommended for long-term pastures in the Brigalow Belt bio-region climate zone.

These legume persistence results are closely aligned with observations of commercial paddocks and consultation with graziers (Peck *et al.* 2011).

Superior stylo varieties identified for southern Queensland
Five stylo accessions were selected for release as new legume varieties for light textured soils in frosty locations in the sub-tropics based on the results from five evaluation trials sown in 2016. Three of the new varieties are Caatinga stylos (cvv. Dura, Cedo, Ultimo), and two are shrubby stylos from the "continental" biotype (cvv. Terra, Roxo).

The five new stylo varieties produced 40 to 70% higher average yields than the best performing, commercially available legume variety (cv. Unica, a Caatinga stylo) across five trial sites in the third and fourth growing season after sowing. These measurements were conducted during severe drought years that were in the driest 10% of years for the districts where the trials were located.

Four of the trial sites were remeasured during the eighth or ninth growing season after sowing to measure performance in average or higher rainfall growing seasons. The Caatinga stylo varieties produced 30 to 60% higher yields (averaged across the four trial sites) than the best performing commercial variety (cv. Primar, a Caatinga stylo). The two new shrubby stylo varieties produced lower average yields than cv. Primar but much higher yields than the commercial varieties of shrubby stylo (more than four times higher average yields).

Evaluating promising shrubby stylo accessions in central and northern Queensland
Two accessions of the "coastal" biotype of shrubby stylo were initially shortlisted from the "evaluating promising stylo lines in southern Queensland" project for further study. When grown in a trial at Mareeba, they produced yields that were approximately four times higher than cv. Seca, which is the industry benchmark variety for shrubby stylo and considered well adapted to the north Queensland climate. These two accessions are now being tested more broadly in a wide range of soil by climate locations across central and northern Queensland to see if they produce higher yields or other benefits compared to cv. Seca.

Investigating old desmanthus trials in southern Queensland
One outstanding desmanthus accession (breeders code: B-Six) has been identified from the old, large plot trial sites to progress towards release as a new cultivar. At the trial site that was harvested 25 years post sowing, B-six produced approximately double the yield of cv. Marc which has been a widely used and persistent desmanthus variety. B-Six also had clearly better leaf retention. The results from this trial are consistent with visual assessments that were carried out at the other old large plot trial site that was still intact (all other trial sites were ploughed out by the landowners). From historic trial data, B-Six had also produced high yields in the first 5 years post sowing at four old trial sites in southern Queensland and northern NSW and has now demonstrated ongoing persistence.

Other promising accessions are likely to be selected from the old small plot trials after more detailed assessment of performance. For example, one desmanthus accession (SPT017) collected from an old trial site has been sown at 7 new trial sites across southern Queensland and was the highest yielding desmanthus at 5 of the 7 sites.

Discussion
More widespread and successful adoption of legumes is critical to sustainably improving the productivity and returns for grazing industries in the Brigalow Belt climate zone that carries 30% of northern Australia's beef herd.

In addition to productivity benefits, these legumes can potentially reduce methane emissions intensity and improve pasture resilience to seasonal variability and grazing.

The network of old pasture evaluation trials across southern and central Queensland described in this paper provided valuable insights about the long-term performance of commercially available legume cultivars as well as identifying better-performing legume accessions for potential release as new varieties. The results from the old trial sites contributed to providing better advice to graziers when selecting legume varieties. The old trial sites also provide a legacy for selecting persistent and productive new legume cultivars. Better varieties combined with better advice will contribute to more widespread and successful adoption of legumes in northern Australia.

Five new stylo varieties that were identified and re-collected from old trial sites have the potential to increase the geographic range suitable for sowing legumes in southern Queensland (i.e. previously there were no suitable commercial legume varieties), as well as improving productivity for large areas where existing varieties are suited. Two additional shrubby stylo accessions were also identified and are being evaluated as potential replacements for cv. Seca, which is the most widely used legume in northern Australia. Additionally, new research has commenced that has identified improved desmanthus accessions, with further work potentially identifying other accessions with useful traits for industry.

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Pathways less travelled to forage legume practice change

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Key words: extension; sown pasture; pasture legumes; practice change.

Abstract

Land condition decline, pasture rundown and dieback are significant issues for beef businesses in central Queensland. Perennial pasture legumes play a role in preventing and remediating these conditions, leading to improved beef production and business profitability. Adoption of perennial legume pastures by beef producers in central Queensland is low; however, there is renewed interest in legume plantings since they have been promoted as an option for greenhouse gas reduction. An extension strategy was developed to use carbon-focused peer-to-peer learning workshops to generate interest in one-on-one support to introduce perennial pasture legumes. Workshops were delivered in three locations in central Queensland in 2023 and were designed with a mixture of group learning activities and presentations. The workshop delivery team included a carbon scientist, carbon project advisor and an experienced extension pasture specialist. Feedback collected from the workshops indicated that 10% of producer respondents intended to make a change on-property involving legume pastures on 3,387 ha. 41% of producer attendees participated in one-on-one action plan support on-property after the workshop, where a total of 16 actions plans for 2,297 ha were documented on 10 properties. In the 11 mo after the initial workshops, producers who participated in the action plan process reported 561 ha of practice change. This change was considered to be incremental towards legume planting and included practices such as soil and seed testing, timber clearing and cultivation. Despite the documented practice changes, the one-on-one support method was labour intensive. Ongoing engagement with producers is continuing into the legume-planting season, such that more data can be collected on practice change. Overall, the strategy of using carbon-focussed events to garner interest in perennial legumes and producer practice change was successful and will be repeated.

Introduction

Beef producers in northern Australia face three significant threats to the long-term productivity of perennial pasture systems – land condition decline, pasture rundown and dieback. Often these conditions occur simultaneously and compound the impacts on the grazing business. In the central Queensland region for example, it is common for pasture dieback to occur in rundown Gayndah buffel (*Cenchrus ciliaris* cv Gayndah) pastures, which then become colonised by weeds or undesirable grasses resulting in poor land condition (Buck 2017).

Perennial pasture legumes play an important role in the cost-effective remediation of pasture rundown due to the nitrogen cycling benefits to soil fertility (Peck et al. 2011). They are also unaffected by pasture dieback, which means they provide cattle feed when grass is dead and are an important component of seed mixes when resowing tolerant species in dieback-affected areas (Buck et al. 2023). Furthermore, they are important 3P (productive, palatable and perennial) species when assessing land condition and have been well documented to increase stocking rates, liveweight gains and grazing periods (Bowen et al. 2018).

Cattle eating perennial tropical legumes such as *Leucaena leucocephala* and *Desmanthus spp* have increased daily liveweight gain and reduced methane production (Stifkens et al. 2022, Suybeng et al 2020), and aged leucaena-grass pastures accumulate enough soil organic carbon to mitigate methane production from cattle grazing them (Radrizzani et al 2011). The positive impact of perennial legumes is recognised by Meat and Livestock Australia (MLA) that has a target for the red meat industries (beef, lamb and goat) to achieve carbon neutrality by 2030 through a range of activities that support the avoidance and reduction of greenhouse gas emissions, including 25 million ha of new legume plantings nationwide (MLA 2020). As a result, industry interest in carbon emissions and the role legumes play in reducing them, has increased.

Sowing perennial legume-grass pastures results in more profitable beef businesses, despite the initial costs of establishment and associated financial risk, compared to having a grass-only pasture system (Bowen and Chudleigh 2018). However, adoption rates of perennial pasture legumes in Queensland Australia are currently low (Peck et al. 2022).

Several extension methods are effective in Australian agriculture including facilitated groups, technology development, training and group presentations, information provision and access, one-on-one individual farm advisory, best management practice frameworks, E-extension, co-innovation and social marketing (Coutts et al. 2017). Nettle et al. (2022) concluded that the strongest effect on adoption was achieved through small group-learning and one-on-one consulting; however, the combination of methods that addressed the human and social elements of the adoption process produced the largest impacts.

Our first aim was to test the methodology of using carbon as a workshop topic to generate producer interest in sowing perennial legumes. The second aim was to create engagement with a one-on-one advisor support process to achieve producer practice change.

Methods

Three workshops titled ‘Carbon, cattle and sustainability’ were delivered to beef industry audiences in central Queensland at Gayndah, Moura and Emerald in December 2023. Attendance data was collected including number of producers and the businesses and properties they manage.

Workshop topics

Workshops delivered information on the carbon cycle, insetting and offsetting carbon emissions, emission intensity in beef production, the impact of pasture legumes on emissions and carbon projects. Topics were chosen to give an industry audience a background understanding of carbon emissions and how practices on farm can influence them. Carbon project information was presented in a way that allowed a producer audience to decide if a carbon project was suitable for their business.

Workshop delivery team

Workshops were delivered by a multi-disciplinary team which included a scientist currently researching carbon emissions in commercial beef operations; a carbon project advisor with experience in managing carbon projects in the beef industry; and two extension specialists with skills in adult learning and peer-to-peer facilitation techniques as well as technical knowledge in pasture management and development, and cattle nutrition and husbandry.

Workshop peer-to-peer learning techniques

Workshop rooms were set up in group tables of 4-6 people where participants were asked to meet others at the table by introducing themselves, providing some background information on their beef operation and then answering an icebreaker question. This process was then repeated with the whole room. Groups completed an expectation activity on flip chart paper answering the questions 'What do you want to learn today?' and 'What concerns you about carbon?' After a presentation on the carbon cycle, insetting and offsetting emissions and carbon baselining, a 'bus stop' activity was conducted using the method described by The Facilitators Network (2024). Questions included: 1) How can you improve weight gain of cattle? 2) How can you improve the efficiency of a breeder herd? 3) What can you do to improve soil and pasture health? and 4) What can you use to keep farm records? Participants were prompted to record learnings in a 'Carbon property plan' which provided space for practices to implement to reduce carbon emissions. After a final presentation on carbon farming projects and some final group discussion, participants were asked to individually share their key 'take home' messages from the day.

Workshop feedback

Participants completed a feedback sheet with a series of questions including rating their knowledge and understanding before and after the workshop, and their intention to make a change in their practices (including what it is, how likely they are to do it and on what area of land).

One-to-one support action plans and practice change

Participants were offered one-on-one support for pasture management and improvement to occur after the workshop and property visits were arranged. When on property, advice was documented in a pasture action plan which included detailed instructions on fallowing and planting techniques, species selection and fertiliser rates. When re-engaging with producers after the property visits, if practice change had occurred the area of land and activity undertaken on the property were documented.

Results

A total of 52 participants attended the three workshops including producers and industry advisors (public and private). Feedback forms were completed by 30 producer respondents whose knowledge and understanding of carbon increased from an average score of 2.5 to 4.8 out of 7. 80% of respondents said they intended to make a change after the workshop and 10% of these said the change would include pasture development with legumes on a total of 3,387 ha.

During the 'bus stop' activity at each workshop, legumes and pasture development were listed by attendees as farm practices that can improve breeder performance, cattle weight gain and soil health.

Properties that were visited to develop pasture actions plans after the workshop are summarised in Table 1. Practice change was recorded in the first 11 mo after the workshops. In total, 16 producers (41% of producer attendees) who managed 10 properties requested property visits. Some properties developed action plans for more than one paddock. Practice change activities were recorded in 5 action plans and included planting an annual forage crop, timber clearing, fencing, and seed quality testing, all of which were steps outlined in action plans. A further two action plans were ready to enact when the seasonal conditions were right.

Table 1. Summary of properties and action plans developed from attendees in Queensland Australia of 'Carbon, Cattle and Sustainability' workshops in December 2023 and the resulting practice change 11 mo later.

Workshop location	Participating properties (no.)	Action plans (no.)	Action plan area (ha)	Action plans with progress (no.)	Practice change area (ha)
Gayndah	4	8	1,242	2	501
Moura	2	3	67	0	0
Emerald	4	5	988	3	60
Total	**10**	**16**	**2,297**	**5**	**561**

Discussion

Workshop success in increasing interest in legume pastures

The workshops were facilitated to maximise group sharing and learning as described by Coutts et al. (2017) as opposed to workshop deliverers teaching concepts. The increase in knowledge and understanding of carbon by the feedback survey respondents demonstrated that the workshop delivery format and combination of technical presentations and several group sharing activities was successful. The introductory activities which included an ice breaker question and a 'Hopes and Concerns' activity allowed participants to feel comfortable with each other and openly discuss the positive or negative impact farm practices have on their carbon emissions. The 'bus stop' activity allowed attendees to contribute ideas for farm practices that increase breeder performance, cattle weight gain and soil/pasture. Legumes and pasture development practices were consistently included in each list across all workshop locations. This demonstrated that attendees understand the concepts taught earlier in the day around emissions intensity, and the overall benefits of perennial legumes to a beef operation. This was despite few having already implemented the practice themselves.

Feedback data indicated that 10% of producer respondents intended to make a change of introducing legumes; however, 41% of producer attendees requested one-on-one support after the workshop. This discrepancy may be due to some respondents prioritizing other practice changes when completing feedback surveys. Regardless of the discrepancy, it is clear the workshops successfully generated interest in the development of pastures with perennial legumes.

One-on-one support action plans and resulting practice change

One-on-one support action plans resulted in 561 hectares of practice change in the first 11 months after conducting property visits, demonstrating the positive impact of providing individualised advice and support for graziers. This is consistent with producer survey data reported by Peck et al. (2022) where most graziers said they preferred one-on-one interactions with advisors to implement perennial legume introduction. Practices implemented by producers after action plan support, included several practices needed to successfully sow legumes into a pasture. However, due to the limited time in which the practice change data was recorded no legumes had been sown and some had not begun any activity as seasonal conditions were not sufficient for the planned actions. This is consistent with best practice recommendations on seasonal fallowing and planting times for the central Queensland region, Australia (Peck et al. 2022) so it was not expected that any plantings would have occurred in this period.

The one-on-one support action plan process was labour intensive for advisors due to the following reasons: every property was located 100 to 400 km away by road travel, took 1 to 4 h on farm to complete plus more time planning visits and documenting action plans, and was attended by at least two advisors. It is theorised that despite the personalised support provided, not all producers who engaged in the action plan process will implement a change long term and the top two barriers to adoption as reported by Peck et al. (2022) of cost and climate/seasons are likely to be applicable here too.

Combining extension methods

Combining peer-to-peer learning workshops and follow up one-to-one support activities has led to an increase in trust between producer participants and advisors, which is an important aspect of facilitating practice change and is an example of the success of stacked extension strategies. Stacking of extension methods involves combining several methods (e.g. facilitated groups and one-on-one support) into a cohesive package for producers (Nettle et al. 2024).

Facilitated small peer-to-peer learning group workshops on perennial legume establishment techniques were conducted by Peck et al. (2022) with success in achieving large areas of legume plantings. However, those workshops were aimed at teaching legume establishment concepts to producers who were already interested in the topic. The carbon workshops delivered in this study, demonstrate the effectiveness of appealing to the values of producers who are also interested in natural capital markets that combine environmental sustainability, product provenance for consumers and the opportunity for niche sales markets.

Conclusion and recommendations

Overall, the strategy of using a carbon-focussed workshop to generate producer interest in the benefits of perennial pasture legumes and garner interest for one-on-one advisory activities was successful and incremental practice change was recorded. Due to the short time since the initial engagement with producers at the workshops, it is recommended that contact between advisors and producers is maintained so that ongoing support for practice change can be provided. More 'Carbon, cattle and sustainability' workshops are being planned for 2024, allowing the strategy to be repeated and the results confirmed.

Acknowledgements

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Long term effects of different stocking strategies on land condition and profitabilty in a highly variable climate

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Key Words: flexible stocking, stocking rate, spelling, weight gain

Abstract

Rainfall variability is a major challenge to sustainable grazing land management in northern Australia. We present data from a long-term grazing trial comparing the performance of different cattle stocking strategies over 27 years of highly variable rainfall. Strategies involved combinations of different stocking rates, fixed versus flexible stocking and wet season pasture spelling.

Individual live weight gain (LWG) and product price were highest at moderate stocking rates applied with or without wet season spelling. Total LWG/ha was highest at heavy stocking rates, but gross margins lowest due to reduced product value and drought feeding costs. Flexible stocking was as profitable as fixed moderate stocking but also avoided the need to destock in drought years.

Land condition as indexed by the proportion of 3P (palatable, perennial and productive) grasses declined rapidly under heavy stocking, reducing resilience and long-term carrying capacity (LTCC). Although fixed moderate stocking at LTCC initially maintained land condition, condition ultimately declined due to the failure to reduce stocking rates in droughts. Land condition also declined with drought under flexible stocking, but recovery appears greater with recent good seasons. Wet season spelling was essential to buffer drought effects and is accelerating recovery post drought.

These results show that over the long term, heavy stocking is a high risk, and ultimately an unprofitable and unsustainable strategy. Although fixed, moderate stocking strategies are lower risk, they will still lead to degradation if stocking rates are not reduced in dry years to match forage availability. We recommend that climate variability be managed using flexible stocking rates in a pro-active, risk averse manner coupled with regular wet season spelling. These should be applied adaptively based on seasonal conditions and observed responses to management actions.

Introduction
Rainfall in northern Australia is highly variable at seasonal, annual and decadal scales making sustainable and profitable livestock management extremely challenging. Failure to manage for this variability has led to a number of degradation events with large shifts in land condition to other, less productive states (McKeon *et al.* 2009). Many graziers have learnt to manage for this variability by, for example, stocking around long-term carrying capacity (Purvis 1986; Landsberg et al. 1998), spelling pastures to accumulate forage for use in drier times and varying stocking rates to match available forage.

Unfortunately, wider adoption of these strategies within industry has been disappointing (Anon. 2017) resulting in ongoing cycles of degradation and economic loss in drought periods. The reasons for non-adoption are complex, but one key factor is that while these strategies are clearly beneficial for land condition, there is little or no data on their relative productivity and profitability.

To address this issue a large grazing trial was established in 1997 in a semi-arid, tropical savanna in northern Australia. The key objective was to quantify the performance of different stocking strategies in a highly variable rainfall environment in terms of their effects on animal production, land condition and profitability. This empirical data would support development of recommendations and adoption products to assist managers to make evidence-based decisions on managing for rainfall variability and help improve adoption of more sustainable and profitable grazing strategies.

Methods
The trial was established in 1997 on the property 'Wambiana' (20° 34' S, 146° 07' E), 70 km south of Charters Towers, Queensland. Long term (114-year) mean annual rainfall is 643 mm (C.V.= 40%), with 70% falling in the hot summer months. The vegetation is an open Eucalyptus-Acacia savanna overlying C4 tropical grasses. The native shrub Carissa ovata is also becoming increasingly dominant.

The trial has five grazing strategies, replicated twice. Paddocks are approximately 100 ha in size and contain a similar mix of the three main soil types. Strategies were: heavy stocking (HSR: 4 to 5 ha/AE [animal equivalent: 1 AE=450 kg steer]), moderate stocking (MSR: 8 to 10 ha/AE), rotational wet season spelling (R/Spell: 8 to 10 ha/AE), flexible (Flex) stocking (4 to 20 ha/AE) and flexible stocking with wet season spelling (Flex+S). Stocking rates in the flexible strategies were set based on end of wet season (May) pasture availability with further check points through the grazing year. In the R/Spell and Flex+S paddocks, spelling was implemented by resting different subsections within paddocks during the wet season. Importantly, strategies are managed adaptively as 'management philosophies' in consultation with a grazier advisory committee.

The trial was stocked with Brahman steers 1.5 and 2.5 years old and managed according to industry best-practice guidelines. Cattle are weighed at the start and end of the grazing year with older steers going to commercial slaughter (O'Reagain et al. 2009). Gross margins (GM) were calculated as product value less supplementation, vaccination, drought feeding and interest on livestock capital costs (O'Reagain *et al.* 2011). Pasture yield and species composition were monitored annually in May using the BOTANAL procedure (Tothill *et al.* 1992). Here we present the % contribution of 3P (palatable, perennial and productive) species to yield as an index of land condition. The key 3P species at the site are *Bothriochloa ewartiana, Dichanthium sericeum* and *Heteropogon contortus*.

Results
Rainfall and management
Rainfall varied widely (246 to1223 mm) over the trial period, with the initial four good years leading into an extended six-year drought (Fig. 1). This was followed by a further wetter phase and then a run of dry years, with

rainfall (246 mm) in 2014/15 being the fourth lowest on record. The 2021/22 season was also extremely dry (348 mm) but conditions changed abruptly thereafter with 2022/23 exceptionally wet (1064 mm).

With the early good years and abundant forage, the Flexible strategies were initially very heavily stocked, leading to overgrazing with the onset of the first drought phase. Stocking rates were subsequently sharply reduced and a more risk-averse approach adopted, involving setting upper limits to stocking rates and increasing the number of stocking rate adjustment decision points.

The HSR initially performed well but stocking rates had to be cut sharply in both the first and second drought periods due to the extreme scarcity (<200 kg DM/ha) of grazeable forage. Drought feeding had to be provided to the HSR steers in seven years of the trial compared to only once in the other strategies (Table 1). In contrast to the HSR, stocking rates in the MSR and R/Spell treatments were maintained throughout almost the entire trial period. One exception was in 2017/18 when, in line with a 'moderate stockers/rotational spellers' management philosophy, both were destocked for the wet season to prevent overgrazing.

In May 2022, due to ongoing drought and the almost complete lack of forage, the MSR, HSR and R/Spell were all destocked, and subsequently rested for the full 2022/23 season. In contrast, as the progressive adjustment of stocking rates in preceding years had ensured sufficient forage for the approaching dry season, the two Flexible strategies were able to remain stocked in 2022/23, albeit at a very light rate (20 ha/AE). The MSR and R/Spell were fully restocked in 2023/24, while the former HSR strategy was changed to a new short duration grazing treatment (Walkington et al. 2025) to facilitate recovery of the degraded land condition. Accordingly, the data presented below are for 26 years for the HSR compared to 27 years for the remaining strategies.

Animal production and economics

Individual liveweight gain (LWG) was by far the lowest of all strategies in the HSR (Table 1). These differences in LWG were amplified in dry years with HSR steers losing 54 kg in the extremely dry (246 mm) 2014/15 season. As a result of the generally poorer LWG, carcass weights and grading were lower for HSR steers resulting in a lower product value. These findings are consistent with those reported in more detail by O'Reagain et al. (2009 and 2023).

Table 1: Average (+/-standard error) liveweight gain (LWG) per steer, LWG per hectare (ha) and gross margin (GM) per ha for different stocking strategies over the 27-year Wambiana trial. The number of years that drought feeding was needed and the number of years with negative GM are also shown. (See text for treatment abbreviations).

Treatment	LWG/hd (kg)	LWG/ha (kg/ha)	Yrs drought feeding	GM/ha (AU$/ha)	Years with a negative GM/ha
Flex	118 (+/-8.3)	15 (+/-1.7)	1	12 (+/-2.2)	3
Flex+Spell	116 (+/-6.5)	15 (+/-1.6)	1	13 (+/-2.0)	3
HSR[1]	97 (+/-10.6)	18 (+/- 2.3)	7	5 (+/-2.0)	14
MSR	116 (+/-8.1)	13 (+/-1.1)	1	12 (+/-4.3)	4
R/Spell	115 (+/-8.0)	14 (+/- 1.2)	1	12 (+/-2.0)	4

[1]HSR based on 26 years of data

In contrast, average LWG per ha was highest in the HSR (Table 1). This difference was most pronounced in wet years but was much reduced or even negative in drought years (O'Reagain et al. 2023). However, the higher LWG/ha in the HSR was only achieved with expensive drought feeding in seven of the trial years compared to only one year in the other strategies. As a result, average annual GM/ha in the HSR was less than half ($5/ha) that of the other strategies ($12 and 13/ha) due to reduced product value and higher costs (Table 1). Gross margins in the HSR were also extremely variable with a far greater number of years with a negative GM/ha relative to the other strategies (O'Reagain et al. 2023).

Land condition

Land condition, as indexed by the % contribution of 3P grasses to yield, declined rapidly under heavy stocking with the onset of the first drought post 2001 (O'Reagain et al. 2023). This decline continued in the second drought, resulting in the 3P contribution falling from 25% in 1998 to only 4% of yield in 2021. Note that in 2024 relatively little recovery had occurred in the former HSR treatment despite good seasons and the paddocks being largely unstocked or only very lightly grazed since May 2022.

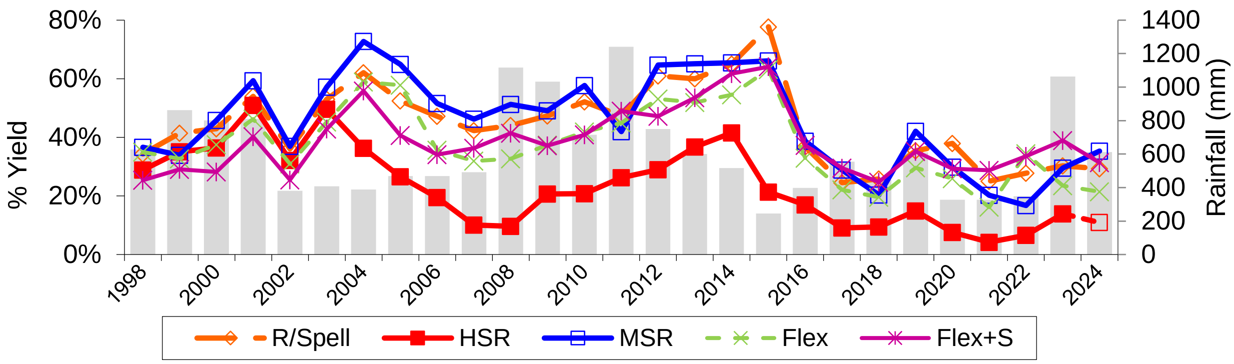

Figure 1: The change in contribution (%) of 3P grasses (palatable, productive, perennial) to pasture yield versus rainfall (grey bars) over 27 years under five grazing strategies at the Wambiana grazing trial. See text for treatment abbreviations. NB: The HSR treatment ended in May 2023.

The Flex and Flex+S strategies performed far better than the HSR in terms of land condition (Fig. 1). Nevertheless, the initial heavy stocking rates applied in these flexible strategies resulted in the %3P grasses being lower than the other strategies until about 2003. Despite the subsequent sharp reduction in stocking rates, the overgrazing at the start of the first dry cycle had a lasting negative legacy, as evidenced by the relatively lower 3P% in the Flexible relative to the MSR and R/Spell strategies until around 2014. In later, more recent years, land condition in these two strategies appears to be as good, if not better, than in the MSR and R/Spell (Fig.1).

In the moderately stocked MSR and R/Spell, land condition was largely maintained for the first 18 years of the trial. However, condition declined drastically post 2015 due to the extremely low rainfall that year and the drought conditions that ensued (Fig.1). This decline was undoubtedly largely due to drought, but the maintenance of the stocking rates in the MSR and R/Spell inevitably led to overgrazing and was thus also partly responsible for the land condition decline (pers. obs.).

Conclusion

These long-term results show that constant heavy stocking is a high risk, unprofitable strategy which leads to a marked loss of land condition. This in turn reduces carrying capacity and drought resilience making the strategy ultimately unsustainable. Although fixed, moderate stocking strategies are more profitable and have much lower risk, they can still lead to overgrazing and degradation if stocking rates are not reduced in dry years to match forage availability. Flexible stocking was as profitable as fixed moderate stocking, had similar if not better impacts on land condition and importantly, avoided the need to fully destock in the recent drought. However, flexible strategies need to be applied in a risk averse manner with upper limits set to stocking rates and stock numbers adjusted rapidly with the onset of drought. While the results presented do not show a strong benefit from wet season spelling, other data from the site (O'Reagain et al. 2023), and many other studies, e.g., Ash et al (2011), indicate that wet season spelling is essential for maintaining and improving pasture condition.

In conclusion we recommend that climate variability be managed using flexible stocking rates in a pro-active, risk averse manner coupled with regular wet season spelling. These principles should be applied adaptively based on seasonal conditions and observed responses to management actions.

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Spelling strategies for recovery of poor land condition

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Key words: annual vs biennial wet-season spelling; *Bothriochloa ewartiana*; basal cover; moderate vs heavy stocking; Wambiana grazing trial

Abstract

Pasture condition has declined across many pasture communities across northern Australia. Pasture spelling is a key recommendation for the recovery of land condition but there is limited information on the optimum length and frequency of spelling or the recovery rates possible under different spelling and stocking rate combinations. This 12-year study examined the effects of early and full wet season spelling applied annually or biennially, on the recovery of poor condition land and the demography of the key perennial grass, *Bothriochloa ewartiana*, under heavy and moderate stocking rates. The study period was characterised by low rainfall and extreme drought conditions in some years. Average basal cover of perennial species declined with the onset of dry years with the effects of drought amplified under heavy stocking. Basal cover later increased as conditions improved but cover under heavy stocking never recovered to that under moderate stocking. Annual early and full wet season spelling under moderate stocking had a positive effect on the basal cover of *B. ewartiana* but this effect was only significant ($P < 0.03$) after 12 years. Spelling had no effect on basal cover under heavy stocking, emphasising the overriding effect of stocking rate on recovery. Basal cover through the drought was largely maintained through the persistence of original tussocks, emphasising the importance of maintaining established plants through good management. In later years, an increasing number of recruits also increased basal cover. Land condition can be improved with annual wet season spelling provided stocking rates are appropriate, but recovery can initially be slow, particularly through dry years. These results emphasise the key role that spelling has in maintaining and improving pasture condition.

Introduction

Pasture condition has declined across many pasture communities across northern Australia as evidenced by the reduced density of many desirable perennial grasses (e.g. Tothill and Gillies 1992). Karfs *et al.* (2009) rated from 20 to 50% of the area of several major catchments in north Queensland as being in C (poor) condition, based on the 'ABCD' land condition rating. Areas in C condition typically have 50% or more lower carrying capacity and a much increased risk of soil erosion than those in A or B condition (McIvor *et al.* 1995; Ash *et al.* 1997).

Wet season spelling (i.e. resting through the growing season) is a key recommendation for maintaining or recovering pasture condition. Work by Ash *et al.* (2011) in northern Australia showed that recovery of condition can occur relatively quickly, at least with annual wet season spelling. However, their study was relatively short (7 years) with the best results achieved on relatively fertile basalt and granodiorite soils. Currently, there is little other relevant information, particularly on the rates of recovery with a different timing, duration, or frequency of spelling, to guide cost-effective (Scanlan et al. 2013) and practical resting regimes for managers. There is also little data available on the demographic processes underpinning how pasture condition responds to management actions like grazing intensity and spelling. As such, management guidelines are relatively unsophisticated, with consequently varying results. There thus remains a major challenge to understand the ecological processes which drive the recovery of poor pasture condition.

The aim of this study was to improve guidelines to recover poor condition land and hence carrying capacity in northern Australia. The study had two major objectives: first, to determine the optimum frequency and duration of spelling for recovery of poor (C) condition land under two stocking rates. And second, to monitor and improve the understanding of the demographics of the major perennial grasses that underpin the processes of recovery.

Method

The trial reported here was established within the larger Wambiana grazing trial (O'Reagain et al. 2009), 70 km south of Charters Towers, Queensland (20º32'S, 146º7'E). Mean annual long-term rainfall is 647 mm with most occurring between October and March. The vegetation is an open eucalypt-acacia woodland. The present study was conducted on an area dominated by *Eucalyptus brownii* and the native shrub *Carissa ovata,* on brown sodosols. The soils are moderately fertile with a pasture layer containing *Bothriochloa ewartiana, Aristida* spp*.,* *Chrysopogon fallax*, and other grasses.

The Wambiana trial was established in 1998 to test different grazing strategies (see O'Reagain et al. 1998). These included a heavy stocking rate (HSR: 4–5 ha/AE) and a moderate stocking rate (8–10 ha/AE). After 14 years of heavy grazing, the HSR paddocks were in C (poor) condition (Quirk and McIvor 2003). In 2011, part of one HSR paddock was selected and equivalent sets of 25 treatment plots (30 × 30 m) laid out in two blocks. One block was near an adjacent MSR paddock. The intervening paddock fence was realigned to incorporate this block containing all treatments into the adjacent MSR paddock, while the other block remained in the HSR paddock.

Four different spelling regimes involving either early or full wet season spelling and applied either annually or biennially were then implemented on these treatment plots in both the HSR and MSR paddocks (O'Reagain et al. 2023). Spelling was implemented by closing up plots with a temporary fence but were otherwise left open to grazing. A series of replicated unrested, continuously grazed control plots were also installed. Twelve 0.25-m^2 quadrats were permanently located in each plot with quadrats stratified to contain an adequate number of *B. ewartiana* plants (O'Reagain et al. 2023). Quadrats were surveyed annually at the end of the wet season (May/June) and the number and size of all individual perennial grasses recorded graphically on gridded paper.

Statistical analysis

Data was analysed by randomised block analyses of variance, with plots as experimental units. Treatment response patterns over seasons were analysed using repeated measures analyses of variance with GENSTAT (release 18.1, VSN International, Hemel Hempstead, UK) with the pre-treatment (2011) basal cover a covariate. For this paper, only the basal cover of *B. ewartiana* was analysed.

Results

Rainfall was good in the first 2 years and following the 3 previous, above-average years. Thereafter drought conditions ensued, with 2014/15 the fourth driest year on record (Figure 1). Rainfall remained below average and was often poorly distributed thereafter, before exceptionally good rains in the 2022/23 season.

Average total perennial grass basal cover increased slightly in the early years of the trial, but then declined in both stocking rates in the dry years between 2013 and 2016 (Fig. 1). This decline resulted from mortality of established plants and a reduction in basal cover of survivors. With the advent of drought, cover declined sooner and to a much lower level in 2016 in the HSR (0.23%) than in the MSR (0.53%). Thereafter, basal cover slowly increased in both the HSR and MSR treatments as seasons gradually improved. However, average basal cover of perennial grasses in the HSR never recovered to that observed in the MSR, even in the exceptionally wet year of 2023. These results show that while drought had a major impact on basal cover under both stocking rates, these effects were amplified under heavy stocking.

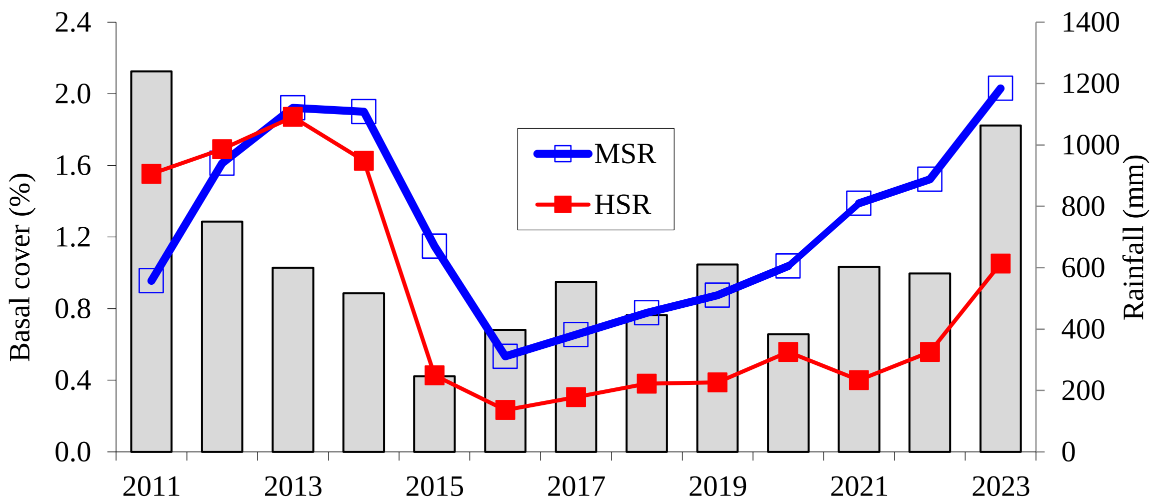

Fig. 1. Change in total perennial grass percentage (%) basal cover, averaged across the annual early wet season spell, annual full-wet season spell and unspelled control for the moderate (MSR) and high stocking (HSR) plotted against rainfall (grey bars).

Wet season spelling had a positive effect on the basal cover of the key species *B. ewartiana*, at least in the MSR (Fig. 2). However, this difference was only statistically significant in 2023 ($P < 0.03$) for the annual early and full wet season spelling, with biennial spelling having little or no effect on basal cover (Fig. 2). Importantly, in the HSR, spelling, even if applied annually and for the full wet season, had virtually no effect on *B. ewartiana* basal cover (data not shown).

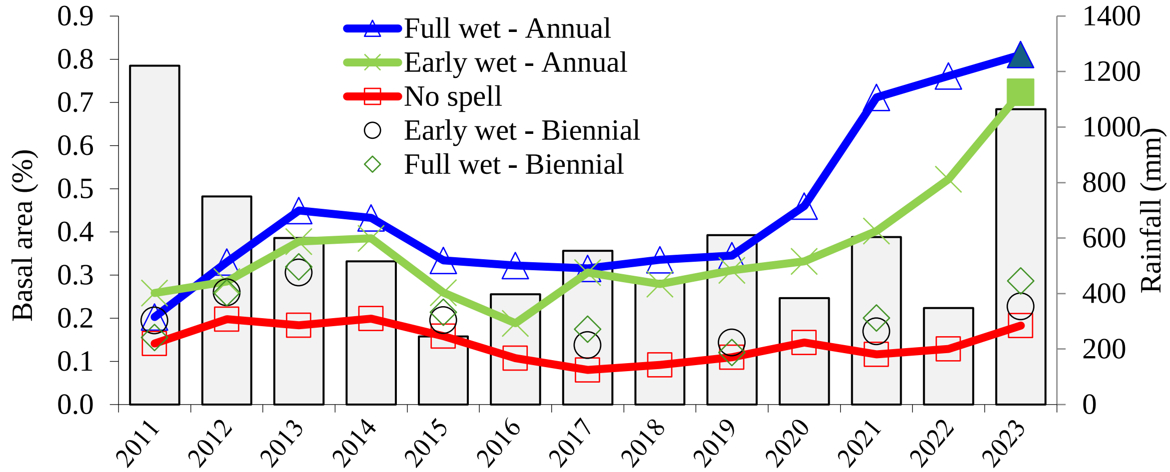

Fig. 2. Change in the basal area of B. ewartiana with different spelling treatments or no spelling in the moderate stocking rate treatment. (Values with a closed symbol in 2023 are significantly different to those with an open symbol; $P < 0.05$.)

The increase in basal cover of *B. ewartiana* in the MSR (Fig. 2) resulted predominantly from the increased basal area of the surviving, original plants from 2011 (Fig. 3). However, new recruits made an increasing contribution to basal cover in later years, at least under moderate stocking. For example, in 2017 the basal area occupied by recruits was 0.04% of a total 1.02% in the MSR.

However, by 2023, basal area from original plants was 1.72%, while the area occupied by recruits was 0.49%, almost a 12-fold increase.

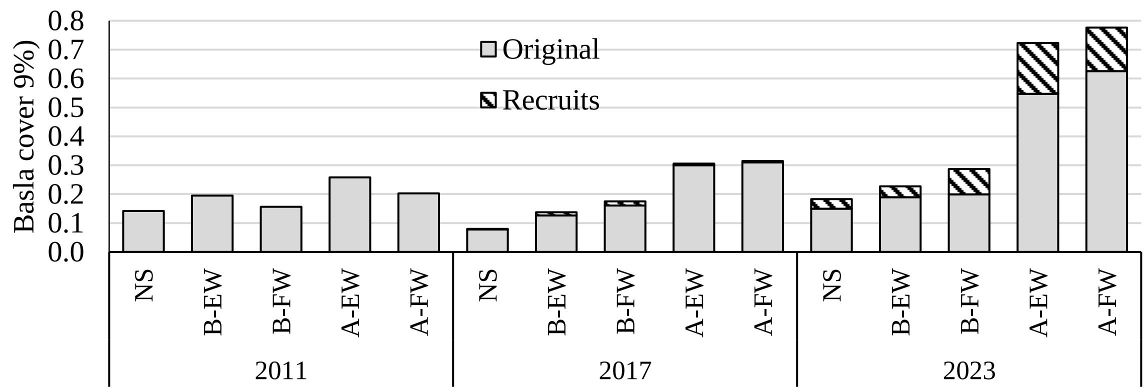

Fig. 3. Contribution of original 2011 plants and new recruits to total basal cover of B. ewartiana under different spelling regimes in 2011 and again in 2017 and 2023.

Discussion

The present study has shown that recovery of land condition can occur with the application of wet season spelling but that this can be an extended process, particularly during below-average rainfall conditions. This partly reflects the fact that *Bothriochloa ewartiana,* the key perennial grass, is a long-lived species whose recruitment appears to be limited by low seed production. These results strongly emphasise the importance of maintaining existing plants by good management, particularly going into drought, as recruitment is very slow (Orr and O'Reagain 2011).

The present results also show that recovery is far faster under annual wet season spelling than under less frequent regimes. This suggests the need for some form of rotational grazing if recovery is to occur. Importantly, spelling had no effect on *B. ewartiana* basal cover under heavy stocking. This clearly indicates that the effect of stocking rate overrides that of spelling, that is, the benefits of spelling are only likely to be realised under appropriate stocking rates.

Acknowledgements
This paper is dedicated to our late friend and colleague Paul Jones who initiated and led this project. The trial is funded via a Meat and Livestock Australia, Queensland Department of Primary Industry and Federal Government donor company project. Animal ethics approval was obtained under SA 2022-11-862.

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Can the principles of multipaddock grazing accelerate land condition recovery?

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Key words: short duration grazing; landscape recovery

Abstract

Recovery of land condition would significantly improve livestock carrying capacity and ecosystem services on many properties in northern Australia. Unfortunately, this is often extremely slow, even with significantly reduced stocking rates and pasture resting. There is interest amongst graziers in using the principles of intensive, multi-paddock, rotational grazing systems to accelerate recovery. However, evidence for their effectivity relative to conventional recommendations is often anecdotal and sometimes contradictory.

To test the ability of these principles to accelerate land condition recovery, a short duration grazing treatment (SDG) was implemented on two poor condition paddocks in a long-term grazing trial in north Queensland, Australia. Two experienced multi-paddock practitioners have been engaged to guide management. The treatment results can assist to develop cost-effective, evidence-based guidelines to accelerate recovery on grazing lands in northern Australia.

Introduction

Land condition has declined in many parts of northern Australia due to grazing practices that have reduced carrying capacity, productivity and ecosystem services. Recovery of the land condition of these areas will have substantial financial and ecosystem benefits but can be extremely slow even with significantly reduced stocking rates and pasture rest, e.g., McIvor (2001). There is growing interest amongst graziers in the use of multipaddock rotational grazing (MPG) to accelerate recovery. These systems vary but in essence involve short grazing periods, moderate to high stock densities and long rest periods, all applied adaptively.

Evidence for the superiority of MPG systems relative to simpler, more conventional, systems involving, for example, moderate stocking and occasional spelling is nevertheless contested (O'Reagain and Turner 1992; Briske *et al.* 2008; Hall *et al.* 2014). However, previous grazing trial research on MPG systems has been criticised as being unrepresentative of industry practice due to the small, relatively uniform paddocks often involved. The rigid application of MPG treatments in research rather than the more flexible, adaptive application adopted by most MPG practitioners has also been highlighted (Teague *et al.* 2013).

To test the ability of such systems to accelerate land condition recovery relative to conventional management, an MPG treatment, termed Short Duration Grazing (SDG) was established on a long-term grazing trial in north Queensland, Australia. The treatment involves applying the key principles of short grazing periods, increased herd density, and long rests (Teague *et al.* 2013) to two previously overgrazed paddocks in poor condition. To address the issue of scale, paddocks are relatively large (100 ha) and spatially heterogenous. Two producer advisors, both experienced MPG practitioners, were engaged to guide management. Here we report on the first year's application of the SDG treatment and its performance relative to the other grazing strategies in the trial.

Procedure

The trial is located on 'Wambiana' (20° 34' S, 146° 07' E), a commercial cattle station 70 km south of Charters Towers, Queensland, Australia. Long term (114 year) mean annual rainfall is 643 mm (C.V.= 40%), with 70% falling in the hot summer months. The vegetation is an open *Eucalyptus-Acacia* tropical savanna overlying C4 tropical grasses. Soils are relatively infertile, ranging from texture contrast to heavy clays. The main trial was established in 1997 with five grazing strategies: heavy stocking (HSR: 5 ha/AE [1 AE=450 kg steer]), moderate stocking (MSR:10 ha/AE), rotational wet season spelling (R/Spell: 10 ha/AE) and flexible (Flex) stocking (4 to 20 ha/AE) applied with/without spelling (S). Treatments are replicated twice. In May 2022, the HSR strategy was terminated with these paddocks used for the SDG treatment from November 2023 onwards.

Paddocks are approximately 100 ha in size and contain a mix of soil-vegetation types in similar proportions. Treatments are grazed by Brahman cattle managed according to industry recommendations (O'Reagain *et al.* 2009). For the SDG treatment, a large herd of cattle from the surrounding property is utilised.

Grazing management and data collection

Prior to grazing, SDG paddocks were assessed and a weighted forage budget based on the proportion of usable forage and a 25% utilisation rate of the 3-P species used to calculate the number of stock grazing days available. The appropriate grazing period was then calculated for each paddock based on the number, weight and reproductive status of the cattle available.

To monitor treatment effects pasture species composition and yield were assessed in the late wet season (May) using the Botanal procedure (Tothill *et al.* 1992). Pasture species are grouped for presentation as: 3-P grasses (palatable, preferred perennials), 2-P grasses (palatable/productive, perennials), annual grasses, legumes, wiregrasses (*Aristida* and *Eriachne* spp.) or 'other' (other grasses, forbs and sedges). An attempt was made to measure animal weight gains using remote Optiweigh[15] walk over platforms but given the short grazing periods, this was unsuccessful. Faecal samples were also collected for diet quality analysis but are yet to be analysed.

Results

Seasonal conditions and treatment implementation

Following nine consecutive (2012-2022) below median, rainfall years, the 2021/22 season was particularly harsh, with extremely low pasture availability at the end of the usual wet season in May 2022. Given the lack of forage (<500 kg DM/ha), the HSR, MSR and R/Spell paddocks were destocked. The two Flexible stocking strategies remained stocked as the progressive adjustment of stocking rates in preceding years had ensured sufficient forage for the approaching dry season.

Paradoxically, the destocking decision was followed by record winter rains, resulting in exceptional (1064 mm), well distributed precipitation over the 2022/23 season. Consequently, the HSR, MSR and R/Spell paddocks

[15] Optiweigh, Armidale, NSW, Australia

experienced a full year's rest under ideal conditions. The MSR and R/Spell were fully restocked in June 2023. The former HSR paddocks were also lightly stocked (12 ha/AE) for four months from July to October 2023.

The SDG treatment effectively began in November 2023 with these paddocks rested for five months until late March 2024 when they were grazed by 354 heifers (443 AEs) for 1.5 and 2 days each. The paddocks were grazed again in late July 2024 by 406 cows (500 AEs) for 2 and 3 days each. These two grazing periods yielded 26 stock days/ha (averaged over both paddocks), compared to the 29 to 36 stock days/ha/year removed from the other treatments on the trial.

Pasture composition

Total pasture yield and 3-P grass yield increased more than four-fold in the SDG treatment between the end of the HSR treatment in 2022 and the start of the new treatment in 2024 (Figure 1). However, the fact that yields also increased to a similar extent in all treatments indicates that this response was almost entirely due to the exceptional rainfall received and the long intervening periods of rest before the SDG treatment was initiated. Interestingly, despite these favourable conditions, both total and 3-P species yield were still lower in the SDG than in the other treatments. This appears to reflect the legacy of the previous 26 years of heavy grazing on the condition of these former HSR paddocks. This legacy effect will be accounted for by comparison of pasture change relative to the other simpler, systems in the trial.

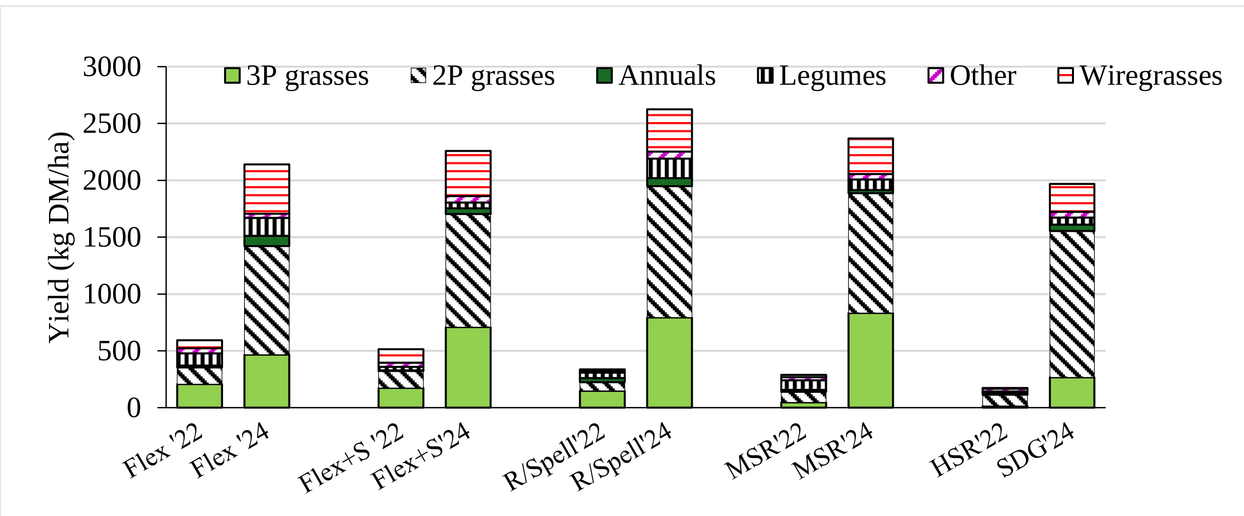

Figure 1: End of wet season (May) pasture DM yield and species contribution to yield in the Short Duration Grazing treatment (SDG) in 2024 compared to the other treatments in 2022 and 2024. See text for abbreviations.

Despite these initial positive results, the available evidence suggests that full recovery is likely to be very slow, e.g., McIvor (2001). In other work at the Wambiana trial site, the key perennial grass *Bothriochloa ewartiana* took nearly 12 years to recover following previous overgrazing, despite reduced stocking rates and annual wet season spelling (O'Reagain *et al.* 2023). Nevertheless, recovery could well be faster in the SDG treatment given the longer, more frequent rest periods and the close matching of grazing pressure to forage availability.

Discussion

The SDG treatment will be continued with the key principles applied adaptively, based on seasonal conditions and pasture response, allowing changes in land condition to be compared to the other simpler, more conventional management treatments on the trial site. Grazing exclosures within the SDG treatment will also allow the separate effects of complete rest and rest with managed grazing on recovery to be quantified.

One challenge will be assessing animal production in the SDG to enable a full assessment of the costs and benefits relative to other systems. An attempt is being made to assess weight gains using remote walk over weighing technology but given the very short grazing periods has not been successful. However, diet quality data combined with stock days per hectare may allow the profitability of the SDG system relative to other treatments to be modelled. Whatever the outcome, these results will be valuable in informing industry of the relative ability of different management techniques to accelerate recovery of paddocks in poor condition. We look forward to reporting this data as the project continues.

Acknowledgements
The Wambiana trial is funded by the Queensland Government, and Australian Government through the Meat and Livestock Australia Donor Company. We thank producer advisors Jamie Gordon and Fran Lyons and the Lyons family of Wambiana for supplying cattle for the SDG treatment. Animal ethics approval was obtained under SA 2022-11-862.

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Legume establishment in challenging environments of northwest Queensland

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Abstract

Establishing legumes on Mitchell Grass Downs country in northwest Queensland has the potential to reduce seasonal nutritional deficiencies, and subsequently increase animal performance within beef production systems. Legumes present an opportunity to increase crude protein (14 to18%) and metabolizable energy (8 to10 MJ/ME/kg DM) in the diet, as the nutritional quality of grass dominant native pastures declines markedly during the dry season (May to October).

Recent research initiated by the Queensland Government, with support from the Australian Government and Meat and Livestock Australia (MLA), has trialled establishment of deep-rooted and productive legumes (*Desmanthus, Stylosanthes*) on a property 80 km northeast of Julia Creek, Queensland.

This site is characterised by naturally treeless cracking clay soils, highly variable summer-dominant rainfall, (550 mm average annual rainfall, CV=0.43) and is highly susceptible to drought. The soil contains adequate Colwell phosphorus levels for legume growth (12mg/kg), however, sulphur (MCP) is low (4.6mg/kg). Rainfall variability, highly competitive adapted annual grass species and high summer temperatures (average maximum of 38ºC) make establishment of legumes difficult.

In January 2024, following 350mm of rain, uncoated *Stylosanthes seabrana* (Caatinga stylo, Primar) and scarified *Desmanthus* (Ray and Progardes) was broadcast onto cultivated strips (10 m wide) prior to further anticipated rainfall. No herbicide or fertiliser was applied. Assessment in March 2024 showed good seedling populations of desmanthus (~20/m^2) with fewer Caatinga stylo (~5/ m^2). In May 2024, the survival of seedling populations under a dense monoculture of Flinders grass (*Iseilema spp.)* was observed. Further measurements will be completed following the 2024/2025 wet season to confirm successful establishment of mature *Desmanthus* and *Stylosanthes* on this site. This research was initiated due to regional producer interest and will be utilised in extension efforts under the north Queensland Pasture Resilience Program (https://futurebeef.com.au/resources/qprp/).

Introduction

Queensland's beef cattle industry is the largest across all Australian states, with 10.7 million head (49% of the national herd) being recorded in Queensland (MLA 2022). The Northern Mitchell Grass Downs country in northwest Queensland has a semi-arid climate, with summer dominant rainfall typically from November to April. Wet season rainfall is reliant on the monsoon trough, and this is followed by a consistent and extended dry period from May to October. During this dry period, the quality of native perennial pastures, Mitchell grass (*Astrebla* spp.*)* and the highly competitive annual grass species Flinders grass (*Iseilema* spp.*),* declines significantly. This decline results in a nutritional deficit for beef cattle production, one of the area's main industries.

The production systems in the Northern Downs are predominantly extensive beef cattle grazing businesses on ‘unimproved’ rangelands native pastures (Chilcott, 2020). Desmanthus (*Desmanthus* spp.) and Caatinga stylos (*Stylosanthes seabrana*) are potentially useful legumes for the region due to their persistence on heavy clay soils in low rainfall environments under grazing, and high levels of seed production enabling them to recruit new plants for long-term pastures (Hall, 2005, Peck, 2012). Introducing legumes into the grazing environment provides an additional, readily-digestible feed source containing improved crude protein (14 to18%) and metabolizable energy (8 to10 MJ/ME/kg DM), mitigating the dry season nutritional shortfall. Compared to grass-only pastures, legume-grass pastures allow cattle to select a diet of higher quality and digestibility, often leading to increased intakes and improved animal production (live weight gain, reproduction) (Gardiner, 2016). Long term stocking rates for land in good condition vary from 10 to 15 ha for an Adult Equivalent animal (450 kg steer).

Northwest Queensland is considered a challenging environment for legume establishment due to its low annual average rainfall (550mm), high rainfall variability (CV=0.43), high summer temperatures (average maximum of 38ºC) and susceptibility to drought (Chilcott, 2020). Treeless cracking clay soils that are common in this area experience surface crusting that challenges seedling emergence if there has been rain after sowing and before seed germination. Soil phosphorus fertility is generally adequate for legume growth (Colwell 12mg/kg); however, sulphur is low (MCP 4.6mg/kg). Although responses to applied P and S are likely, application of fertiliser on extensive areas is costly and overall is not considered a viable option for legume pastures in this region.

Establishment of suitable legume strips into existing Mitchell and Flinders grass pastures has the potential to help to lessen the seasonal protein and energy shortages for grazing animals and support improved animal weight gain and production. The deep tap root of these legumes supports the production of green leaf well into autumn and winter. Additional benefits expected from introduction of legumes also include increased access to high quality forage, increased nitrogen fixation in the soil and thus improved soil fertility.

In response to regional grazier interest into methods to effectively establish pasture legumes in the region, a small on-property demonstration was developed by Queensland’s Department of Primary Industries with support from the Australian Government and Meat and Livestock Australia. This site will be utilised under the Queensland Pasture Resilience Program to demonstrate feasible options for establishing legumes in northwest Queensland under challenging environmental conditions.

Methods

Following 350mm of rain and prior to further anticipated rainfall, a 10-ha unfenced site within a larger paddock was directly sown into 6m x 1000m strips. Caatinga stylo (Primar) and desmanthus (Ray and Progardes*)* were tested for germination performance (8/16 hours, 20/35° Dark/Light) and treated for hard seed dormancy by mechanically scarifying seeds prior to planting. The site had previously contained dense Flinders grass that had been baled to reduced existing dry matter. Sowing rates were adjusted to account for low germination percentage (hardseed content) and are presented in Table 1. No herbicide was applied.

No fertiliser was applied to best replicate typical extensive beef production systems in the region and to determine viable options for legume establishment in existing soil conditions. The seed was oversown into the cultivated strips using a fertiliser spreader. Rainfall on the site (30mm) shortly after planting prohibited planned rolling from occurring. A further 130 mm of rainfall was recorded from planting until the first assessment. At the first assessment in March 2024, seedling populations were recorded based on frequencies per m^2. Observations in May 2024 confirmed seedling survival. Further population counts, and pasture yields will be taken at the end of the 2024/2025 wet season.

Table 1. Legume species and adjusted sowing rates used in the legume establishment trial

Species	Variety	Recommended sowing rate (kg/ha)	Acceptable germination %	Germination test %	Adjusted sowing rate (kg/ha)
Desmanthus	Ray and Progardes	2 kg/ha	70%	60%	2.3 kg/ha
Caatinga stylo	Primar	2 kg/ha	70%	40%	3.5kg/ha

Results and Discussion

Initial seedling establishment was successful for Desmanthus populations (~20/m^2), but fewer Caatinga stylo plants (~5/ m^2) were recorded in the trial strips. The seedlings were small (estimated 3 to10 cm in height) however, and under a dense monoculture of Flinders grass. Most of the seedlings survived until May when the Flinders grass began to senescence but would undoubtedly have suffered from competition for light and nutrients. The rapid establishment of Flinders grass seedings needs to be considered when using cultivated strip systems. Potential options could be staggered cultivations to kill Flinders grass seedlings before sowing, either by repeated cultivation or application of a suitable herbicide before or immediately after sowing, or the use of selective herbicides to control the grasses post-emergence.

Despite the competition from the Flinders grass, this small strip trial indicates potential for simple approaches to desmanthus and Caatinga stylo planting and establishment into northwest Queensland Mitchell Grass Downs pastures. If further yield measurements confirm successful establishment, it may pave the way for successful adoption of legumes into these environments, with a range of associated benefits for pasture quality, soil improvement and animal performance.

Acknowledgements

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Crafting a New Narrative for Sustainable Rangeland Management in Africa

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Institutional capacity building and co-design of novel management practice unlock greater potential in communal grazing lands in Sub-Saharan Africa

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Key words: capacity building; grazing management; rangeland restoration; pastoralism; aridity

Abstract

In communal grazing lands in Sub-Saharan Africa, two immediate problems face pastoralists and other users of communal lands: (1) weak local institutional oversight of common pool resources in grazing lands; and (2) inadequate evidence for the cost-effectiveness of various grazing management and restoration practices, especially in arid and other non-equilibrium rangelands. In this synthesis of local capacity development and restoration work across multiple systems and locations, it is shown that there are significant commonalities in terms of how progress may be achieved, as well as a number of important differences. Specifically, shared commonalities include: capacity building of grazing management institutions improves local oversight; local or ‘traditional’ knowledge may be generally sufficient for grazing management, though can improve with appropriate integration of global or ‘expert’ knowledge; local knowledge may be generally insufficient for restoration, but has a strong role to play; implementing new grazing management or restoration practices requires fitting to local systems, plans, and goals; this fitting can be accomplished through pastoralist–expert co-design of grazing and restoration practices; and, as decades of development experience have shown, new grazing management or restoration practices that fit local conditions poorly are generally ineffective or unsustainable. Differences among systems and locations include aridity and associated equilibrium (more humid rangelands are less variable) and non-equilibrium (more arid rangelands are more variable) ecosystem behavior; degree of privatization; livelihood priorities (crops, livestock, or both) and management goals; scale of grazing lands and their institutions, and processes and rate of capacity development; degree of previous degradation and rate of change in range condition; and the technical practices applied. Not only are these commonalities and divergences useful for improving environmental performance including carbon storage, they are essential to supporting local pastoralist institutions to enhance resilient livelihoods.

Introduction

Communal grazing lands in Sub-Saharan Africa face two immediate challenges—the strength of local institutional oversight, and inadequate evidence for the cost-effectiveness of management practices. Local institutions responsible for management of common pool resources in grazing lands have become weakened (Reid et al. 2014) in many pastoralist rangelands around the world, partly due to weak security of land tenure, lack of investment and support, and policies that are inadequate or ill-fitting in communal rangelands. Where cohesive communal management does not exist at local level, weak oversight allows for chaotic and disorganized grazing patterns, a significant driver of rangeland degradation in combination with climate change-induced volatility in rainfall. Meanwhile, evidence for the relative cost-effectiveness of various grazing and restoration practices is generally inadequate (Mudau et al. 2022) or even absent, and most especially so in arid rangelands. While pastoralist local knowledge on grazing management is generally strong, local knowledge on restoration is often less developed and effective in addressing new challenges linked to climate change and other pressures upon rangeland systems. Experience in local capacity development, and in restoration co-design, across multiple systems and locations shows several commonalities among rangelands, as well as important differences that are often associated with variation in aridity.

Results

Commonalities among rangelands and regions

Capacity building of local institutions can significantly improve oversight of grazing management. Improvement in local institutional capacity to manage rangelands is a commonly noted initial result of CBRM approaches, time and again, from southern (Coppock et al. 2022) and East Africa (Reid et al. 2021, Waweru et al. 2021) to central Asia (Ulambayar and Fernández-Giménez 2019). Neither good nor poor management should be assumed, as in practice, rangelands with poorly functioning local institutions can be as common as those functioning well, generally speaking. The goal of practitioners supporting community range management should be helping local institutions to progressively and sequentially develop and intensify their system toward optimal livestock production and environmental performance. Introducing new grazing management or restoration practices requires fitting into local systems, plans, and goals (Bayer and Waters-Bayer 1989), and producer–practitioner–researcher co-design of grazing (Sircely and Seidou 2018) and restoration (Sircely and Seidou 2018, Sircely et al. 2022) practices can accomplish this fitting.

In many rangelands, local or traditional knowledge can be sufficient for reasonably sustainable pastoralist rangeland livestock production, with modest impacts on rangeland ecosystems, and high wildlife compatibility, often in spite of dramatic climatic volatility. Local or traditional knowledge is highly useful for grazing management (Reid et al. 2014, Sircely and Seidou 2018), yet appropriate and cost-effective integration of global or 'expert' knowledge may significantly benefit management through regenerative grazing techniques. However, it remains exceptionally difficult to prescribe grazing management practice that can deliver win-win pastoralist livelihoods and environmental conservation (Bayer and Waters-Bayer 1989, Ferguson 1990). Prior understanding of basic spatial patterns of local rangeland use through the seasons of the year is required before advising a certain community on a basic grazing plan, into which restorative or regenerative grazing techniques can be fitted (Robinson et al. 2020), as feasible given the various constraints they face. To ensure that novel grazing practices are successful, practitioners and researchers must first understand the basics of local systems, by mapping out the rangeland with pastoralists, and clarifying their formal or informal grazing plans and bylaws or other means for encouraging adherence to these grazing plans. Potentially effective and feasible means of improving the grazing plans can then be suggested by practitioners or researchers (Robinson et al. 2020). Most of the proposed options are likely to be rejected by pastoralists as infeasible. Any options that are not rejected can be considered further, or the proposed options can be modified to improve feasibility.

For rangeland restoration, local knowledge is useful—and often essential—although producer–expert co-design will generally produce better tailored, more effective, more sustainable, strategic rangeland investments. The degradation observed in most rangelands is historically a relatively new problem, one significantly attributable to erratic rainfall resulting from global climate change (Girvetz et al. 2019), along with other more recent trends such as conversion to farms or private lands that place great pressure on communal rangeland systems (Galvin et al. 2008). In rangelands, foresight for a decade or more ahead is an absolute requirement for effective restoration planning. To achieve this type of vision, the fusion of global scientific knowledge (if shallow or 'skin-deep') with highly local producer knowledge (yet deep over decades to millennia) may be considered fundamental. The role of researchers in producer–practitioner–researcher collaborative design infuses research with both internal and external validity (Sircely et al. 2022). Site selection and restoration technique targeting to specific sites serve as an excellent example—pastoralists sometimes wish to pursue more "modern", intensive techniques on severely degraded lands, at high cost per area and with a moderate or higher risk of failure. Alternatively, the same resources might be better invested in the restoration of much larger areas, through less intensive or more passive techniques in lands only moderately degraded, at low cost per area and with a low risk of failure. Benefit:cost analyses are desperately needed to quantify the cost-effectiveness of various restoration techniques across gradients of contextual factors in rangelands, especially aridity. Development of low-cost, 'light-touch', ecosystem-based techniques, enabling feasible restoration of very large rangeland areas, is needed to provide alternatives to costly measures with mixed success rates (Mudau et al. 2022). For restoration, experience shows that producer–practitioner–researcher co-design and testing of restoration techniques, combined with support on restoration planning, is an effective strategy to identify, plan, and implement rangeland restoration at scale.

Differences among rangelands linked to aridity

In arid desert and semi-desert zones (e.g., < 350 mm/yr in the tropics), an individual rangeland (or 'rangeland unit' managed by a particular local rangeland management institution) will generally be much larger than in semi-arid zones (in turn larger than in humid climates), much like private ranches. As a result, pastoralist institutions that oversee rangeland management operate at vastly different spatial scales, from < 100 km^2 in wetter semi-arid climates to > 5,000 km^2 in the most arid zones in East Africa, for example. As aridity increases, livelihood alternatives to livestock become much more limited, with rainfed cropping infeasible in arid areas and access to markets and services severely restricted by the remoteness of many desert areas. As livelihood priorities shift toward livestock, so too do land management objectives. In semi-arid regions, where rainfed cropping and non-mobile livestock production are often feasible, the rate and degree of privatization of communal land are often much greater than in arid zones. Each of these factors contributes to the lower populations in arid regions, as well as lower livestock densities. As scale increases, so too do transport and transaction costs for local institutions, along with the need for local institutions to communicate and coordinate with lower-level sub-units of a rangeland covering a vast area. These social constraints combine with the fundamental control of low and variable rainfall to determine the feasibility and cost-effectiveness of various rangeland management options along the gradient from semi-arid to arid rangelands.

Aridity has mixed costs and benefits for rangeland livestock production. Agro-ecologically, there are dramatic differences between wetter semi-arid savanna rangelands and arid desert and semi-desert rangelands. Low and extremely variable rainfall in arid rangelands requires people and livestock to be more mobile, enhancing the resilience of these rangelands to degradation in terms of woody encroachment and loss of grass cover, and enabling these rangelands to respond quickly to restoration. In more arid zones, non-equilibrium rangeland dynamics prevail (Ellis and Swift 1988), where extreme variability in rainfall makes prediction of spatial patterns of rainfall nearly impossible at the scales of rangeland management, and where carrying capacity rises and falls annually or seasonally depending on how much rain falls (Behnke and Scoones 1992, Campbell et al. 2006). Equilibrium rangeland dynamics, in which predictable rainfall enable more confident forecasting of carrying capacity, occur in more humid rangelands and in wetter semi-arid rangelands. Not only are non-equilibrium rangelands more variable, they are less susceptible to degradation (von Wehrden et al. 2012), and are often in a less degraded state than many semi-arid rangelands. Social factors that contribute to the lower vulnerability of arid rangelands to degradation include the the lower likelihood of receiving pastoralist visitors from elsewhere, both during the annual dry seasons and during major large-scale droughts, along with decreasing susceptibility to forcible invasion given that these areas dry out before semi-arid zones. Finally, lower rainfall and the infeasibility of rainfed cropping in most arid rangelands reduces their susceptibility to farm conversion and rangeland fragmentation, which often lead to further degradation of rangelands. Consequently, changes in rangeland condition in response to restoration or modified grazing management are generally much faster in arid than in semi-arid rangelands.

As a result, the technical practices applied by pastoralists often change with aridity—high rainfall variability often leading to more flexible, opportunistic management (Westoby et al. 1989). In arid areas, grazing management practices often become less reliant on predictable, pre-planned, prescribed resource use, and more reliant on the flexibility that allows tracking and utilization of rapidly changing resources in an opportunistic manner. Similarly, decision-making processes and the means for achieving community members' adherence to bylaws and management plans are often more flexible and less prescribed in advance, rather evolving in real-time as conditions change in these erratic environments. Restoration practices should generally differ (Sircely et al. 2022), with large arid rangelands requiring more low-cost, 'light-touch', ecosystem-reliant techniques as opposed to heavily input-reliant intensive restoration approaches that may cost more than they produce.

Discussion

The commonalities and aridity-linked divergences noted here may be practically useful in several ways to those seeking to support pastoralists to enhance resilient livelihoods. The uses may include, but are not limited to, approaches for capacity building of local pastoralist range management institutions, as well as enhancing the environmental performance of rangeland restoration in pastoralist areas. Aridity, scale, and remoteness arguably constrain almost all aspects of land management in communal pastoralist rangelands, firstly by limiting the production of forage and browse, livestock, and other ecosystem services. In arid zones, the long distances and low population density reduce market access, increase the cost of service delivery, and create large transaction costs for local institutions responsible for coordinating grazing management. Limited livelihood options in arid rangelands leads to greater livestock-dependence. Grazing practices generally differ along this aridity gradient, becoming more flexible and opportunistic, as do decision-making and means for achieving adherence to bylaws. Restoration practices should generally differ as well, with large arid rangelands requiring more ecosystem-reliant techniques as opposed to input-reliant approaches.

Greater emphasis should be placed on conducting basic research in truly arid systems, including validation of remote sensing and ecosystem simulation models, documentation of local or traditional management goals, practices and their effects, and integration of these to bring pastoralist rangeland management into the 21st century through co-design processes. The extreme variability and context-dependency of socio-ecological dynamics in arid rangelands most especially underscores the need for action research and co-design. In the meantime, the important aridity-related differences highlighted here, as well as the commonalities among pastoralist rangelands, provide significant information that can greatly inform the design of rangeland management and restoration approaches for communal pastoralist rangelands.

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Local feeding practices as mitigation option for low-carbon livestock systems in Sub-Saharan Africa

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Key words: Crop residues; legume trees; supplementary feeding; ruminants; enteric methane; Africa

Abstract

Enteric methane emissions (eCH_4) from ruminants are the main source of greenhouse gas (GHG) from the livestock sector in sub-Saharan Africa (SSA). The SSA countries face significant challenges in assessing their climate commitments in the livestock sector, particularly in terms of mitigation measures due to the lack of accurate GHG data obtained through *in vivo* measurements. The objective of this study was to directly measure and analyze eCH_4 in pastoral and agropastoral systems using an advanced methodology: the GreenFeed® system. Different ruminant feeding strategies were tested with the aim to identify those that contribute to the reduction of absolute emissions, emission yield, and emission intensity. Cattle were fed natural rangeland fodder, cultivated forage (green and hay), and combinations of grass with main crop coproducts or legume tree forage. Data collection lasted 2.5 years and included 35 trials (diets). Each trial lasted 3 weeks and was split into 2 weeks of diet adaptation and 1 week of data collection. The dry matter (DM) intake in animals was 20±2.4 (12 to 29 g/kg of body weight per head), the DM digestibility, 48±4.6 (30 to 70 %), and the eCH_4 emissions, 70±17.8 (28 to 114 g/d per head). Green herbaceous forage and tanniferous forage, such as legume tree forage and legume crop co-products, showed good potential to increase livestock productivity and reduce eCH_4 emissions yield by up to 33%. These results will help policymakers promote clean technologies and sustainable livestock practices in SSA, and help implement the IPCC Tier 2 methodology to accurately estimate emission factors by cattle categories and breeds.

Introduction

In extensive livestock farming (pastoral and agropastoral) in Sub-Saharan Africa (SSA), animal productivity is low, resulting in higher emission intensities (mass per unit of product) and yields (mass per unit of intake). Depending on the type of ruminant livestock system, enteric methane (eCH_4) can contribute up to 61% of total carbon emissions from a livestock system (de Figueiredo et al. 2017). According to Gbenou et al. (2024a), the hot dry season has the greatest potential for eCH_4 mitigation because it is the period when eCH_4 yields are very high.

The low quantity and quality of feed resources during this season on rangeland that prevents the rumen from functioning optimally is one of the causes.

Feeding strategies suggested in the international literature on GHG mitigation, in particular eCH_4, are often not adapted to the SSA context because they involve costly inputs that are inaccessible locally. Furthermore, they sometimes are in competition with animal productivity and are technically complex to apply. In contrast to these literature strategies, SSA's livestock farmers have access to a variety of crop coproducts, tree legumes, and agro-industrial byproducts, which they use for feeding their animals in agropastoral systems (Gbenou et al., 2024b). The aim of this study was to test the eCH_4 mitigation potential of these locally available and accessible feed resources with the goal to promote low-carbon livestock system in SSA.

Methods

The study was carried out at an experimental station in South-Western Burkina Faso. The study involved ten Sudanese Fulani zebu steers of 2.7±0.1 years and 138.4±10.1 kg average, kept in a barn. Grasses, such as *Panicum maximum* C1 (hay and green), *Andropogon gayanus* (hay), and *Brachiaria ruziziensis* (hay), and rangeland fodder (hay or green), according to seasons were used to feed the steers. Cattle were also supplemented with the most commonly used livestock feed, selected from a survey of farmers: cereal coproducts (maize, sorghum, millet and rice straws), legume coproducts (cowpea and peanut haulms), and tree legumes (*Gliricidia sepium* and *Leucaena leucocephala* dry leaves). The animals were fed at an intake level of 3.2% or 2.3% of their body weight (BW) in dry matter (DM). The grasses and rangeland fodder were provided as stand-alone control diets (100%) or mixed with crop coproducts or LEGTREE legume in constant proportions (75:25 on a DM basis, experimental diets). Access to lick stone and water was *ad libitum*. Data collection lasted 2.5 years and included 35 trials (diets). Each trial corresponded to a diet and lasted 3 weeks split into 2 weeks of diet adaptation and 1 week of data collection. The diets were grouped into four categories: 1) grass diets (diets with 100% *P. maximum* C1, *A. gayanus*, *B. ruziziensis*, or rangeland fodder - GRASS), 2) cereal coproduct diets (mixed diets containing grass and cereal coproduct at 75:25 ratio - CEREAL), 3) legume coproduct diets (mixed diets containing grass and legume coproduct at 75:25 ratio - LEGUME), and 4) tree legume diets (mixed diets containing grass and leaves of tree legume at 75:25 ratio - LEGTREE).

Table 1: Average chemical composition of diets offered to Sudanese Fulani zebu steers.

Item	GRASS	CEREAL	LEGUME	LEGTREE	SEM	P-value
DM (g/kg diet)	96.1	92.2	92.5	94.6	0.01	0.074
OM (g/kg DM)	823.8 ^{B}	806.5 ^{D}	817.0 ^{C}	909.6 ^{A}	0.09	<0.001
CP (g/kg DM)	26.9 ^{C}	29.0 ^{C}	61.8 ^{B}	99.9 ^{A}	0.14	<0.001
NDF (g/kg DM)	689.7 ^{A}	645.9 ^{C}	598.5 ^{D}	658.5 ^{B}	0.35	<0.001
ADF (g/kg DM)	429.5 ^{A}	400.5 ^{C}	386.1 ^{D}	408.3 ^{B}	0.18	<0.001
GE (MJ/kg DM)	16.5	16.2	16.5	19.1	0.04	0.103

GRASS: diets with 100% *P. maximum* C1, *A. gayanus*, *B. ruziziensis*, or rangeland fodder; CEREAL: mixed diets containing grass and a cereal coproduct at 75:25 ratio; LEGUME: mixed diets containing grass and a legume coproduct at 75:25 ratio; LEGTREE: mixed diets containing grass and leaves of tree legume at 75:25 ratio; DM: dry matter; OM: organic matter; CP: crude protein; NDF: neutral detergent fiber; ADF: acid detergent fiber; ADL: acid detergent lignin; GE: gross energy

A,B,C Values within a row with different superscripts differ significantly at $P < 0.05$

Daily individual DM intake was calculated as the difference between the quantities offered and refused. Daily excreted faeces were collected from faecal bags fitted to each animal for apparent digestibility calculation. Individual representative samples of feed (offered and refused) and faeces were collected daily, and their chemical compositions were determined using NIRS (CIRAD laboratory, Baillarguet, France), as described by Gbenou et al. (2024a, 2024c). The eCH_4 emissions were measured using a GreenFeed® (GF) unit (ID: 252, C-Lock Inc., SD, USA). Measurement times were tailored to the feeding behaviour of the animals, with random access to the GF unit at 6:30 am (overnight fast), 10 am (immediately after feed intake), 2 pm (during rumination) and 6 pm (immediately after feed intake and at sunset). On the 7th day (last day) of each trial, an additional measurement was performed at 00:00 (during total rest). The total number of visits was 29 per animal per feeding condition, exceeding the minimum number of 20 visits recommended by Manafiazar et al. (2017). Each animal spent an average of 3 min±02s (2min20s to 4min15s) at the GF unit per visit.

All statistical analyses were performed using R software version 4.1.2. (R Core Team 2021). The DM intake, apparent digestibility, and eCH_4 emissions were analyzed using the general linear model (GLM) procedure. The least squares means and their SEM presented a table were compared using the duncan.test (de Mendiburu 2023) in the event of a significant difference (P<0.05). The statistical model used for the variance data analysis was $Y_{ij} = \mu + C_i + (1 \mid A_j) + \epsilon_{ij}$, where Y_{ij} = variable of interest; μ = overall average; C_i = fixed effect representing the different diet categories; A_j = random effect representing individual variations among animals; and ϵ_{ij} = residual error.

Results

Chemical composition of diet categories

The CP contents in LEGUME and LEGTREE were twice and three times those of GRASS or CEREAL, respectively (Table 1). Fiber content was lower in all categories of mixed diets (P<0.001).

Diet intake and digestibility

The highest intake was obtained with LEGUME and LEGTREE. No significant difference in DM digestibility was observed between diets (Table 2).

Enteric methane emissions

All supplemented diet's categories (CEREAL, LEGUME and LEGTREE) induced eCH_4 yield (g/kg DMI) mitigation from 19% to 47% compared with GRASS (Figure 1). The eCH_4 mitigation in %GEI followed the same patterns in diet's categories (Table 2).

Table 2: Dry matter intake, feed apparent digestibility, and eCH_4 emissions by Sudanese Fulani zebu steers fed different diet categories

Item	GRASS	CEREAL	LEGUME	LEGTREE	SEM	P-value
DMI (g/kg LW)	16.4 ^{B}	18.0 ^{B}	25.5 ^{A}	26.2 ^{A}	0.31	0.006
DMd (g/kg DMI)	46.0	48.1	49.7	48.8	0.00	0.092
eCH_4 (g/kg DMI)	30.6 ^{A}	24.8 ^{B}	22.3 ^{BC}	20.0 ^{C}	0.53	<0.001
eCH_4 (% GEI)	9.3 ^{A}	7.9 ^{B}	6.8 ^{BC}	5.8 ^{C}	0.17	<0.001

GRASS: diets with 100% *P. maximum* C1, *A. gayanus*, *B. ruziziensis*, or rangeland fodder; CEREAL: mixed diets containing grass and cereal coproduct at 75:25 ratio; LEGUME: mixed diets containing grass and legume coproduct at 75:25 ratio; LEGTREE: mixed diets containing grass and leaves of tree legume at 75:25 ratio; DMI: dry matter intake, DMd: dry matter digestibility; eCH_4: enteric methane, GEI: gross energy intake

A,B,C Values within a row with different superscripts differ significantly at $P < 0.05$

Discussion and Conclusion

This study investigated local feeding practices with the aim of identifying mitigation options for low-carbon livestock systems in Sub-Saharan Africa (SSA). The feeding practices tested are among the most widely available in West Africa and the most commonly used by livestock farmers (FAO 2014; Sib et al. 2019). GRASS can provide sufficient quantities above the daily required CP (7% DM) recommended by NRC (2000) for ruminant maintenance. LEGUME and LEGTREE presented high nutritional quality (CP) compared with GRASS and CEREAL due to the nutritional quality of different resources used to supplement animals. In fact, legume crop coproducts are more nutritious than cereal crop coproducts (Jarial et al. 2020), and legume trees are more nutritious than legume crop coproducts (INRA 2018).

DMI varied according to diet categories. The highest intake obtained with LEGUME and LEGTREE was associated with their highest CP content (Gaviria-Uribe et al. 2020). There were no significant differences between GRASS and CEREAL intake, which hadsimilar nutritional qualities (CP, NDF and ADF). There was no significant difference in DMd between the four diet categories despite the intake improvement in LEGUME and LEGTREE, possibly due to the effect of anti-nutritional factors (Soltan et al. 2017).

This study's innovative feature is that it demonstrates how local feeding practices in a real-world setting can help design low-carbon livestock systems, specifically by using crop co-products and legume trees. The eCH_4 yield mitigation induced by mixed diet categories was 19, 33 and 47% for CEREAL, LEGUME, and LEGTREE, respectively, and could be explained by the tannin content in those diet categories. The mitigation rates induced by LEGUME and LEGTREE are higher than those obtained with the most promising feed additives (Red seaweed and 3-nitrooxypropanol - Bovaer®) in ruminants (EPLM 2024). However, the average eCH_4 yield (24.4 g/kg DMI) recorded across all diet categories (20 – 31 g/kg DMI) was similar to that reported by IPCC (2019) Tier 2 for SSA cattle. The rate of loss of GEI in the form of eCH_4 (Ym - 15 to 52%) that CEREAL, LEGUME, and LEGTREE prevent could be redirected in milk and meat production for improved food security in SSA.

In conclusion, compared with grass-exclusive diets, local feeding practices improve diet quality and influence intake and eCH_4 emissions in livestock. Diets based on cereal and legume co-products, and legume trees resulted in significant eCH_4 yield mitigation and consequently low-carbon livestock systems.

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Comprehensive strategies for sustainable rangeland ecosystem restoration

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Key words: Rangeland health; rangeland governance; rangeland assessment; regenerative grazing; multi-stakeholder engagement.

Abstract

The development of a resilient and sustainable pastoral landscape is crucial for reversing degradation and ensuring long-term ecological health. Historically, unsustainable practices and climate change have severely degraded these landscapes. The context for restoration involves complex socio-economic, cultural, and ecological factors, necessitating a holistic approach. Key risks and drivers of change include climate variability, land tenure conflicts, and socio-economic pressures on land use. This paper presents comprehensive strategies for sustainable rangeland restoration, drawing on over two decades of experience in arid rangeland restoration and supported by relevant existing literature. Effective planning requires a deep understanding of socio-cultural dynamics, land tenure, and rights to access, rather than focusing solely on biophysical and technical aspects. Identifying target groups that are homogenous and less prone to conflict is essential to initiate restoration efforts effectively. Setting clear restoration priorities and targets, determining appropriate interventions, and understanding the specific uses of restored areas are critical components of the planning process. The basic steps for restoring a degraded ecosystem include agreeing on a common goal, establishing robust governance structures, and devising effective strategies. Removing sources of degradation or conflict is fundamental, followed by physical and biological restoration efforts. Patience is vital, as ecological restoration is a time-consuming process. Success factors include multi-stakeholder engagement, leveraging institutional collaborations to enhance resource utilization and efficiency, securing long-term investments and commitments, and supportive national and local policies. Utilizing local practices and knowledge, along with community empowerment, ensures ownership and sustainability of the restoration process. In summary, intervention strategies for restoring degraded pastoral landscapes are site-specific, requiring tailored approaches rather than a one-size-fits-all solution. Restoration efforts must be coupled with effective management to be successful, and inappropriate policies can exacerbate damage. Developing national institutions' capacity through new tools, monitoring, and grazing management is essential for sustained restoration and rehabilitation efforts.

Introduction

The degradation of pastoral landscapes, particularly in arid regions, is a pressing environmental concern that threatens ecological stability and the livelihoods of pastoral communities. Unsustainable land use practices, exacerbated by climate change, have contributed to the widespread decline of these landscapes, leading to reduced productivity and biodiversity (Zhang et al. 2023). In fact, restoring degraded pastoral landscapes requires a multifaceted / holistic approach that integrates ecological, socio-economic, and cultural practices of the communities involved. As such, the restoration process must be rooted in a thorough understanding of local contexts, which includes identifying key risks such as climate variability, socio-economic pressures, and land-use conflicts (Semplici and Campbell 2023; Birhanu et al. 2024).

In addition to understanding these contextual factors, the success of restoration efforts hinges on planning that prioritizes stakeholder engagement, governance, and long-term sustainability (Gann et al. 2019). It is crucial to set clear restoration goals, determine appropriate strategies, and ensure the involvement of all relevant stakeholders. A collaborative and inclusive approach, leveraging local knowledge and institutional support, can help guide efforts and ensure that the restoration process is both effective and sustainable (Slayi et al. 2024).

This paper presents practical approaches for reestablishing ecological health in pastoral landscapes, drawing on two decades of experience in arid rangeland ecosystems. By examining key drivers of change and the essential elements of successful restoration. Through a synthesis of literature and case studies, critical factors that contribute to successful restoration and rehabilitation will be highlighted, with a focus on ensuring the long-term viability of both ecosystems and the communities that depend on them.

Participatory methodologies and approaches

The International Center for Agricultural Research in the Dry Areas (ICARDA) and in collaboration with the International Union for Conservation of Nature (IUCN) have developed a toolkit (Fig.1) which advocates for holistic approach for addressing the socioecological aspects leading to more resilient pastoral systems (Louhaichi et al. 2022). The key elements of the approach are listed below:

Set up the governance structure and build partnerships: This process begins with understanding the socio-cultural context, land tenure systems, and rights to access. Targeting relatively homogenous groups with minimal conflicts can further support restoration efforts (Naylor et al. 2012) Collaborative partnerships among stakeholders foster shared responsibility, optimize resource allocation, and drive innovative solutions to complex challenges

Identify the root causes of degradation: Conducting a thorough site evaluation is essential to uncover the underlying causes of rangeland degradation. These may include factors such as overgrazing, agricultural encroachment, invasion by woody plants, or unsustainable land management practices. Identifying these root causes provides the foundation for developing targeted interventions to restore and sustain the health of the rangeland ecosystem (AbdelRahman, 2023).

Define the overall goal and specific objectives: Restoration goals should be specific, measurable, and time-bound, aiming to improve soil quality, enhance biodiversity, or increase livestock productivity. Prioritization is key, focusing on the most critical areas for restoration based on the severity of degradation and the ecological importance of the site. Setting clear restoration and rehabilitation priorities, along with specific targets, is essential. This includes determining the type of intervention required, where it should take place, how it will be implemented, and what intended use, ensuring that the approach is tailored to local needs and conditions (Holl and Aide 2011).

Planning and Design: Engaging local communities and stakeholders in the planning process is crucial, incorporating traditional land-use knowledge to inform decisions. Restoration strategies should be tailored to local conditions, including species selection, grazing management, and erosion control measures. Additionally, it is important to plan for future climate variability to ensure that restoration efforts are resilient in the long term.

Set up robust monitoring protocols: Establishing comprehensive monitoring protocols is crucial for understanding and managing rangeland health effectively. Begin by assessing the current condition of the rangeland to create a reliable baseline for future comparisons. This involves examining key indicators such as soil health, vegetation cover, biodiversity, and erosion levels. Regularly updating this data provides valuable insights to inform adaptive management strategies, enabling timely responses to emerging challenges and supporting the long-term sustainability and productivity of rangeland ecosystems (Eyre et al. 2011).

Use site specific tools and procedures: Two rules to keep in mind 1) No "one-size-fits-all" approach exists, and (2) it is crucial to fix the physical structure (e.g., erosion) before addressing the biota. For arid ecosystems, water-harvesting techniques such as building check dams or contour lines are essential for retaining moisture and improving the hydrological balance. Vegetation management involves reintroducing native plants and grasses suited to local conditions to stabilize the soil and boost biodiversity. Therefore, before planting the right species in the right place, it is essential to conduct a thorough needs assessment, drawing on indigenous knowledge. The selection process should involve local communities to ensure the choices align with local contexts. Prioritize multi-purpose plant species based on both socio-economic and environmental criteria, with a preference for indigenous and well-adapted species. It is also crucial to select species that require minimal care and protection, reducing demands on capital and labor. Emphasizing social fencing over physical fencing can further enhance sustainability and community ownership (Brancalion and Holl 2020).

Grazing management: Grazing is a critical factor in any restoration. Whether the restoration technique used (i.e.: reseeding, planting shrubs and trees), grazing remains essential. For instance, long term protection (no grazing) can lead to the collapse of the entire ecosystem. Therefore, careful consideration must be given to the timing, intensity, and duration of grazing. Recently, there has been increased emphasis on regenerative grazing, which prevents overgrazing and promotes vegetation recovery (Bartley et al. 2023).

The SRM toolkit has been successfully adopted by the HERD project, funded by GEF, in West Asia. More recently, it was applied to a silvopastoral site in semi-arid Tunisia, which was recognized last year as one of the 12 selected success stories worldwide at the FAO Global Conference on Sustainable Livestock Transformation.

Conclusions/Implications

This paper presented comprehensive strategies for sustainable rangeland ecosystem restoration. In summary the key elements to keep in mind include: 1) engaging multiple stakeholders and fostering institutional collaborations to leverage resources, share knowledge, and enhance efficiency; 2) securing long-term investments from financing agencies alongside sustained commitments from key actors; 3) establishing favorable and supportive national and local policy frameworks; 4) integrating local practices and traditional knowledge into implementation strategies; and 5) empowering communities to take ownership of the restoration process.

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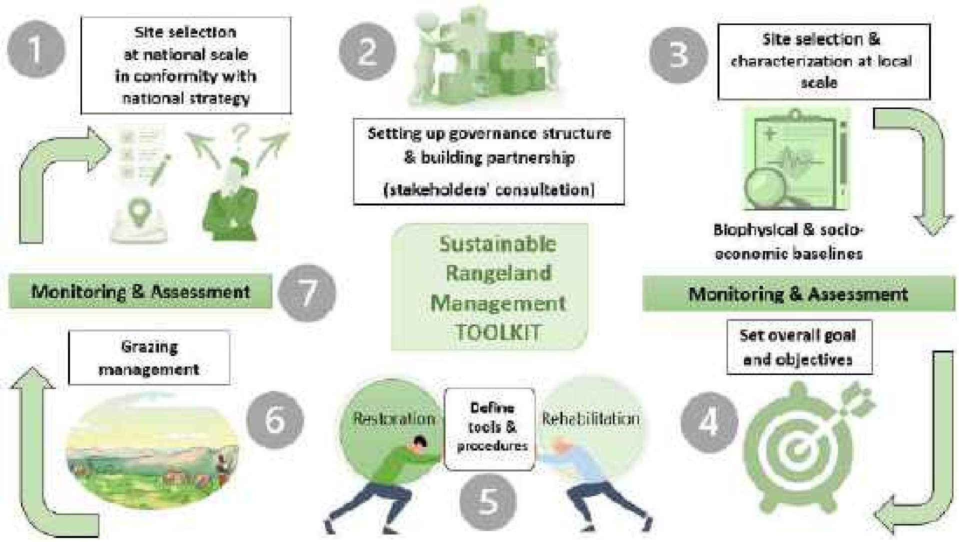

Fig 1. Comprehensive Sustainable Rangeland Management (SRM) Toolkit: A Step-by-Step Process for Developing Resilient Pastoral Systems

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In which biome is the most degradation happening? The case of croplands, rangelands, forests, and irrigation water in Tunisia

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Key words: Ecosystem services; combat resource degradation; valuation; inaction.

Abstract

This study estimated the quantities and monetary values of ecosystem services (ESS) lost due to in/inadequate action to control agricultural resource degradation in Tunisia. We used a combination of GIS, remote sensing, and data from publications and official statistics to generate estimates of total and percentage of crop lands, rangelands, and forests falling in one of three (low, moderate, and severe) degradation classes and the corresponding biomass yield (ton/ha). We used a combination of market and non-market valuation methods to estimate the value of ESS lost due to inaction. The estimates are provided for each biome x province combination.

Using extremely conservative assumptions, we estimated that in/inadequate action is causing Tunisia to lose at least 1.97 million tons of potential production of different food crops, 209 thousand tons of forest biomass, and 2.5 million tons of forage from rangelands, and at least 736 million cubic meters of irrigation water annually. In addition, Tunisia is losing at least 141.68 million tons of soil which is also associated with the release of at least 779 thousand tons of carbon into the atmosphere. Rangelands constitute 73.51% of the total national soil erosion out of which 67.7% is happening in the five Southern provinces where erosion rates as high as 52t/ha are recorded.

The monetary value of all the ecosystem services that Tunisia is losing annually in all biomes is estimated to be at least $2.17 billion (4.65% of GDP). The main cost of in/inadequate action in the country in monetary terms is related to crop lands which constitute 53.98% of this loss followed by irrigation water, and rangelands which contribute 28.19% and 12.09% of total cost of inaction, respectively. These estimates have generated much discussion among high officials in Tunisia on the need to solicit funds to control land degradation, especially in rangelands.

Introduction

Desertification induced by land degradation affects most of the dryland areas of the Tunisia and has the knock-on effect of contributing to climate change by releasing soil carbon into the atmosphere. The drylands of Tunisia, which are already challenging areas for food production are also experiencing loss of biodiversity and ecosystem services that support agrifood systems (Rosendahl, 2022). The impacts of degradation of agricultural resources in Tunisia is evident not only in terms of the growing difficulty for farmers to produce food, but also in terms of the growing gap between food demand and supply, leading to the country's growing dependence on imports, as well as the consistently increasing food prices which historically even led to popular uprisings. Loss of land productivity due to desertification and weather shocks is also a contributing factor to food and feed shortage and conflicts which are the major causes of forced migration of people, predominantly the youth, from dryland areas. Left unchecked, these challenges are expected to increase with time and put the inhabitants, particularly the farming communities, at greater risk.

Few studies were carried out in the past to estimate the extent and monetary value of resource degradation in the country. For example, a World Bank study covering all sectors (including agriculture, tourism, manufacturing, and transport) estimated the cost of environmental degradation in Tunisia in 1999 to be 2.1% of GDP (Sarraf et al., 2004). Another study was also conducted only for the Medninne province (Sghaier and Belgacem, 2011) which estimated the cost of land degradation in the province to be 36.4 million Tunisian Dinars. A more recent study (GIZ, 2023) covering the provinces of Béja, Siliana, Kairouan, and Kasserine (representing about 14% of the total national area) estimated that, at discount factors of 7% and 10%, every dollar invested to control land degradation will bring back 14 and 12 dollars, respectively – indicating that combating land degradation is not only a worthy effort in terms of its environmental benefits, but also a financially viable endeavour. On a positive note, Daly-Hassen (2017) reported that the country has made good progress in carrying out afforestation in many parts of the country leading to positive outcomes.

All the past studies are either old and hence less relevant, limited in terms of their geographic and agricultural biome coverage, and are lumpsum with no disaggregation by province and biome – making them less useful for policy makers. This study aimed at providing credible estimates of the costs of inaction in terms of the quantities and values of ecosystem services lost due to failure to intervene to control land degradation. The study covered the whole country, with disaggregation at provincial levels, and included the four main agricultural biomes, namely, crop lands, rangelands, forests, and water.

Methods

Most economic valuations of land degradation are based on comparisons with a counterfactual that refers to a scenario with no-land degradation. This implicitly assumes that after the interventions, land will be restored to 100% of its potential (Quillérou et al., 2016). We argue that these assumptions are not realistic as it is difficult, if not impossible, to know the land attributes if degradation would not have taken place (the counterfactual). Interventions may not restore land to its original state and, hence, the benefits of action and the costs of inaction may be overestimated.

In this study, we follow Gregersen et al. (1995) to classify the total value of land resource into two broad categories: Use and non-use values. Use values are further classified into direct and indirect use-values. Direct use values are again classified into consumptive and non-consumptive use-values. Consumptive use-values include ecosystem service values that are produced on the land for immediate consumption (such as grain and straw on crop fields, wood and timber on forest lands, hay and leafy biomass from pastures, etc.). Non-consumptive use-values refer to recreational, educational and research values. Indirect use values are classified into the following four categories: (i) Watershed, soil protection, and nutrient recycling; (ii) gas (carbon dioxide and oxygen) exchange, carbon storage and climate stabilization; (iii) habitat and protection of biodiversity and species; and (iv) aesthetic, cultural and spiritual values. As the Aralkum desert is far away from human settlements, for the on-site valuation, we focus only on the non-use values of land and trees, with focus on their potential to serve as a carbon sink. In general, non-use values of natural resource or environmental assets are classified into three broad categories: (i) Option values (values of the option of not using it in the present time); (ii) existential values (values of its mere existence); and (iii) bequest values (the amount of the ability to bequeath it to future generations). Following Yigezu et al. (2020), we use a combination of market and non-market valuation methods to monetize the ecosystem services lost and have used area weights to aggregate province-level estimates to generate national level estimates.

Results

The results showed that inaction to control degradation in natural capital in the agriculture sector (croplands, pasturelands, forests, and water) in Tunisia is causing the country to lose substantial amounts of ecosystem services (ESS). Using extremely conservative assumptions, we estimated that Tunisia is annually losing at least 1.97 million tons of potential production of different crops (cereals, legumes, vegetables, fruits, and others), which represents 22.41% of current production and the associated crop residues. Degradation also causes the loss of 209.25 thousand tons of forest biomass (0.53% of total forest biomass stock), and 2.5 million tons of forage (equivalent to 28.03% of current forage supply) from natural pastures. Moreover, due to inaction or inadequate action to conserve water and reduce losses, the country is losing at least 736 million cubic meters of irrigation water (28.78% of total irrigation water supply from surface and ground water sources). In addition, the country is losing 147 million cubic meters of rainwater (11.98% of total precipitation) due to surface runoff. Tunisia is also losing at least 141.68 million tons of soil (i.e., 13.14 ton/ha or 0.94% of total soil stock) every year due to erosion on crop, pasture, and forest lands, which is also associated with the release of at least 779 thousand tons of carbon into the atmosphere. This does not include the amount of soil eroded from the other land use types including urbanization, infrastructure, abandoned agricultural lands, etc. and the associated carbon emission. In addition to these losses, the country is suffering different kinds of harm (including health, infrastructure damages, extreme weather, water quality deterioration, soil salinity, etc.) related to degradation of the natural capitals in the agriculture, forest, and water sectors, some of which are not addressed and hence no detailed estimation is provided in this report.

The monetary value of all the ecosystem services that Tunisia is losing annually in all biomes is estimated to be at least $2.17 billion (4.65% of GDP). The main cost of inaction in the country in monetary terms is related to crop lands which constitute 53.98% of this loss followed by irrigation water, and rangelands which contribute 28.19% and 12.09% of total cost of inaction, respectively. Direct use values (including crop and biomass, forage, and forest biomass lost constitute 80.87% of the total loss while indirect use, including the value of soil eroded and the associated soil carbon emissions, constitute about 15.15%.

Discussion

It is noteworthy that despite the low current level of forage biomass production in the rangelands, the biomass loss in rangelands accounts for about 54% of total which is higher than the 36.6% share of rangelands in total agricultural land. Rangelands, especially those in Southern Tunisia, also constitute most of the areas with the highest erosion rates per unit area which go as high as 52t/ha. Only the five Southern provinces constitute about 82% of the total national soil erosion. Rangelands constitute 73.51% of total national soil erosion out of which 67.7% (i.e., 91.8% of total erosion in rangelands) is happening in the five Southern provinces which constitute 66.8% of total national rangeland area. This calls for concerted efforts between national and international research organization, the relevant departments within in the Ministry of Agriculture, national and international development organizations, and financing institutions in the voluntary carbon market to join forces in identifying packages of policy, institutional, and technological innovations that are believed to be effective in combatting resource degradation in each biome for each province. These packages will need to be refined through a series of consultations with panels of experts. Such efforts should give the utmost priority to rangelands where the extent of land degradation in the form of soil erosion is the highest.

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Australian pastoralist groups session

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XII INTERNATIONAL RANGELAND CONGRESS AUSTRALIA 2025

Where will we be in 20 years?

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Key words: Respect; regionally specific; connection; diversity; resilient

Abstract

While we are local to our neighbours, very central to major cities, we are very remote from the politicians and decision makers, always a challenge to have our perspective heard, I reckon in 20 years that will change.

The year is 2045. This paper explores the author's insights looking forward into the future, revealing both key aspirations for Australia's rangeland communities and potential roadblocks. For pastoral Australia to thrive in the future, management based on landscape needs will be the norm. There will be greater populace and regional economic developments in our rangeland communities. The term remote will become a thing of the past, and national affections for the rangelands will be regarded highly by all stakeholders. Failure to reach these goals will be to the detriment of the rangelands and its people.

Introduction

We live in Far Western NSW, between Wentworth and Broken Hill, on the Anabranch River. With the combination of river floodplains and undulating sandy rises, there is naturally a lot of diversity in our landscape on our 31, 000 ha property that we manage. Diverse landscapes can be found across the rangelands of NSW, and indeed across all of Australia. The way we manage our landscapes is underpinned by our awareness of ecological health and biodiversity. Something as targeted as managing for increased ground cover or adjusting stock numbers according to seasonal conditions can go a long way for sustainable management of the land (Soils For Life 2024). Importantly, diverse landscapes should be respected and appreciated, as diversity is strength and ensures resilience, of which is so important in our variable climate.

The following paper is based on the author's own opinion of 2045, as seen from the perspective of an Australian pastoralist. Current realities are firstly addressed, followed by what '20 years from now' might look like with aspirational change.

Current Situation

Although Australia's rangeland area is vast, the proportion of Australia's population residing in the rangelands is low, around 2% (Nielsen et al. 2020). This provides a huge challenge for the rangelands, with limited capacity to care for our rangelands and support and endorse healthy rangelands. Looking 20 years into the future, one can't help but consider the changes needed to secure a prosperous future for Australia's rangelands communities.

Some see the opportunities of renewable energy as providing a secure future of rangeland populations, unfortunately we haven't learnt how to value the land when building energy infrastructure. Others see the best option for the future as being large areas turned into National Parks, this decision comes with its own problems of shifting increased costs onto existing land owners, biosecurity, pest plants and animals as well as increasing fire risk, potentially risking biodiversity.

There is very little knowledge about rangelands and their management in the state and federal Government offices and too often decisions are either not made or blanket decisions are made across large areas, suited to some, not others. There is no question that certainly some decisions around National Parks, appear to be more about buying urban vote, than landscape health. No question that for most voters they genuinely want to make good decisions for the future of our wonderful environment, not many really know what that is and are open to options presented by politicians via media, "game changers". Without the support of those living and working in the Rangelands, these decisions only succeed in increasing the divide between urban and rural areas.

State boundaries can cause divisions in communities, with different legislation around livestock (e.g. SA doesn't allow goat enterprises on pastoral leases), stocking rates (some states cap stocking rates), clearing (how regrowth is defined) and services (electricity and roads). While state Govts enjoy the income in the form of royalties, leases and taxes, that return is very quickly gobbled up by large capital cities that are very demanding.

Enterprise diversity is really important in an arid/variable environment, the current depressed state of the wool industry will impact regions ability to maintain economic viability if it continues, reducing diversity. With the costs increasing much faster than the price received for products, this encourages increasing scale, reducing the number of people and thus reducing the amount of care that the land receives, that is the cycle we are in.

Technology for the rangelands brings great opportunity, while also trepidation. With some looking for the "silver bullet", the tool that will make managing the land and livestock simple, can be mostly done from home via a screen. While quality land managers are slowly adopting tools that help them improve their connection with the land and livestock and/or improve communication amongst the management team.

Some parts of the Rangelands have been seen as "carbon mines", areas that have been targeted for carbon projects to offset emissions from remote places (urban areas). While this has seen a large influx of capital into those regions, a gold rush, there will be a significant hangover, a legacy of fixed land management that will continue for generations. Land management in these areas needs to change as new information becomes available, they need to be the best managed patches of land in those regions.

20 years from now

Looking forward into 2045, I am optimistic for a new status quo, as describe by the following. The year 2045 will be a turning point for pastoral Australia, as it will be the start of management based on landscape needs, and while land tenure is still held by the state, management based on outcomes will override archaic legislation.

Many other aspects of life in the rangelands are coordinated by regional systems, rather than state based, such as health, education, housing and infrastructure. This has seen a real change in the population spread, where moving to the rangelands is quite common now.

With the acknowledgement and respect of the many ecosystem services that land managers can provide in the Rangelands, this has bought many more people to call the rangelands home and show their love of the land.

Although technological advancements still occur, it is not technology that has taken over the management of the environment. Humans still have a key role to play, such as managing livestock and use of fire. Being able to become involved in rangeland management is now a sought-after role.

There is much more balance to the discussion about carbon emissions, than there was 20 years ago. Take Rangeland livestock for example, where methane emissions are easily offset by biodiversity credits, improved water infiltration and the "platinum badge" for healthy eating.

While for many the renewable energy boom in the 20's and 30's was a great income support, now with the understanding of there being no such thing as "low value land", renewable energy projects and transmission lines are planned with that in mind. This has seen a large reduction in transmission lines and renewable energy sites are rarely visible in the landscape, such is the sensitivity of the new planning guidelines.

Conclusion

For Australia to secure a prosperous future for its rangelands, it will be important that changes are made in line with fostering thriving communities of diverse landscapes. It is hoped that this paper ignites a fire inside you and challenges you to examine the future. Some questions to ponder: "What value do we place on our unique and wild Outback and those that choose to live there?"; "Is our society so busy *putting out fires* in urban areas to even think about those that live in remote Australia?"; and "Do we accept *Geographical Narcissism* as discrimination, while having zero tolerance for racism, sexism?".

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Visions for 2045: A pastoralist's perspective on advocacy with purpose

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Key words: Land use; accountability; technology; natural capital; biodiversity

Abstract

Visitors to my home in the Arcadia Valley north of Injune in Central Queensland remark at the breathtaking beauty that surrounds us. Framed by the sandstone cliffs of the Expedition and Carnarvon Ranges, beef cattle graze on a diverse pasture comprising dense perennial pastures and mixed legume species. Looking forward 20 years from now, I envisage I will be looking out over my paddocks with an immense sense of pride knowing that in 2045 the land continues to reward generational stewardship and advocacy. However, this reality will require ongoing commitment to sustainable practices, as well as business agility, as new markets emerge, and unforeseen challenges arise. In this paper, I present my own firsthand experience of business advocacy with purpose directed at environmental stewardship and accountability. I then present a case for concern on the legacy impacts of coal seam gas extraction in the rangelands, as an example of competing land use challenges. The system designed to protect the interests of all stakeholders cannot be compromised for short term financial gain, as this will only lead to increased risks of adverse longer-term environmental impacts, production losses and psychosocial trauma. I will end with future expectations relevant to all rangeland users and policy makers.

Introduction

I live in the "Arcadia Valley" region located north of Injune in Central Queensland, Australia. Here, my husband and I and our three children (Price Cattle Company Pty Ltd) produce organically certified, grass-fed beef in the Brigalow Belt Bioregion (DES 2018). This region, characterised by brigalow (*Acacia harpophylla*), a native woodland (DCCEEW 2024), is home for many of thousands of years to the Traditional Owners, the Iman Aboriginal People (DESI 2019). This bioregion is also a known biodiversity hotspot, given the high historical rates of land clearing that has occurred (Thornton and Elledge 2022) and subsequent ecological communities reported as being threatened (CSIRO 2022).

Since European settlement, clearing of the brigalow bioregion of Queensland and New South Wales has made way for agriculture. In the last decade, the Arcadia Valley and Darling Downs regions of Queensland have been identified and targeted for development of the coal seam gas (CSG) reserves under prime agricultural land (Dougall 2024). The production of CSG, also known as coal bed methane, sourced from underground well extraction has become an integral part of the gas industry. A major driver was a decision in 2000 by the Queensland Government to boost the contribution of gas to the State's power supply (Commonwealth of Australia 2014), with 1996 seeing the commencement of Queensland's domestic CSG production (Towler et al. 2016). The expanding activities of the CSG industry in Queensland's rural, agricultural areas has come with public scrutiny, particularly with regards to environmental and social impacts, and as a result, government regulation has been evolving, including amendments to the land access framework (Towler et al. 2016).

Our firsthand experience of confronting such competing land use challenges confirmed the rules that govern such mandatory "land access" considers only that, i.e., accessing our private land. This single dimension does not address the multiple dimensions of impacts that hosting a gas production and processing facility has (e.g., see Dougall 2024), such as on our business, our values and our common rangeland commitments.

With growing local and global concerns about loss of biodiversity and environmental degradation, and the need to maintain a social license to operate and address climate change risk, means land users in the rangelands must prioritise better environmental outcomes. Advocacy with purpose, at all levels, I believe, will be key to reaching this goal. This includes advocating your own business and commitment to land management, paving the way for others through proactive leadership, advocating collaboration and adoption of technologies to better inform policy, and advocating for equity and accountability from all rangeland users.

The following paper presents our own business advocacy in the rangelands, provides a case for concern about competing land use challenges, and ends with visions for 20 years from now.

Our systematic approach to advocacy

Land settlement and agricultural developments: An historical directive for the Fitzroy Basin

Broadscale clearing of Brigalow in central Queensland was directed by the state under the Land Development Fitzroy Basin Scheme initiated in 1962 (Thornton and Elledge 2022). My husband's father was 19 when he drew a ballot block that was part of the 1962 land development scheme (e.g., see Cowie et al. 2007 after Donohue 1984 and State Library of Queensland 2019). He was directed to broadscale clear the standing brigalow scrub, erect fences, plant improved pastures and build infrastructure on the land. Today, the Fitzroy Basin carries the largest cattle herd in any natural resource management region in Australia, making up a quarter of Queensland's herd (Thornton and Elledge 2022).

Some of the challenges we face today as pastoralists is pasture condition decline. In the Fitzroy, pasture rundown and dieback are particularly concerning (Bowen and Chudleigh 2017) and something we have had to deal with ourselves. We partnered up with the Department of Primary Industries and established new pasture plantings (grass and legumes) and adopted grazing practices aided by technologies (see next section).

Advocacy & leadership: Embracing technologies, backing yourself and paving the way for others

Since transitioning to a certified organic production system in 2014 and establishing our Fullblood Wagyu herd, we have ensured access to an exclusive beef market for our cattle that allows us to achieve premium market returns for our beef. Our land and herd management practices are targeted towards improving animal production while also protecting biodiversity and natural resources. This is done through the adoption of agribusiness-based technologies to improve decision making, such as using Optiweigh (remote walk over weighing) and CiboLabs Pty Ltd (pasture imagery service), to give us the frequent data capture required to forward plan and make more informed decisions on holding and selling of stock (DPI 2022).

We are firm believers of "healthy food starts with healthy farms". It is possible to grow production animals and look after the natural resources they depend on, providing there are sound decisions being made, such as adjusting stocking rates according to seasonal conditions. Through our participation in industry programs, we are more aware of innovations and methods to improve our efficiencies and reduce our carbon footprint. As further examples of industry best practice, we have used satellite derived estimates of food on offer and ground cover to not only inform stock movements to manage pasture utilisation, but to also identify low cover areas needing attention (e.g., either more rest from grazing or mechanical intervention required). We have also developed our water infrastructure so that cattle grazing distribution and evenness of grazing can be better managed. A spin-off from this has been improved calving rates and weaning weights (DPI 2022), where cattle spend less time walking to water (i.e., reduced energy expenditure).

We (Price Cattle Company) are serious about and committed to responsible, professional pastoral practices, and we have been recognised for this and acknowledged as industry role models. Our varied industry related activities have included hosting field days on pasture dieback, hosting a property tour during the internationally recognised Beef Week 2024, speaking on panels, being interviewed for agricultural publications on topics ranging from succession to technological advancements, through to providing a recipe and article for a Workplace Health and Safety cookbook.

In 2022, we received a prestigious Farm Biosecurity Producer of the Year award, that acknowledged our professionalism towards farm biosecurity, innovation, technology, record-keeping, environmental sustainability, and business transparency (Farm Biosecurity 2022). Business transparency is particularly important to us as we know from our own experiences that industry compliance can be overwhelming. This prompted us to use social media as a platform to help others and share with other pastoral businesses our own farm biosecurity plans.

Issues of competing land use: Changing legislation to create equity in advocacy

We have firsthand experience with competing land use challenges. We were taken to the Land Court of Queensland by a fossil fuel mining company because they wanted to be granted approval to drill more CSG mining wells on our land, in accordance with their legal right. In response, we initiated proceedings against the mining company for breaches of the existing Conduct & Compensation Agreement (CCA) that for five years the mining company ignored requests to address. They did not keep their word and act in accordance with their public statement that they only accessed land where they were welcome and when questioned as to why they were pursuing access, the response was a changed narrative that they were now choosing to gain access in accordance with their legislated rights.

We had previously invested significant resources and time into negotiating an agreement with the mining company, to which they did not honour. When the company wanted to drill more wells without addressing ongoing breaches, we choose to fight. Our response was strategic and wide ranging. The mining company had been threatening our family with legal action for many years and we planned our response to prepare for this worst-case scenario.

Most pastoralists are so busy on their farm they do not spend much time away from it. In our case we had to be proactive in raising our profile as best practice operators. The threat to commence court action materialised when new lawyers were engaged. We were in mediation with the CSG mining company and notice was given that the mining company was withdrawing from the negotiation process and immediately commenced Land Court proceedings.

We learnt this threat of legal action was a tactic to force us into signing a new CCA. The attitude of the CSG mining company was if they can't comply with the agreed CCA they would just have a new one written that did not contain any of the previous clauses.

Going to court is very expensive and this multinational company expected us to back down to avoid court. They did not expect us to fight and provide documented evidence of their operating practices. We had drone footage evidence of vehicles traversing unauthorised access roads, photographs of mining infrastructure that created animal welfare risks, reports from experts outlining the land degradation caused by unrehabilitated land disturbed by the mining company and five years' worth of correspondence that demonstrated the tactics of the mining company towards our family.

During the time since 2018 when the CCA had been signed and then breached we were ensuring all avenues for landholder complaints were being exhausted and extensive evidence was being collated to demonstrate the non-compliant conduct of the mining company. When the actions of mining company staff resulted in hundreds of organically certified cattle losing their organic status and corrective action notices being issued by our organic certifier, the mining company further compromised our certification by ignoring deadlines for stockproof fencing to be erected. We followed the regulatory process and lodged complaints with the various Government Departments, the Queensland Gasfields Commission and the Queensland Land Access Ombudsman. The process took years, and we learnt the legislative system creates a situation whereby the Government and the resource company, as the Authority Holder, exclude the landholder from their interactions. While we were told there was confirmation of Environmental Authority breaches that correlated with our lodged complaint, we learnt the system we expected to protect the rights of the landholder and the environment worked slowly and secretively.

Although disappointed by the lack of transparency in resources governance and procedural fairness, we did not lose focus. In choosing to be active participants and advocate with purpose we broadened our knowledge, network and experience. Often the skillset associated with the business of farming is underestimated. Successful pastoral operations understand the importance of working both “on” and “in” their business. Working parallel with the legal process we looked at the tactics employed by the mining company and ensured our small family business was not only credible but formally acknowledged as industry leaders. We did not target the mining company; we instead became advocacy generalists. When asked for our commentary on any issue relating to our business and operating environment we provided it.

We took the position that if mining fossil fuels is necessary for the economy and would continue to expand its footprint, then transparency and accountability must occur. Agreements between other landholders and mining companies were not our concern and we make no judgement of landholders who embrace mining on their pastoral land. Unlike the mining company, we do not have shareholders wanting high financial returns on their investments. Price Cattle Company stakeholders are the future generations of our family who will make their assessment of our performance using different key performance indicators. The battle in the court was therefore only one aspect of our strategy. It was important to provide an inside-out perspective of the legislative and regulatory system involving mining leases on pastoral land. We chose to engage with the individuals, organisations and departments tasked with a component of the system, no matter how small their contribution. We documented, questioned and held everyone to account.

Visions for 2045: The role of pastoralists and standards for all rangeland users

A shared vision of caring for our rangelands sits forefront in my mind. For me, as a pastoralist, experiencing moments when nature is communicating with you, often at daylight or dusk, is a reminder that we are part of something greater than ourselves, and that is something worth protecting. Only after we have, over many years, challenged ourselves to engage, understand and adapt to the changing environment, can we become empowered enough to step outside of our comfort zone and start making real, transformative change.

As land users of the rangelands, it is important that we embrace our role as guardians of the ecosystem. It is hoped that in 2045, rangeland monitoring technologies will be well evolved that they are not only used to aid decision making but also used to demonstrate on-ground validation of environmental stewardship. For pastoralists this might include ecosystem services payments. By then it is hoped pastoralists won’t have to fight for third parties to treat the land respectfully. The systems will be transparent with enforceable actions that prioritise environmental sustainability over corporate agendas and mining royalty payments.

The International Year of Rangelands and Pastoralists commencing in 2026 provides a unique opportunity for Australia. Using the year to establish a shared, documented vision for the rangelands could create a blueprint for their future management. All stakeholders should operate within the same base rules of conduct when it comes to environmental outcomes. Pastoralists have a great opportunity to share their stories in 2026 and embrace a narrative that demonstrates their environmental stewardship credentials. Often the public only hear the well scripted, well resourced, non-substantiated attacks on Australian farmers and their farming practices. As environmental offset programs and transitioning land use for carbon projects in Australia creates ripple effects in the rangelands, the need for standardised environmental assessments will become increasingly important.

Conclusion

From my own perspective as a pastoralist managing the land, I accept I work with nature as well as in it. I also believe that advocacy with purpose will be key for improving the future protection and management of the rangelands. The reality of competing land use challenges needs strong advocacy to ensure systems in place designed to protect the land are accountable, impartial and effective. Pastoralists also need to be actively raising their business profile and public visibility, embracing scientific innovations and celebrating generational wisdom. Established credibility is essential when questioning the frameworks, regulations and legislations of other industries operating in the rangelands. In 2045, it is hoped that rangeland communities will be vibrant, and the next generation of land managers will be in tune with nature, tech savvy, strong advocators of conservation, and are able to thrive under changing environmental, social and economic conditions.

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Challa Station in 2045

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Key words: Future vision; technology; carbon farming; natural capital; biodiversity

Abstract

Sometimes it's good to look at what we are doing now and imagine what we will have achieved in the future. It gives us hope and encouragement to continue.

This paper, set in 2045, explores the research projects conducted at Challa Station, with a focus on carbon management, biodiversity conservation, and sustainable grazing land practices. The author reflects on what the future might look like in 20 years, suggesting that current research efforts provide a promising preview of what could be achieved. By 2045, Challa Station, through Australian-led rangeland innovations, has become a flourishing landscape despite increasingly variable rainfall patterns. This success has been made possible by advancements in understanding and monitoring landscape function and soil health, as well as the ability of land managers to make more objective, rapid decisions and implement precision grazing strategies.

The United Nations' proclamation of the International Year of Rangelands and Pastoralists in 2026 gave us hope that all aspects of rangelands would be promoted and supported in the future. By 2045, pastoralists are recognized for their contributions to society, particularly in mitigating the impacts of climate change through carbon sequestration and the protection of natural capital. Australian rangelands pastoralists also understand that carbon is only one aspect of sustainability. A thriving, robust ecosystem has become the true measure of value. In 2045, our natural landscapes function effectively, our human communities are resilient, and rural regions remain wonderful places to live.

Introduction

In Australia, pasture-raised beef accounts for 78% of the country's red meat ruminant livestock methane emissions (Mayberry et al. 2018). To achieve carbon neutrality by 2030 (CN30), grazing management has focused on promoting carbon storage (MLA, 2020). For instance, restoring soil carbon through improved grazing pressure management—preventing animals from selectively overgrazing—and using mechanical interventions to rehabilitate bare areas helps reduce soil erosion and biodiversity loss by restoring ground cover and pasture biomass. Additionally, revegetation offers rangeland managers an opportunity to address and mitigate climate change risks effectively.

Challa Station is our family run red meat operation that spans 206,000 hectares in the southern rangelands of Western Australia. Through participating in an Australian Government carbon project coined 'Human Induced Regeneration' (HIR) (Clean Energy Regulator 2024) – being the focus of regeneration of native forests, we were able to gain a deeper understanding of critical biodiversity habitat and carbon sequestration. This not only led to changes in how we manage the land and our livestock but has also provided us with new visions for the future.

This paper explores our journey of adopting research and development on Challa Station and where we ultimately would like to be in 20 years' time.

Restoration and revegetation: improving land condition through adaptive grazing management

The Challa Human Induced Regeneration (HIR) carbon project, initiated in 2019, became the catalyst for embracing new research in biodiversity, conservation, and livestock management. Initially, so little work had been conducted in our region that we began discovering previously unknown species in the rangelands, such as *Baeckea sp. 'London Bridge'*, a shrub identified on Challa Station in 2000. This discovery motivated us to implement measures to trap and reduce goat numbers, thereby alleviating grazing pressures on the landscape. Scientists have since identified and named many more plant species and developed a clearer understanding of the grazing thresholds necessary to avoid suppressing or adversely impacting the growth of native flora, including species like *Baeckea* and *Canthium*.

In 2019, the HIR carbon project changed the way we managed our station. It provided the opportunity to be rewarded for managing our herd in a way that discouraged grazing on native Mulga (*Acacia aneura*) forests, allowing for regeneration and carbon sequestration. This initiative provided financial input through carbon credits, enabling us to improve how we managed our property. These improvements included reducing herd size by 30% whilst simultaneously improving the quality and productivity of the cattle. We invested in new water infrastructure to better distribute grazing pressure evenly across the landscape. Each of the watering points had a set of Total Grazing Management yards built to allow better control of our herd and feral herbivores. We built fences to protect the regrowing native forest and other sensitive areas. These changes not only supported environmental goals but also enhanced the sustainability of our business operations.

Satellite-based technologies: Adopting innovations that improve efficiencies and reduce our carbon footprint

Challa Station has been in the Dowden family since 1888, with five generations contributing to a deep understanding of the property. Over the years, the red meat enterprise on Challa Station has evolved, transitioning from small ruminants (sheep and goats) to large ruminants (cattle) and adapting cattle genetics, shifting from Droughtmaster to Santa Gertrudis breeds. The move away from sheep, beginning in 2008, was driven by the need to mitigate the impact of dingo attacks.

Challa Station has always been quick to embrace technological advancements to improve efficiencies and reduce its carbon footprint. One notable example was the implementation of satellite water monitoring devices back in 2015. This innovation allowed us to remotely monitor water tank levels from our home office, reducing the need to drive hundreds of kilometres to conduct physical water checks. Previously conducted every four days, these checks are now carried out every ten days. This change not only significantly reduces fuel consumption for vehicle-based mill runs (water checks) but also frees up valuable time for other essential management tasks.

Technological advancements have significantly improved our understanding of cattle behaviour and their movement across the landscape. For example, satellite tracking ear tags (Ceres Tag; CSIRO, 2020) have revealed areas preferentially grazed by cattle, such as alluvial plains (Vercoe and Durmic 2024). These tags have also enabled us to locate cattle more efficiently, including heifers (young female cows yet to calve) that might otherwise miss mustering because they had not yet established their home territory.

The potential of precision agriculture in the rangelands is vast. Tracking and monitoring livestock location is just one application. Advanced technology, such as accelerometer-equipped ear tags, can also link ear movements to behavioural cues. With the development and validation of specific algorithms, these devices can predict activities like grazing, ruminating, and even calving (Hu et al. 2024; Trotter et al. 2018). This precision enhances both livestock management and our understanding of animal behaviour in the rangelands.

Furthermore, the advent of plant DNA analysis from animal dung provided us with new awareness of the plants on offer and selected by our cattle. This is explored in the next section.

Diet ID project: UWA BeefLinks

The Diet ID project (Vercoe and Durmic 2024), which was run with Meat & Livestock Australia and the University of Western Australia, used DNA metabarcoding of plant DNA detected in animal dung to determine the animal's dietary botanical composition (i.e., which plant species were being ingested). This information was assessed together with information on animal whereabouts (previous section) and the nutritional value of plant species (see Vercoe and Durmic 2024). Although the dung sampling was limited to a snapshot in time rather than continuous sampling over a year or across seasons, it did however reveal interesting results on animal diet selection. Firstly, there were more plant species making up cattle diets revealed by DNA metabarcoding than was perceived or easily observed closer to water. Secondly, differences in diet selection between individual cattle was apparent, and thirdly, plant species frequently ingested by cattle could be ascertained (e.g., native shrub species *Eremophila* and *Maireana*).

Biodiversity monitoring: manual and automated monitoring sites and application

Biodiversity monitoring technology was installed on Challa Station in collaboration with AxisTech Pty Ltd. To-date this has included four automated 'prototype' monitoring sites and a mobile monitoring unit. In brief, the close monitoring of environmental conditions (atmospheric and soil condition monitoring using weather stations and carbon soil probes, respectively) and above ground species diversity (flora and fauna monitoring using fixed cameras) is providing data for machine learning on how the landscape is performing. Challa Station also had 48 manual monitoring sites, which were established in the year 2000 (photo monitoring and plant counts). This new data on species richness and landscape function will help direct and validate grazing management decisions.

Future aspirations: moving cattle in response to pasture condition

In 2045, we reflect upon our achievements. At Challa Station, we have successfully integrated technologies that enable rapid, whole-system monitoring—including plants, landscape function, animal production, and nutrient availability—facilitating real-time decision-making. Precision agriculture, such as satellite monitoring and geo-referenced animal sensors, has optimized our grazing systems, improving both animal production and land condition outcomes.

A key innovation has been the adoption of virtual fencing technology, which was in its infancy in 2024 (Durmic et al. 2024) but now functions seamlessly in the rangelands. This technology allows us to precisely control the location, timing, and duration of grazing pressure. By implementing adaptive grazing strategies, we can now ensure that livestock remain productive while preventing overutilization of vegetation, enabling regeneration and enhancing resilience to climate change risks. It has made shifting cattle to different areas remarkably easy, allowing us to simply adjust the virtual fence line on our computer to create a new grazing inclusion zone. This flexibility enables us to respond quickly to localized rainfall events and protect sensitive areas undergoing regrowth. This approach not only enhances grazing efficiency but also supports better land stewardship and resource management.

Today, the benefits are evident across the landscape. An abundant understorey of white, gold, and pink wildflowers, primarily everlasting daisies (*Xerochrysum viscosum*), now flourishes during winter, showcasing the harmony between sustainable livestock management and ecological health.

In addition to mitigating the risk of landscape and biodiversity degradation, understanding the diet selection of our cattle opens up opportunities to access provenance markets—markets that value red meat produced in rangelands with recognized and valued plant species. For instance, cattle on Challa Station selectively graze on potential anti-methanogenic species such as *Eremophila* sp. Research has documented the anti-methanogenic properties of this genus, including *Eremophila glabra* (Li et al. 2014). This insight not only enhances the environmental credentials of our production system but also creates avenues to meet the growing demand for sustainable and environmentally conscious meat products.

In 2045, we manage cattle movements with unprecedented precision, responding to pasture conditions with far greater accuracy than ever before. Advancements in ecosystem and biodiversity monitoring have transformed how we assess land health. Using rapid data capture via handheld devices, we can simply wave our mobile phones over a section of land to instantly receive accurate, quantitative data on pasture condition, eliminating the guesswork from rangeland management.

We now also have a deep understanding of the nutritional value of plants and the specific anti-methanogenic species that cattle reliably graze. Rangelands cattle are celebrated for their carbon-negative status, and high-quality red meat from these regions has become synonymous with sound environmental stewardship and the preservation of biodiversity values. These advancements not only enhance production but also solidify the role of sustainable rangeland management in combating climate change and maintaining ecosystem health.

By 2045, the rangelands will provide a multitude of benefits that extend far beyond supporting numerous families in marginal areas and producing red meat to feed a growing population. Pastoralists will be widely acknowledged for the ecosystem services we deliver, playing a vital role in enhancing and safeguarding natural capital for the benefit of the entire community.

Additionally, the rangelands will be valued for contributions that cannot be measured economically, such as the resilience of our communities and the deep trust and strong friendships that are the backbone of rural life. These intangible but essential values underscore the enduring importance of the rangelands, not just as a source of production but as a foundation for social and environmental well-being.

The strong global foundation and momentum generated by the United Nations' proclamation of the International Year of Rangelands and Pastoralists helped shift the narrative about the rangelands. By 2045, we can confidently celebrate a bright future for Australia's rangelands, recognizing their vital role in sustainable agriculture, ecosystem health, and community resilience.

Conclusion

Adopting innovations to enable greater efficiencies and better-informed decision making is important to livestock grazing enterprises paving a path to carbon neutrality. One way for rangeland managers to combat climate change is to improve ground cover. In doing so, this reduces the risks of soil erosion, where increases in pasture biomass will allow for improved soil carbon and biodiversity. In addition, Natural Capital Accounting is expected to assume even greater importance in the future. This will increase the demand for sophisticated monitoring of ecosystems and landscape function, so that rangeland managers can demonstrate they are sustainable. For this reality, science advancements will need to continue to ensure the required monitoring technologies are available and practical to implement in the rangelands.

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Meeting the needs of multiple stakeholders from the rangelands of Saudi Arabia: The AlUla experience

There are no full papers linked to this session

Enhancing climate resilience across rangelands - from research to extension

Development and verification of thermal stress forecasts for cattle in Australia's Rangelands

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Key words: cattle comfort; heat stress; chill, forecast; temperature

Abstract

The highly variable weather and climate of northern Australia can pose a significant threat to cattle and other livestock, with prolonged heat waves and sudden chill conditions known to increase mortality risk. For example, the compounding impact of high temperatures, high humidity and calm conditions led to significant cattle heat stress and dozens of animal deaths in southern Queensland in late January 2024. Conversely, the combination of flooding, low temperatures, and high winds associated with a tropical low caused thousands of cattle deaths in northern Queensland in February 2019.

Currently, the Australian Bureau of Meteorology issues national sheep graziers' alerts for potential risk of chill Test and exposure, however there are no such equivalent chill (or heat) warnings for cattle. A key objective of the Northern Australian Climate Program (NACP) is to develop prototype forecast products of thermal stress that can be utilised by livestock producers to help manage the risks posed by extreme weather and climate events.

In this research, we describe NACP's latest prototype forecast maps of the Heat Load Index (HLI) and Cattle Comfort Index (CCI), derived from the Bureau's numerical weather prediction system - ACCESS-G3. These forecasts display the predicted chill and heat conditions across Australia out to 7 days. We also assess how well the predictions of CCI performed for a extreme heat event in southern Queensland in January 2024.

Introduction

According to the Australian Bureau of Statistics in 2021, there were approximately 24.4 million dairy and beef cattle in northern Australia, with 44% (10.7 million) and 7% (1.7 million) in Queensland and the Northern Territory, respectively[16]. Cattle in Australia's far northern tropics typically encounter hot and humid wet seasons (October to April), often punctuated by monsoon bursts (Berry & Reeder, 2016). Further south, in the arid regions,

[16] https://www.mla.com.au/news-and-events/industry-news/herd-and-flock-numbers-for-each-region-released/

cattle experience hot, dry summers and cold winters. As such, Australian cattle are highly susceptible to thermal stress risk from both chill (Cowan et al., 2022) and heat stress events (Lees et al., 2019). For example, a humid-heat wave event in southern Queensland and northern New South Wales across late January 2024 (during the Australia-day long weekend) culminated in cattle deaths in feedlots across the western Darling Downs, southern Darling Downs and South Burnett regions (Condon, 2024).

The Australian Bureau of Meteorology (hereafter, the Bureau) currently provides sheep graziers' warnings for chill risk in its forecast districts (Nixon-Smith, 1972) and, during the warmer months, an Australia-wide gridded 3-day heatwave forecast service for people (Bureau of Meteorology, 2024). However, the Bureau does not officially provide gridded thermal stress forecasts for livestock. Based on an anonymous survey conducted in June 2022 with 76 beef producers across northern Australia, more than 60% of respondents expressed a desire for a cattle heat stress forecast map (Cowan et al., 2024).

As part of the Northern Australia Climate Program (NACP), researchers are developing gridded thermal stress forecast products for cattle. The NACP is funded by the red meat sector to develop innovative forecast tools to help graziers better manage drought and climate risk (Lavender et al., 2022). In this study, the first objective is to introduce the latest prototype cattle thermal stress forecasts, like the Cattle Comfort Index and Heat Load Index, developed in collaboration with the Bureau, using their deterministic 7-day numerical weather prediction system, ACCESS-G3 (Australian Community Climate and Earth-System Simulator, Global – v3). The second objective is to assess the performance of forecasts for thermal stress during the late January 2024 heatwave event in southern Queensland.

Methods

Thermal Stress Metrics

The HLI is a dimensionless measure of the instantaneous heat load in cattle, derived from the black globe temperature (which includes solar irradiance and temperature), relative humidity and wind speed (derivation in Gaughan et al., 2008). Hourly data is required to calculate the HLI, from which the Accumulated Heat Load Unit (AHLU) can be derived. When the HLI exceeds a given critical threshold value (e.g., 86 for Angus cattle, 96 for Brahman), cattle begin accumulating heat (McCarthy & Fitzmaurice, 2016). When the HLI < 77, the animals will shed their heat load, whilst the AHLU remains constant if the HLI is between 77 and the critical threshold.

The CCI covers both cold and heat extremes, describing an adjustment to the temperature due to changes in the relative humidity, solar irradiance and wind speed (see derivation in Wang et al., 2018). For temperatures warmer than 25°C, increases in relative humidity lead to an enhanced warming, whereas higher wind speeds will act to cool the CCI. Increased solar irradiance produces a warming effect but has less of an influence as humidity increases.

ACCESS-G3 Numerical Weather Prediction System

The Bureau's deterministic ACCESS-G3 model has a N1024 (~12 km) horizontal resolution with 70 vertical levels reaching a height of 80 km. It assimilates satellite measurements and surface observations (including 0.25° daily sea surface temperatures) at a N320 (~40 km) resolution (Bureau of Meteorology, 2019). We utilise forecasts of screen temperature and relative humidity, 10-metre winds and downwards shortwave radiation at the surface – these forecasts are generated by ACCESS-G3 at four daily initialisation UTC times: 00, 06, 12, and 18z (Zulu time) (10, 16, 22, and 04 Australian Eastern Standard Time [AEST]). For the prototype forecasts maps, we display only the 12z initialised forecasts at 3-hourly intervals, extending up to 9 days, starting from 10 AEST. In addition to CCI and HLI forecasts, we also produce forecasts for the Temperature Humidity Index (THI; a combination of temperature and dewpoint temperature; Wang et al., 2018) and AHLU, the latter calculated for five different HLI thresholds, representing different cattle breeds (e.g., 86→Angus, 96→Brahman)(Gaughan et al., 2008).

To verify these forecasts, we use observations from a network of Bureau operated Automatic Weather Stations[17]. These stations record temperature, wind speed and relative humidity. For solar irradiance observations, we rely on daily global solar exposure, derived from visible radiation measurements from geostationary satellites (Poulsen & Majewski, 2022).

Results

Gridded Thermal Stress Forecasts

An example CCI forecast for 10am AEST on 29 October 2024, is shown in Figure 1. For this forecast product, we have deliberately separated the dark reds to maroon colours (indicating heat) from the blues (indicating chill) with more neutral bland colours (indicating normal conditions). Additionally, we are currently trialling an email alert system for the THI across the northern Western Australian and Queensland Local Government Areas, as well as Northern Territory pastoral regions. The alerts are designed to notify our regional NACP extension officers (called Climate Mates) about the likelihood of extreme THI conditions over the next 1 to 5 days in their regions. The Climate Mates can then pass that information onto their network of local producers and stakeholders.

Verification of the southern Queensland heat stress event in January 2024

Next, we assess how well the ACCESS-G3 forecasts performed during a real-world cattle thermal stress event, specifically the heat conditions in southern Queensland in late January 2024, which led to reported cattle deaths across numerous feedlots (Condon, 2024). We focus on the town of Dalby in the Western Downs Region of Queensland.

It is apparent that the ACCESS-G3 forecasts did not predict the heat event at a 7–10 day lead time, as the CCI and THI were well underpredicted (Figure 2).

Closer to the event, we see the 3-5 lead time forecasts captured the diurnal cycle of the CCI and THI, however the model tended to overpredict the intensity of the heat. The reason for this is the model under-predicted the rain event on 27 January, leading to an overestimate in the solar irradiance (and underestimate in relative humidity) contribution to the CCI.

[17] http://www.bom.gov.au/climate/data/stations/about-weather-station-data.shtml

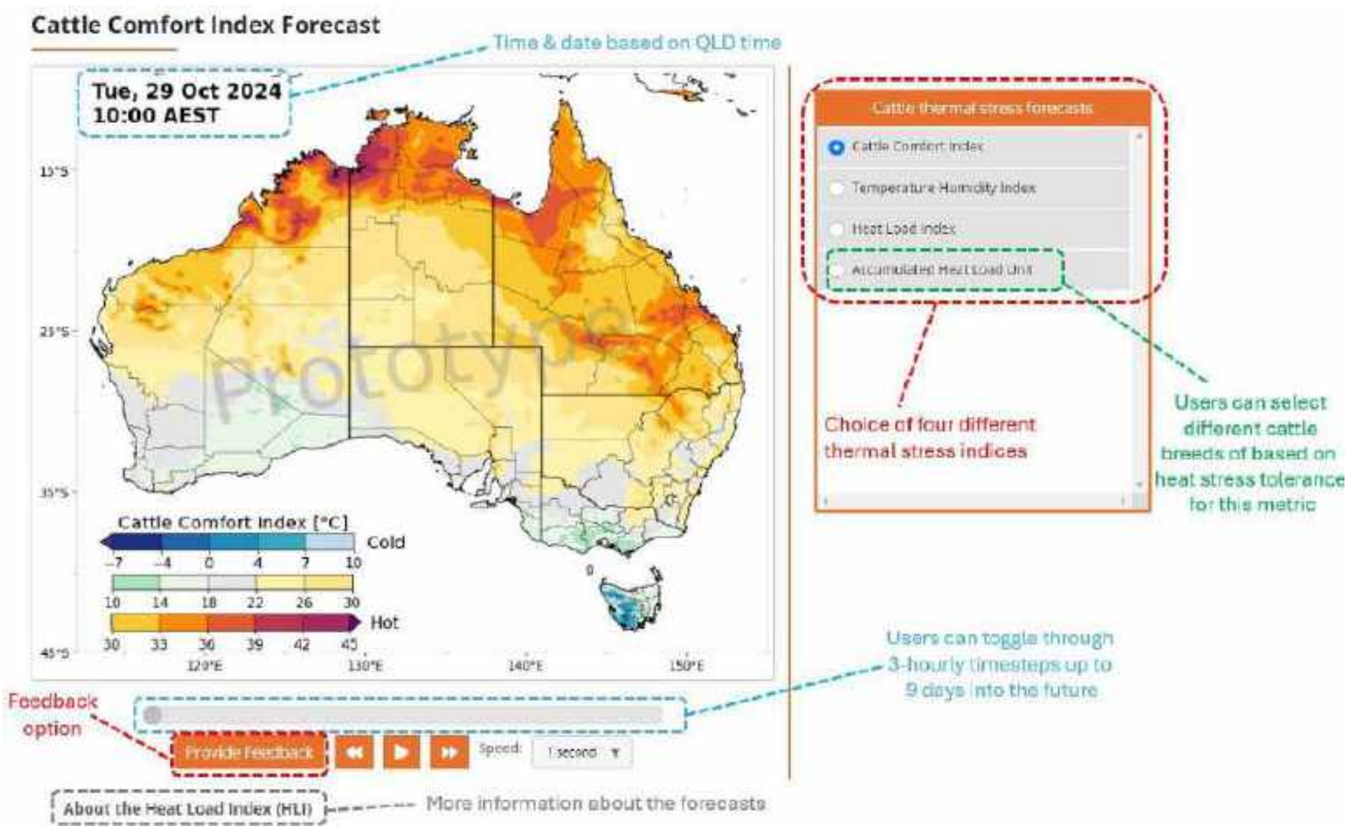

Figure 1: Example of a Cattle Comfort Index (CCI) forecast map from the Bureau's ACCESS-G3 numerical weather prediction system. This forecast is taken from https://nacp.org.au/cattle_thermal_stress_forecasts.

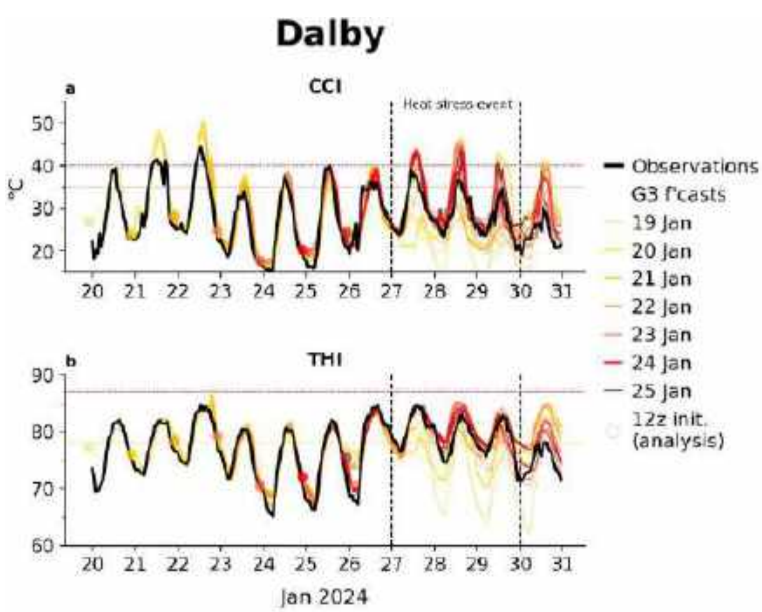

Figure 2: Observed heat stress event (black lines) in Dalby, Queensland (27.16°S, 151.26°E) in late January 2024, as indicated by (a) the Cattle Comfort Index (CCI) and the Temperature Humidity Index (THI). The coloured lines (yellow to red) show the ACCESS-G3 forecasts from 19-25 January. Circles indicate the model forecast initialisation at 12z each day (e.g., 10pm local time).

Discussion

This paper has introduced a suite of cattle thermal stress forecast products, based off the Bureau's deterministic numerical weather prediction model, ACCESS-G3. Initial verification results suggest that forecast skill is relatively good up to 5 days, however beyond that lead time, wind and relative humidity become harder to predict, and hence, Cattle Comfort and Heat Load indices show greater divergence from observations. There is scope to expand these forecast products to include other indices such as the Livestock Chill index, which would be of value for sheep/wool producers in central/northern Queensland. Other improvements could include using higher resolution modelling, such as the Bureau's ACCESS-City models, that are centred over metro regions at a 1.5 km horizontal resolution. The NACP team are also exploring ways to enhance forecast visualisations on the product website, including the potential for users to zoom in on a region of interest. This would improve the accessibility and utility of forecasts. Future NACP research will target the defining of heat and chill thresholds for cattle under Australian climate conditions, noting that temperatures in the cooler months are not as severe as in Europe or North America, however cattle can still be significantly impacted.

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Northern Australia's Green Break of Season (GBOS) dates and their relationship with pasture

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Key words: Green Break of Season (GBOS); Green Date (GD); Pasture Growth; Northern Rainfall Onset (NRO); Northern Australian Climate.

Abstract
Across northern Australia's rangelands, livestock production depends heavily on rain-fed pastures that rely primarily on rainfall during the wet season months of October to April. Planning for the onset of pasture growth (called green cover onset) after the dry season enables graziers to set appropriate stocking rates based on the available fodder at the end of the previous growing season. This reduces costs and alleviates the strain on existing livestock. This study focuses on the 'green break of season' (GBOS) date, defined as the first occurrence of meaningful rainfall over a 3-day period after the dry season, and its relationship to the green cover onset. By utilising robust model-derived estimates and satellite observations of pasture growth at representative locations, we examine the relationship between the green cover onset and GBOS for various rainfall thresholds and find a strong linear relationship. Additionally, we investigate the historical or long-term 'green date', at which the GBOS reliably occurs in 70% of all years. We analyse the spatial distribution of green dates over northern Australia and examine how these dates are influenced by the phase of the El Niño-Southern Oscillation. Ultimately, our findings aim to assist producers and graziers in determining their "decision date" for better management of livestock and resources.

Introduction
Australia is the world's third-largest exporter of beef (Meat & Livestock Australia, 2022) and relies heavily on pasture to feed cattle in its northern regions. Pasture growth and cattle liveweight gains in northern Australia are closely linked to October-April wet season rain, which accounts for over 90% of the area's annual rainfall (Lisonbee et al., 2022). Northern Australia also experiences substantial seasonal and interannual rainfall variability, sometimes resulting in droughts and floods (Thi Tran et al, 2016; Johnson et al. 2016). These conditions affect cattle enterprise management and livestock production (Cobon et al., 2019), creating challenges in balancing forage supply with herd sizes (Cobon et al., 2020b) and significant financial risks.

There are various rainfall-based definitions to help estimate the timing of new pasture growth for grazing management, such as the “green season” (McCown, 1981), “green break of season” (Balston and English, 2009), and Northern Rainfall Onset (NRO) (Cowan et al., 2020; Drosdowsky and Wheeler, 2014). These definitions highlight the complexity of identifying a singular onset date for productive green pastures. In this study, we define the Green Break of Season (GBOS) as the first day after 1 September when 50 mm of rainfall accumulates over three consecutive days. The GBOS signals the anticipated start of pasture growth, initiating green cover and supporting liveweight gain in stock (Balston and English, 2009). We then examine the Green Date (GD), commonly used in the grazing industry (FutureBeef, 2021), defined as the date representing 70% of GBOS dates across all historical years. By combining the GD with an estimated end of growing season date, producers can set an appropriate dry season stocking rate, crucial for maintaining land and pasture condition (O’Reagain et al. 2009). Understanding the GD helps graziers ensure sufficient feed for livestock and maintain adequate groundcover in most years (FutureBeef, 2021, Meat & Livestock Australia, 2018). The aim of this paper is to 1) evaluate the capability of short-term rainfall accumulations to predict the onset of pasture growth at a representative location in northern Australia and compare this approach with the NRO; and 2) investigate the distribution of GDs across northern Australia with respect to ENSO phases.

Methods

Our study investigates the effectiveness of a 3-day rainfall accumulation as a measure for defining the GBOS across northern Australia (10°S-29°S, 112°E-154°E). Using historical rainfall observations, we evaluate the capability of short-term rainfall accumulations to represent the onset of pasture growth and compare this approach with the Northern Rainfall Onset (NRO).

We use gridded daily rainfall observations (1900–2023) from the Scientific Information for Land Owners (SILO) database (Jeffrey et al., 2001) to calculate GBOS, NRO and GD, and the grass production biophysical model GRASP (Rickert et al., 2000) to estimate daily pasture growth (1990–2020), based on long-term grazing trials at Wambiana Station (20° 34’ S, 146° 07’ E) in northern Australia (O’Reagain et al. 2009).

We define the GBOS as the first occurrence of a 3-day rolling sum of 50 mm rainfall between September 1 and April 30 (with additional thresholds ranging from 10-80 mm also tested). The GD is defined as the date on which 70% of all historical GBOS events occur. During El Niño and La Niña years, we identify the reliable GBOS using a 70^{th} percentile threshold for GBOS in those years, based on average Southern Oscillation Index (SOI) values exceeding ±5 from June to November (Allan et al., 1996). A Student’s t-test is applied to assess significant differences between the reliable GBOS during ENSO years and the GD for all years.

We use the green cover variability dataset (1990–2020) from Wambiana, to calculate the Green Cover Onset (GCO), which is defined as the date when green pasture cover reaches and sustains a minimum of 5% after 1 October. The relationship between GBOS and GCO is evaluated using statistical regression analysis, with confidence intervals calculated at the 95% level.

Results

The Green Date (GD)

Figure 1 illustrates the GD at Longreach (23.45°S, 144.25°E; central Queensland) which occurs significantly earlier during La Niña years and later during El Niño years compared to all years. This timing is consistent with the ENSO-driven rainfall patterns in northern Australia (Cowan et al., 2020). The overall 50 mm threshold GD spatial pattern for northern Australia, demonstrates early onsets in the north and northeast regions, with later GDs in central and interior regions (not shown here but refer to Fig. 3 in Naha et al., unpublished manuscript/pers. comm.).

Green Cover Onset (GCO) at Wambiana and its relationship with GBOS and NRO

The analysis of GCO at Wambiana highlights instances of false starts and false dry periods, demonstrating cases where early pasture growth fails initially due to insufficient follow-up rainfall (Figure 2a), or exceeds a certain threshold value (e.g., 2.5%) and maintains a marginal green cover during the cooler months (e.g., July-August; Figure 2b). Thus, careful identification of sustained green cover is essential.

The regression analysis between the GCO and GBOS shows a strong correlation between the two variables, particularly at a 50 mm threshold (Figure 3), explaining about 94% of GCO variability with respect to any change in GBOS. This suggests 50 mm as an optimal threshold for predicting GCO at Wambiana. Furthermore, the analysis comparing the NRO and GBOS (Figure 3) reveals a stronger correlation between GBOS and GCO (R^2 = 0.94) than that between NRO and GCO (R^2 = 0.62), suggesting that GBOS, which reflects short bursts of rainfall, is more effective than NRO for determining the onset of pasture growth at Wambiana.

Discussion

Our study investigates the timing and reliability of the GBOS, a rainfall-based metric aimed at marking the onset of new pasture growth in Australia's northern tropics. By examining the correlation between GCO and GBOS, calculated using various rainfall thresholds (not shown), at a representative location in northern Australia (Wambiana), our research highlights that 50 mm over three days offers the most ideal threshold in determining the relationship between GCO and GBOS at this location, with an explained variance being greater than 94%. At this threshold, the GCO demonstrates a stronger correlation with GBOS than with the NRO, providing the first clear evidence that pasture growth is more related to short bursts of rainfall, than the slower accumulation of rainfall (as observed for Wambiana). This suggests that GBOS may be a more effective indicator for determining the onset of productive pasture. The study also examines the historical GD, representing the start of the pasture growing season and the climatological GBOS across northern Australia. This analysis reveals significant shifts during La Niña years, which tend to advance the onset of pasture growth through earlier effective rainfall. The findings have practical implications for graziers, enabling them to better estimate pasture availability and prepare for stocking and feeding through the dry season. By understanding regional GD patterns and the influence of ENSO phases, graziers can plan ahead for livestock needs, optimising decisions on calving/lambing and stocking rates.

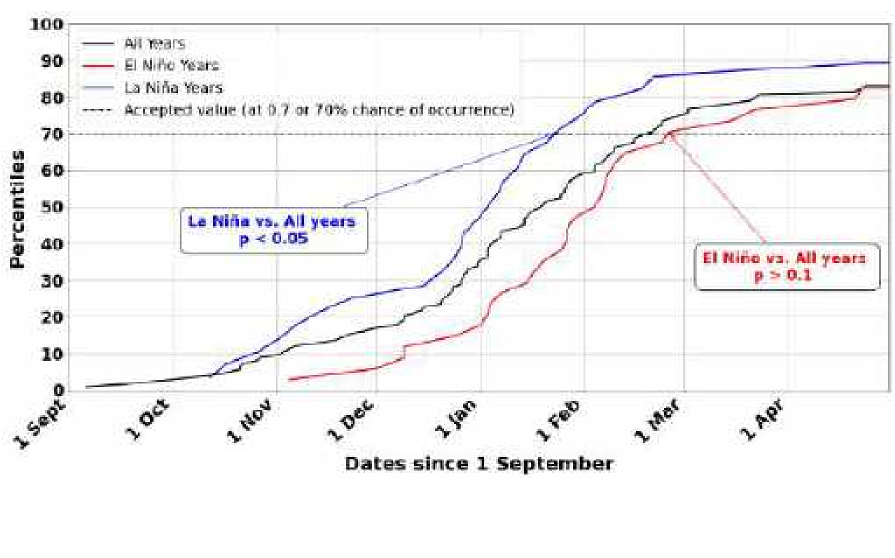

Figure 1: Percentiles of GBOS for Longreach (23.45°S, 144.25°E) from 1900 to 2023, determined using a 50 mm threshold over 3 days. The black dashed horizontal line indicates the 70th percentile, which defines the GD. The solid black, red, and blue curves represent the GBOS percentiles for all years, El Niño years, and La Niña years, respectively. P-values shown are from a Student's t-test comparing the reliable GBOS during ENSO years with the GD for all years.

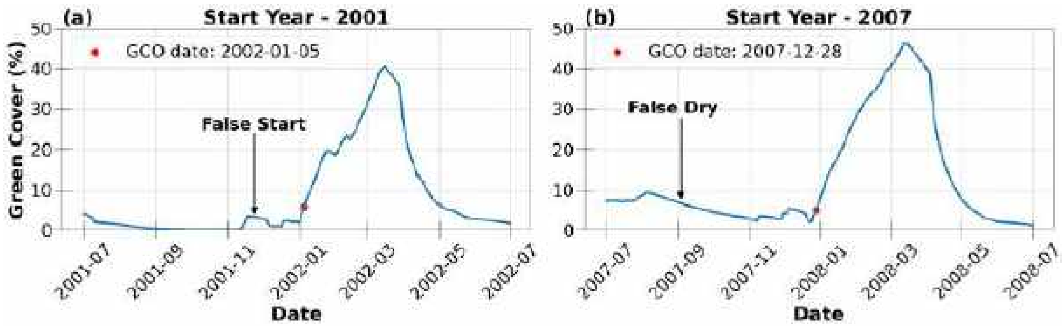

Figure 2: Examples of (a) a 'False start' in green cover onset (2001), and (b) a 'False dry' in green cover (2007).

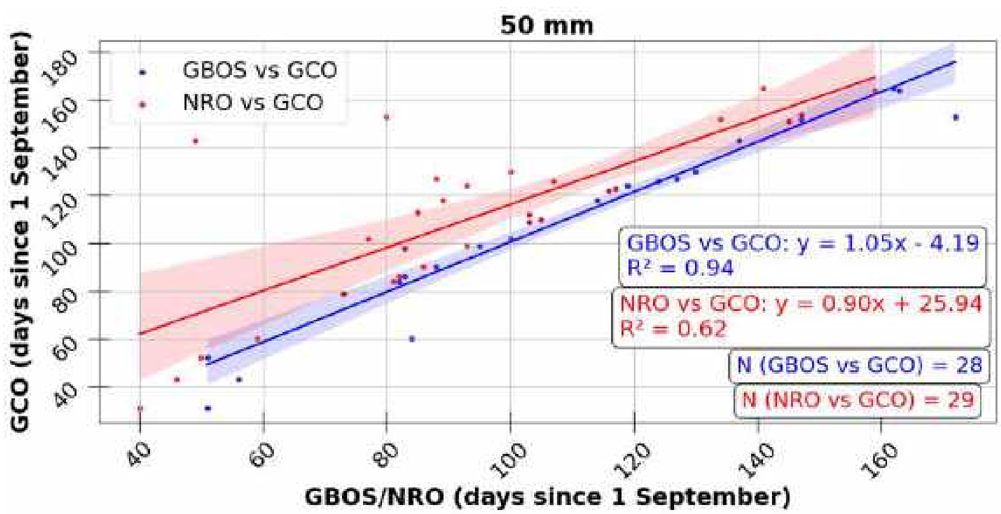

Fig. 3: Linear relationship between GBOS versus GCO and NRO versus GCO at Wambiana Station for a rainfall threshold of 50 mm from 1990 to 2020. The blue shading in the background represents the 95% confidence intervals. The letter 'N' denotes the number of data points included in each regression analysis.

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Brush, burn, return: maintaining rangeland health following catastrophic fires

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Key words: fuel treatments; shrubland management; prescribed livestock grazing

Abstract

Rangeland vegetation in California has evolved with a long history of fire. Reports from early Spanish explorers provide insight into Native American use of fire to maintain grasslands for hunting, oak tree germination and acorn production. Lightning also ignited natural fires, and the combination of the two created a mosaic of different age classes of brush with grasslands intermixed, creating natural fire breaks to minimize the spread of wildfire. Brush control by fire ceased in the 1980's due to a range of factors including administrative barriers (permitting), environmental impact, and costs.

While California's Mediterranean shrublands are ecologically adapted to periodic fire, identifying and adopting strategies to reduce the impacts of severe wildfires in shrublands is now key to reducing their destructive impact. One strategy is livestock grazing, an extensive land use (occurring on roughly 33% of land area statewide) that is also frequently adopted by State and local agencies as a fuel management practice. Shrubland ecosystems accounted for approximately 38% of California's burned areas from 2000-2020 but there is relatively little research into long-term management strategies to mitigate the impacts of shrubland fires. Livestock have been documented to browse on resprouts and slow the spread of shrubs; a management strategy that could reduce shrub encroachment.

To understand shrublands' influence on fire intensity, we analyzed changes in land cover type resulting from major fires (based on hectares and structures lost). Results indicated that with no management, and depending on time and climate, shrublands quickly recovered, becoming the dominant vegetation type. However, while shrublands and grasslands fluctuate in extent, results indicated that forests are not recovering. Every fire footprint had similar changes, indicating that these vegetation patterns are not a feature of the most devastating fires only, but occur following any fire in land cover types that contain shrublands and forests.

Introduction

California has a long history of fire with most of our vegetation evolving with it. Stories from early Spanish explores provide insight to Native American use of fire to maintain grasslands for hunting, oak tree germination and acorn production. Lightning strikes have been a natural ignition of fire and the combination of the two created a mosaic of different age classes of brush with grasslands intermixed, forming natural fire breaks to minimize wildfire spread. With settlers and ranching, control of brush to maintain grasslands for livestock became a common practice (Murphy and Leonard, 1974). Roughly in the 1980's most of the brush control came to a stop. The knowledge of ecosystem functions was lost and the understanding of how grazing keeps a system functioning. With the increase in catastrophic fires experienced in California over the past 20 years, there's a growing interest to manage range and forest lands to lessening wildfire severity. We explore if shrublands (brush) management could be a key to having a resilient community and healthy rangelands.

Methods

While California's Mediterranean shrublands are ecologically adapted to periodic fire, identifying, and adopting strategies to reduce the severity of severe wildfires in shrublands is key to reducing their destructive impact. Even if fine fuels are controlled, the management of shrublands is forgotten. Shrubland ecosystems account for approximately 38% of California's burned areas from 2000-2020 (Calhoun et al. 2022) but there is relatively little research into management strategies to mitigate fire impacts in shrublands.

To better understand the influence of shrublands' regrowth, we examined vegetation types before and after fires occurred. We assessed impacts from the largest California fires, we selected the largest in size (hectares) and most damaging structurally (houses, buildings), according to California Department of Forestry and Fire Protection (Cal Fire) data from 2001 to 2021, a twenty-year span, (Table 1).

We identified twenty-five fires as our sample data point to analyze. Year and season of each fire was entered, and the land cover characterized utilizing National Land Cover Dataset (NLCD) to identify six classes across the footprint of each fire: deciduous forest, evergreen forest, mixed forest, scrub/shrub, herbaceous, and other (developed land). From these six, three basic functional groups were created: forest, shrubland, herbaceous. We used Python 3 and PANDA Python Package to calculate within each fire footprint the percent of the three land cover classifications over time.

Each of the twenty-five wildfires was graphed to show the percent area of each classification (y-axis) and years (x-axis). This allowed changes in each classification before and after the wildfire to be apparent. Wildfires were then grouped into three categories based on the length of time since the fire occurred, or the length of recovery post fire for the vegetation data. In ARCGIS, a web application was created to map all historic fires to 1950. Predictions were made based on the trends observed for vegetation patterns for the fire footprints in the "pre-recovery" fires.

Results

Wildfires distributed across California represent a mix of public and private landowners under a variety of management and idle (no use) land. In all fires examined the same pattern was observed. Forest and shrubland covers decrease immediately post fire and herbaceous layers experience a dramatic increase in cover. After fires, herbaceous cover plummets and shrubland's cover increases, levels well above the pre-fire percentages. The length of time this vegetation shift lasts varies, but within five years, the grassland layer is back to pre-wildfire levels or lower, and the shrubland layer is either at or above pre-wildfire levels. The forest layer drops and even in the longest "recovery" classified wildfires, never seem to recover to pre-fire levels, appearing to be replaced by the shrub layer (Fig. 1).

The Cedar fire started in October 2003, in San Diego County, burning for two weeks, burning 2,232 homes, and killing 15 people. It cost at least $1.331 billion (2003 US).

Table 1. Twenty-five wildfires included in analysis, year occurred, season started, hectares and number of structures destroyed (Cal Fire data).

Wildfire	Year	Season	Hectares	Structures
August Complex	2021	Summer	417,898	935
Camp	2017	Fall	62,053	18,804
Caldor	2021	Summer	89,773	1,003
Carr	2018	Summer	92,936	1,614
Cedar	2003	Fall	110,579	2,820
Creek	2020	Fall	153,738	858
CZU Lightning Complex	2020	Summer	35,009	1,490
Dixie	2021	Summer	389,837	1,311
Glass	2020	Fall	27,310	1,520
Klamath Theater Complex	2008	Summer	77,715	0
LNU Lightning Complex	2020	Summer	146,990	1,491
Mendocino Complex	2018	Summer	185,800	280
Monument	2021	Summer	90,295	28
North Complex	2020	Summer	129,068	2,352
Nuns	2017	Fall	22,008	1,355
Rim	2013	Summer	104,131	112
River Complex	2021	Summer	80,678	122
Rush	2012	Summer	110,038	0
SCU Lightning Complex	2020	Summer	160,508	225
Thomas	2017	Winter	114,078	1,063
Tubbs	2017	Fall	14,895	5,636
Valley	2015	Fall	30,783	1,955
Witch	2007	Fall	80,128	1,650
Woolsey	2018	Fall	39,234	1,643
Zaca	2007	Summer	97,208	1

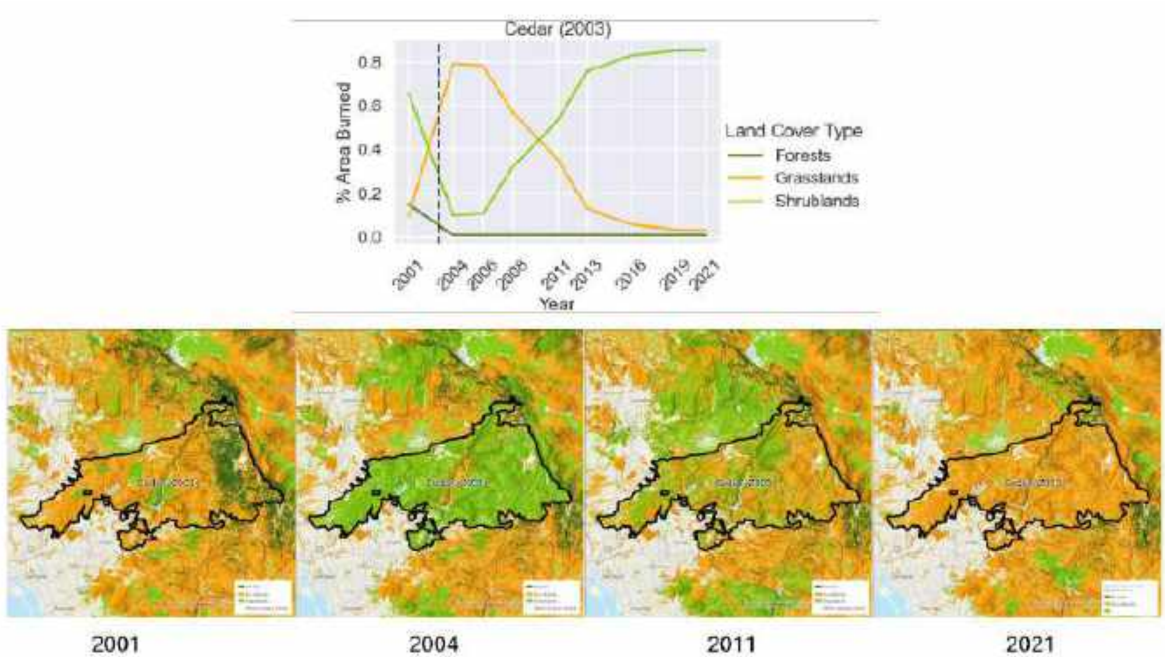

Figure 1. Cedar Fire, October 2003, 110,579 hectares.

Discussion, Conclusions & Implications

Research showed that wildfires are making large vegetation changes to ecosystems with the most drastic changes predominantly in shrublands, both in the short term and long term. Without interventions to maintain shrublands at the pre-fire levels, and steps to reforest fire footprints, there will be continuing shifts in species. Species that rely on forested land cover will either need to adapt to shrubland habitat, relocate, or will disappear completely. Vegetation pattern changes also raise questions about post-wildfire management. Livestock as well as wildlife have been documented to browse on resprouts and slow the spread of shrubs (Rouet-Leduc et. al., 2021). Our data shows that choosing no post fire fuel treatments will result in a decrease in forested landscapes and an increase in shrublands. Fires can destroy permanent fencing on rangelands but with temporary electric fences or even virtual fencing areas could be targeted for vegetation management using ruminants.

Our findings document that some form of fuel treatment is needed following a catastrophic wildfire to assist rangeland health. Fuel treatments can alter fuel conditions so that wildfire is easier to control and less destructive (Reinhardt et. al., 2008). The costs of fuel treatments vary widely, yet the relative cost and success must be considered as opposed to doing nothing and having the fuel loads return (Strand et. al., 2014). Potential benefits of fuel treatments such as reduced wildfire risk, reduced fire suppression costs, and reduced structural losses will be site-specific. Thus, a site-specific analysis must account for the cumulative cost of fuel treatments, the likelihood of wildfire return, with or without treatments, and the overall health of the rangeland. Grazing with cattle, sheep, and goats can support post-wildfire recovery to extend the return interval of the shrubland, and therefore lengthening the fire return interval, mimicking what was naturally occurring before European settlers. Grazing for fuel reduction has the potential to offer a low cost, landscape-level fuel treatment (Germano et. al., 2012). With fire hazard increasing as fuels go untreated, management after catastrophic fires will become more critical to maintain rangeland health.

Research indicated that with no management, after a period, depending on climate, shrublands become the dominant vegetation. While shrublands and grasslands fluctuate, the data indicated forests are not recovering. Other fires assessed had similar vegetation (land cover changes), indicating this pattern is not a factor of the most devastating fires only, but any fires that occur in land cover types containing shrublands and forests. More active prescribed grazing post-wildfire is needed to manage the abundance of herbaceous and re-sprouting shrubs. Prescribed grazing can manage the height and structure of herbaceous growth, result in changes in fire behavior and the decrease of catastrophic fires on the landscape.

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Enhancing climate resilience through the NACP extension service

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Key words: Climate, resilience, extension, adoption

Abstract

The Northern Australian Climate Program (NACP) extension service delivers workshops, field day talks, property visits, and webinars to provide the support and confidence for regional producers to use weather and climate information in decision making. This service helps producers to make more informed assessments of climate forecasts and understand the factors that can influence their specific region in the days, weeks, and months ahead.

Integration between research, development and extension allows for the most relevant and up-to-date climate information to be used in the field to meet end-user needs, and for industry feedback to further inform the program's activities for the benefit of agricultural communities. This iterative model has proven very successful in Australia, as evidenced by the industry funding of the third NACP program (NACP3). One of the main measurements of the success of the program and its impact on producers is meeting Category C goals, which describe the number of practice changes (189 to date) resulting from timely and effective use of the NACP extension and adoption service.

We highlight how the NACP extension service is helping the grazing industry to manage drought and climate risk in northern Australia by improving weather and climate awareness, improving knowledge and skills, providing support and confidence to use this in decision making, and delivering practice change to reduce climate risk and drive positive financial, environmental and social outcomes.

Introduction

The Northern Australia Climate Program (NACP) delivers innovative climate research, product development and targeted extension outcomes to improve the capacity of the red meat industry in managing drought and climate risk across northern Australia. NACP extension and adoption activities are undertaken by regionally located extension officers called Climate Mates, who are leaders in their local community with extensive networks and knowledge of the local industries. Climate Mates are selected for their capacity to communicate with industry and community, and thus they have a unique role to improve the use of weather and climate forecasts through training and engaging with agricultural producers, natural resource managers, advisors and supporting the broader extension teams in the regions. Supported by climatological experts to understand contemporaneous climate forecasting for use within the NACP extension program, Climate Mates take feedback received from clients and communicate it to project partners at the University of Southern Queensland and Bureau of Meteorology to aid in the focus of research and development tools.

Methods

The NACP extension and adoption service integrates and embeds climate forecast information into industry and community networks to improve resilience to weather-climate variability, extremes and change. The program works to:

- Deliver a climate service to producers and graziers across northern Australia
- Facilitate practice change and related decision making by working with stakeholders one-on-one
- Document practice change by providing metrics that meet a triple bottom line (economic, environment, social)
- Facilitate two-way communication with researchers to improve both the relevance of research-driven products and the uptake of forecast information by industry and community
- Seek industry advice on climate needs and product development
- Develop linkages between agriculture producers, natural resource managers, advisers and key supply chain stakeholders to drive adoption of best practice weather/climate management strategies

NACP extension and adoption is modelled on the 'staircase of engagement' (Figure 1; Hewitt et al. 2017, Lavender et al. 2022), which provides a valuable framework for planning, implementing and evaluating the extension activities. Through this, Climate Mates are tasked with achieving key performance indicator targets relating to delivery of awareness (Category A), change in knowledge, attitude, skills, aspirations (KASA; Category B), change in practice (Category C) and demonstrating impact (Category D). Awareness is achieved through passive engagement by providing information, usually through quick presentations, newsletters, websites and tools, and a change in KASA comes through providing dialogue-based activities often in interactive groups such as workshops. A change in practice (e.g. adoption of climate forecasts to inform decision-making) necessitates active engagement with tailored and targeted discussions and focused relationships, often through face-to-face interaction between Climate Mates and producers. Climate Mates record each Category A, B and C outcome using a Customer Relationship Management platform, which enables results to be tallied around the engagement of producers with our educational resources and regional climate information.

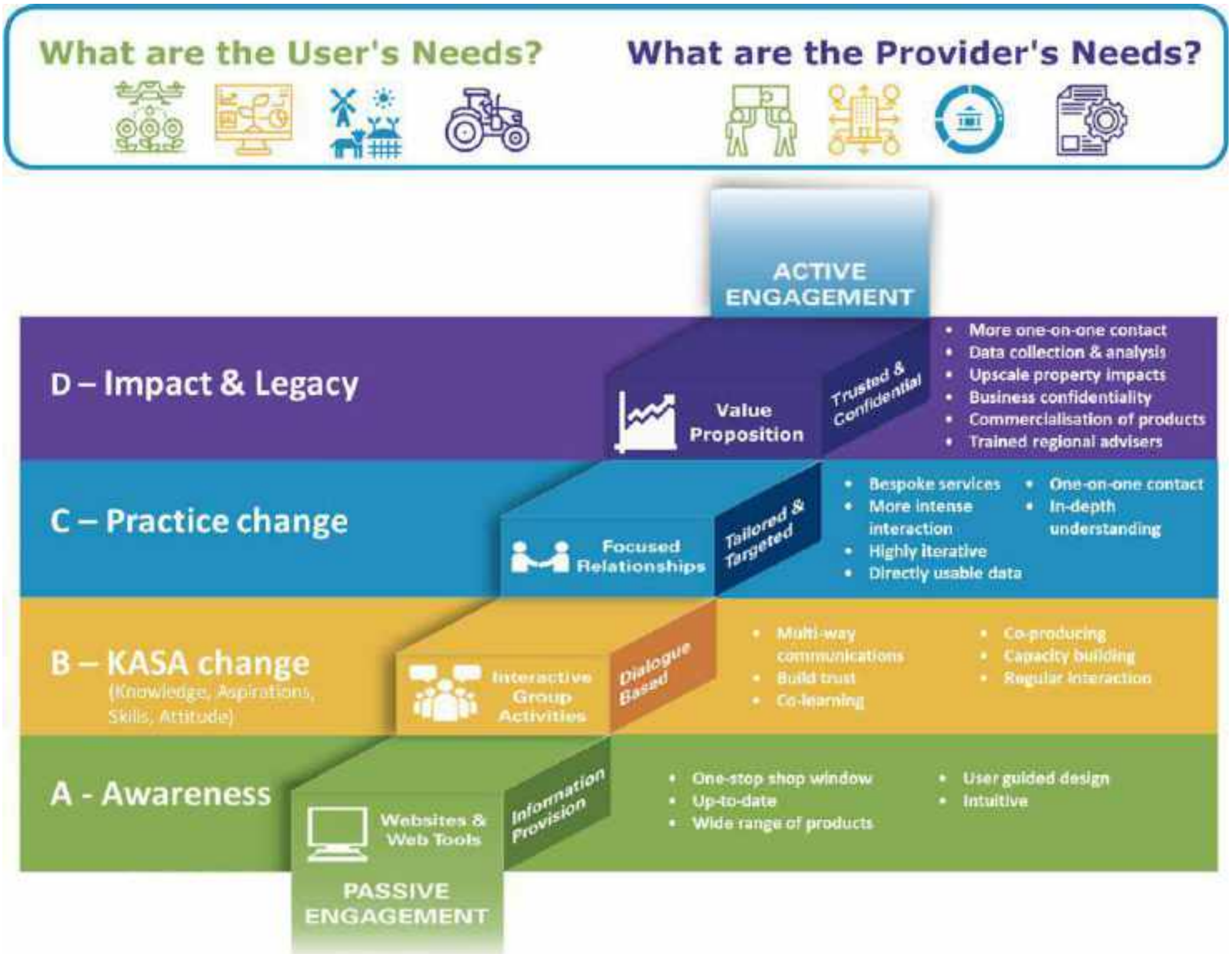

Figure 1: Schematic of four broad categories of NACP engagement with primary producers, adapted with permission from Hewitt et al. (2017).

Results

NACP incorporates robust monitoring, evaluation, and learning activities with tailored extension and adoption services that have been built around:

Category A goals: Producers have improved awareness of NACP, its aims and benefits for Australian agricultural industries, commodities, and stakeholders through the provision of web-based drought information and tools.

Category B goals: Producers have improved knowledge, aspirations, skills and attitudes in the use of forecast products and tailored information for effective decision making.

- Climate Mates have provided ongoing training to producers in interpreting drought and climate forecasts and information demonstrating climate resilience.
- Regular communication between stakeholders and Climate Mates has built knowledge, confidence, and trust around forecasts tools, and the capacity of producers and graziers to use that knowledge to maximise climate resilience. This has led to increased uptake and improved interpretation of forecast products, and improved trust and confidence in Bureau of Meteorology forecasts and services.

- The NACP extension and adoption service, tailored to each region, has been dialogue based and built around interactive group activities; workshops, field days, training sessions, online demonstrations, property visits, agricultural shows, and regular email updates. This direct engagement has fostered transformational change across various levels (property, community, regional) and enhanced the integration, coordination, and sustainability of climate resilience practices.

Category C goals: Practice change has resulted from timely, effective use of the extension and adoption service.

- Personalised and focussed one-on-one interactions between producers and Climate Mates have led to effective uptake of climate products in operational and strategic decision-making and improved economic, environmental, and social outcomes.
- Measures of practice change have also included the extent to which stakeholders and industry are incorporating the NACP extension and adoption service in their decision-making, and the observed strategic changes in enterprises that arise from the service.

Category D goals (in progress): Impact and Legacy

- Centred on the core principles of confidence and trust in climate knowledge and forecast information, this is measuring the improved capacity of producers to be resilient, sustainable, productive, and profitable by using the NACP extension and adoption service in decision making.
- Case studies are providing a comprehensive understanding of how informed decision-making impacts natural resource management on properties, enhancing climate resilience, and improving the project's overall capacity.

All Category data has been managed using a Customer Relationship Management platform to capture, manage, and report on producer engagement, adoption, practice change, and project milestones. To date, NACP3 (2022-present) has delivered 11,941 Category A, 4,291 Category B, and 189 Category C outcomes for producers, exceeding those achieved in NACP2 (2018-2022; Lavender et al. 2022). Importantly, Category C outcomes in three years of NACP3 are already 126% of those achieved in the four years of NACP2 (150 Category C outcomes), demonstrating growth and interest in the use of the program across northern Australia.

Category A, B, C, and D outcomes are assessed through feedback from community, industry, and advisors via emails, reports, surveys, and stakeholder interviews. This monitoring, evaluation, and learning framework has demonstrated its capacity to drive significant behavioural changes and foster greater trust and confidence in climate forecasts among producers.

The NACP website highlights several case studies that illustrate how on-property decision making has benefitted from the use of climate information delivered through the program's extension service (https://nacp.org.au/outreaches/case_studies). For example, producers in Batchelor NT (south of Darwin) have gained a greater understanding, confidence and trust in forecast information from participating in face-to-face training sessions with the regional Climate Mate and extension program coordinator. This has resulted in lower stress, more informed decision making, and better outcomes that include improving the land through revegetation works, weed and erosion control (Category C). This is helping to balance social, economic, and environmental considerations for their business (Category D).

Conclusions

Delivered across northern Australia, the NACP extension and adoption service provides region-specific information through Climate Mates; extension officers with local knowledge, landscape management expertise, and commodity-specific connections.

NACP incorporates robust monitoring, evaluation, and learning activities with tailored extension and adoption services that are built around awareness (Category A), change in KASA (Category B), practice change (Category C) and demonstrating impact (Category D).

The tailored extension and adoption service is utilising existing monitoring and forecast products to help the northern Australian red meat industry make proactive decisions to minimise the economic, social, and environmental losses associated with climate variability and extremes in the days, weeks, and months ahead.

Drawing on the success of the program, future directions may include adapting the NACP model to other farming regions and commodities in livestock and horticulture, with a key focus on planning and preparedness for building drought and climate resilience across Australia.

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Enhancing climate resilience as a NACP Climate Mate

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Key words: extension services; climate literacy; decision support.

Abstract

The Northern Australia Climate Program (NACP) is improving the capacity of the red meat industry to manage drought and climate risk across northern Australia. NACP runs an extension and adoption service that enables producers to better understand the main climate and weather influences in their region, interpret forecast information from days to seasons ahead, and make better informed decisions on property, particularly in the management of pastures for production (Lavender et al. 2022).

Undertaken by regionally located extension officers called Climate Mates, the NACP extension and adoption service includes one-on-one property visits, field day talks, newsletters, workshops, webinars and monthly mailouts. Climate Mates come into the role with existing community networks, and a sound knowledge of local industries. However, most have limited knowledge of weather and climate to begin with, and so with help from peers and researchers at the Bureau of Meteorology, Climate Mates quickly develop an understanding of concepts such as tropical convection, climate drivers, and seasonal variability.

Introduction

Climate Mates are part-time outreach advisers also known as extension officers or agents, who bridge the gap between researchers and pastoral producers by delivering tailored climate and weather information that is accessible and relevant to the needs of northern Australia. The NACP's use of Climate Mates as extension advisers is crucial for improving the uptake of climate information and enhancing the resilience of pastoral industries in northern Australia (Cobon et al. 2021). The program's success depends on the clear communication of complex climate data (observations and forecasts) in ways that are practical and understandable for local producers.

Climate Mates are employed to service one or several pastoral districts of northern Australia from their state or Territory. The focus of this paper is to highlight the experiences from the role of Climate Mates, and how satisfying and successful the work has proven to be.

Figure 1 The NACP extension team, NACP conference, Darwin NT, November 2021.

Methods

On employment, the Climate Mates are not expected to have qualifications in climate science, with employment criteria focussing on the ability to exchange information clearly, as well as having existing connections to the pastoral industry. This ensured that those employed in the roles were active stakeholders of the industry and held a vested interest in the program benefiting their industry. Many of the Climate Mates are beef producers, or work in affiliated industries, such as cattle transport, carbon mitigation, animal nutrition, pasture production, and natural resource management.

Most Climate Mates are located in agricultural communities. Climate Mates are employed on a part-time basis, which could be considered a hindrance to the employment of potential candidates seeking full time work, however this provides benefits to those employed in the pastoral industry to complement their existing work. This local knowledge of pastoral production systems and the beef supply chain, along with established industry networks in their regions, make them trusted intermediaries between researchers and pastoralists.

Unfortunately for many of the Climate Mates, their employment began during COVID in 2020-2021, resulting in the climate literacy training being delivered online. Delivery of content was via videos and power point presentations from colleagues at the University of Southern Queensland's Centre for Applied Climate Science (UniSQ CACS), and program researchers employed by the Australian Bureau of Meteorology. The Climate Mates found benefit in being able to watch training content over again to gain understanding but felt disadvantaged in being unable to ask questions amongst new colleagues that they had yet to establish working relationships with. "I didn't want to appear stupid or be the only person asking the question" pers comms. N. Pilcher, September 2021.

Results

The initial intake of Climate Mates in 2018, completed their climate literacy training in-person, onsite at the University of Queensland's Toowoomba campus, during 20-21 August 2018.

These sessions were delivered by a team of senior climate researchers to the newly appointed Climate Mates. According to Climate Mate, A. Huey, the training was poorly designed, "the climate mates were a group of practical, no nonsense, mostly extroverts, who had been plucked straight out of northern Australia and into the middle of a southern winter, presented complex graphs, and an onslaught of acronyms over a short time". Several of the climate mates present at that initial training agreed that the "training content and delivery was unrelatable, and high level" and it was suggested that one of the newly recruited Climate Mates was so overwhelmed with the content and quantity of information presented, that they left the program as a result. While a disappointing outcome, ironically, this outlines the exact need for extension services at the core of NACP, to ensure clear communication and education of complex climate and weather information to primary producers and land managers, in a practical and relatable way.

The Climate Mates employed in the program, regardless of their initial training design have all now gained a solid understanding of influential climate and weather systems, as it relates to their regions. This has been achieved through regular group updates, mentoring, conference attendances, workshops, roadshows with Bureau of Meteorology research staff, online meetings, self development and their own research. According to Climate Mate V. Mayne, the improved understanding can be attributed to the relationship between the Climate Mates and the researchers employed in the NACP from the Bureau of Meteorology and the UK Met Office. V. Mayne says "having access to experts over the phone and in person" provides valuable knowledge and explanations of the climate systems, and forecasting models that Climate Mates can then provide in their conversations with producers. "It gave us a lot of confidence in what we were delivering, gave our producers a chance to ask tricky questions that we didn't have an answer for, and gave the Bureau of Meteorology a face and a person to relate to" (V. Mayne, pers. comms.). At workshops or property visits, V. Mayne says that "having the Bureau there was great. It was a two-way relationship. Producers would get firsthand explanations of the forecasts, and our research team would learn about beef production and really get an understanding of the lives of our producers".

Several of the NACP climate researchers have participated in climate road shows. These are multi week trips through the remote pastoral districts of northern Australia accompanied by the local Climate Mate and/or natural resource management officer to visit cattle stations to deliver climate literacy workshops. Long distances, heat and cold, flies, roadhouse food, station accommodation or swags under the stars, these trips have been exhausting at times but highly rewarding for all involved. These researchers can now include pregnancy testing amongst their skill sets, along with the knowledge of cattle breeds, cattle genetics, pasture production, bottle feeding calves, weighing cattle, changing flat tyres, and a valuable early lesson that running cattle in a distant paddock are not going to attack you. NACP researchers have stated that these trips are some of the highlights of their careers, "being able to demonstrate your research work, and to see it being used and appreciated, and how it applies in their world, it's just so satisfying", pers comms T. Cowan October 2024.

Personal interactions with producers allow the Climate Mates to provide insights to NACP researchers, highlighting information gaps and possible tools that could be used by agricultural land managers, one example is the development of the Bureau of Meteorology's Chance of three-day totals forecast maps. These maps, show the chance of receiving at least a particular rainfall total, over three consecutive days in the forecast period. This was particularly important for agriculture to plan work activities such as windows for crop planting, expectations around pasture response and grazing times, and consider access issues to paddocks and infrastructure. After the development of this tool, many of NACP's engaged producers, have used it to plan the preparation of paddocks and the date of cotton planting, organised fuel and food delivery to the station before road access becomes an issue, and in understanding the likely response of pasture growth. An important, but less discussed value of our extension service, is in the trust and confidence that land managers gain from their involvement. With increased understanding of the forecast products, producers make informed decisions about grazing management, removing some of the risk of land degradation, economical hardship, and emotional stress. Climate mate A.Huey, says that one of the highlights of her role is "the value of giving people the info and skills to filter out all the white noise and media hype that can cause a lot of undue stress if you just read a headline". This was recorded in a producer interaction from central Australia, where a station manager Z. Groves, attended a NACP climate literacy workshop in 2021, after two years earlier, experiencing drought and hardship in the 2018-2019 season. She shared in group feedback discussion, that if she had known this information prior to this time, that it would have "saved a lot of stress". She recalls that they were "hoping for rain", rather than following trusted information with confidence. She said "it wouldn't have changed the drought but it would have meant there were no surprises, and that they were better prepared". As Climate mate J. McLaughlin states, "considering climate has an influence on every part of life in the bush, to be able to review what the climate is likely to do in the months ahead is pretty powerful. The return on investment is huge".

Figure 2 (L) Climate literacy roadshows" Taking BoM to the bush", Central Australia, July 2023
Figure 3 (R) More than just a workshop, Climate Scientist and NACP researcher Dr Andrew Marshall changing a flat tyre, July 2023.

Discussion

A legacy of the extension and adoption service is the production of Rain Gauge, a Profitable Grazing Systems (PGS) training course through Meat and Livestock Australia. This course embeds climate literacy into grazing production systems across Australia. This contextualised knowledge will be available nationally to producers for future use. It also offers the Climate Mates of NACP, continuity in delivering tailored climate and weather information after finalisation of NACP. Since its commencement in 2018, NACP has engaged with over ten thousand red meat producers, extension officers, government agency staff and industry stakeholders, across northern Australia (Cobon.D. 2024).

From personal experience, the rewards of delivering climate extension services across northern Australia are many. From being able to visit and explore the vast rangeland landscapes of the NT and showing graziers the tools to use to interpret the forecasts, through to utilisation of these tools in decision making. I am convinced that the information and education I provide, is helping people to make decisions that will benefit the rangelands environment. We forewarn of drier or wetter than normal conditions, and promote herd management decisions, such as reducing grazing numbers, or spelling paddocks. Other benefits are the personal relationships formed through continued extension and contact, I count many of the producers I have engaged with as friends now, and I'm always rewarded at a visit with a station meal and beef to take home. Once just an avid rain radar watcher, and appreciator of intense tropical storms, four years into the role, I now understand and speak confidently about the seasonal drivers and influences of northern Australia's climate.

Figure 4 Climate Mate Emily Hinds bottle feeding a calf, Mount Sanford station, NT, August 2023

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Livestock grazing systems: a problem or a solution for our planet?

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Key words: Livestock grazing system; climate change; controversies; metrics

Abstract

Within the context of global change, livestock production is undergoing major restructuring. For several decades, demand for animal products has been rising sharply. This “livestock revolution”, together with expansion of land cultivated for food and feed, has exacerbated human pressure on land and natural resources. Ruminant livestock farming is one of the most heavily criticised sectors, notably for its significant contribution to greenhouse gas (GHG) emissions (12% of total emissions) and its role in degrading sensitive environments (desertification in the Sahel, deforestation in Amazonia). In addition to being a simple factor in reducing the environmental impact of food systems and, in particular, in adjusting GHG emissions, the productive purposes of livestock grazing systems and agro-pastoral systems are now being widely revisited. It is no longer just a question of ensuring food security, but of considering the many services provided by this activity, which is also heavily impacted by climate change. It is a complex question, and we need to go beyond simplistic visions and solutions. To contribute to the debate, we examine the major developments in the various types of livestock sector over the last few decades, particularly the ruminant sector, and their impacts on climate change. Then we propose to debate the controversies linked to the need to reduce emissions, which have made livestock farming a particularly problematic environmental and social issue. What are the options for sustainable grazing systems, combining adaptation to climate change with mitigation? What is the future of grazing livestock under the influence of intensifying and accelerating climate change? In order to facilitate transformation of the livestock sector, it is essential to reconsider the evaluation metrics used to assess the sector's impact on nature and its sources. This will enable a more comprehensive and detailed understanding of this sector, which will in turn inform its future development.

Introduction

According to a recent FAO (2023) assessment, livestock production accounts for 12% of anthropogenic greenhouse gas (GHG) emissions, or 40% of total emissions from the agrifood system. Critics point to its role in deforestation in the Amazon, desertification in the Sahel, competition between animal feed and human food, and concerns about the impact of meat consumption on human health and animal welfare. However, these generalisations fail to take into account the diversity of livestock farming systems, species, production methods and consumption patterns. Livestock farming fulfils important environmental, social and economic functions beyond its impact on GHGs, and it is therefore unwise to consider solely an emission reduction target. Effective assessment of livestock’s contribution to climate change requires context-specific approaches, improved evaluation methods and consideration of its multiple and interdependent agro-ecological and socio-economic dimensions, particularly in developing countries where data on livestock GHG emissions are limited. Given significant transformations in the sector in recent decades, this paper reviews briefly livestock's impact on climate change and explores options for sustainable systems. It also addresses controversies that make livestock farming a contentious societal and political issue. We hypothesise that appropriate assessment methods can help to better address the trade-offs between environmental, economic and social functions, towards sustainable livestock systems.

How does livestock farming contribute to climate change?
Global livestock production has grown faster than the human population (except for beef), intensifying its environmental impact (Gerber et al. 2013, FAO 2023). Over the past few decades, this growth has led to the expansion of land cultivated for food and feed, significantly increasing the ecological footprint of the livestock sector, which is now a major contributor to agricultural GHG emissions.

According to the FAO (2023), livestock systems account for 12% of anthropogenic emissions, with methane as the primary contributor (54%), followed by carbon dioxide (31%) and nitrous oxide (15%). GHG emissions vary widely across regions and are not strictly tied to production volumes. Ruminants contribute 70% of livestock emissions, but grass-fed livestock systems account for just 20% (Gerber et al. 2013). Regions like sub-Saharan Africa, with low productivity, and Latin America, where forests are converted to pastures and feed crops, exhibit the highest emissions per kilogram of carcass produced (70 kg eqCO2/kg).

These figures are still the subject of debate within the scientific community. In particular, the contribution of livestock farming to emissions linked to land-use change and carbon sequestration has not yet been properly assessed. However, references on the specific contribution of livestock systems in southern countries to GHG emissions are insufficient and often based on data from developed countries. Besides in developed countries, livestock remains an important component of mitigation and adaptative strategies to climate changes through mobility, rangeland biodiversity preservation and source of income (see Alary et al. 2021).

What are the options for sustainable food systems?
Over the past 40 years, the rapid growth of livestock farming has certainly considerably increased GHG emissions. However, a more nuanced, context-specific approach (Blanfort et al. 2023) is essential to ensure that global solutions do not undermine rural communities and agro-pastoral systems, which often contribute to sustainable development. According to the United Nations, to feed nearly 10 billion people by 2050, livestock production should continue to grow, particularly in regions such as sub-Saharan Africa, India and South-East Asia, where populations are increasing rapidly and consumption of animal products remains low. To meet this demand, three options can be considered: i) increasing the number of livestock, ii) intensifying production or iii) importing animal products. These three options do not have the same impact on GHG emissions, respectively on: i) the increase in GHG emissions, ii) the reduction in GHG emissions per kg of product due to the increase in productivity but reduction in carbon storage in livestock farming systems, and iii) the carbon footprint linked to transport and imported deforestation (the direct or indirect deforestation caused by the production of raw materials or processed products outside the consumer's national territory).

Reconciling growth in the supply of animal products with global GHG emission reductions remains a major challenge. While alternatives advocate reducing meat and dairy consumption, particularly in the developed world, they often rely on industrialised models. A more viable approach, particularly in pastoral systems, is to minimise losses and waste throughout the animal product chain in pastoral systems: the circular bio-economy. This offers significant potential to reconcile sustainable economic development with global challenges such as food security, climate change and resource management (Vayssières 2011). Livestock systems that use grazed and harvested resources are also characterised by a capacity to store carbon in soils, which is highly effective in controlling carbon fluxes According to Gerber et al. (2013), soil management offers the greatest potential for reducing agricultural emissions. This approach is becoming increasingly integrated into sustainable development plans for the livestock sector. However, the current metrics and methods of assessment may prove inadequate for evaluating grazed ecosystems, particularly in tropical regions, where the potential for carbon sequestration is significant due to the extensive land area involved.

Better assessment methods to address controversies in the livestock sector and facilitate its transition

In recent decades, livestock production has generated controversies over its role in meeting the world's demand for protein and its impact on the environment, particularly in relation to climate change. Addressing these challenges requires integrating both aspects to steer agriculture towards sustainable food systems.

The report ‘Livestock's long shadow’ (Steinfeld et al. 2006) highlighted the significant negative impacts of livestock on land use and climate. Meanwhile, livestock issues are increasingly central to climate negotiations, such as the methane pledge at the 26th Conference of Parties in the United Nations Framework Convention on Climate Change (UNFCCC COP26) in 2021, and broader mitigation. Soil organic carbon (SOC) now plays a key role in climate regulation, accounting for 47% of agriculture's mitigation potential (Bossio et al. 2020), with most SOC stored in forests (30%) and grasslands (30–35%, Lal et al. 2012). Maintaining or increasing these stocks is one of the few options identified by the Intergovernmental Panel on Climate Change (IPCC 2019) that can simultaneously mitigate climate change, combat land degradation and biodiversity loss, and improve food security. These synergies inspired the international initiative 4 for 1000: soil for food security and climate, launched at UNFCCC COP21 in 2015. The positions and narratives on livestock thus vary across political, scientific and social spheres, influencing each other. Understanding the actors behind these diverse narratives and metrics helps clarify the current view of livestock and its impact on policies.

Some metrics persist unchallenged, shaping pro- and anti-livestock discourse. Questioning these metrics (on their nature and sources) on today's agricultural trends should allow a more objective and nuanced view of the livestock sector. However, measuring the role of livestock farming in global change is complex and requires new, contextualised evaluation methods to accurately assess carbon flows. These assessments are crucial for designing mitigation actions: i) reducing GHG emissions and ii) promoting carbon transfer and storage from the atmosphere to terrestrial compartments. Several cases of field research on livestock grazing systems in emblematic tropical areas reveal effective mechanisms for soil carbon sequestration and methane emission reduction by cattle. In Amazonia, in areas where farmers have stopped deforestation, research is supporting a low-carbon development path. The renewable resources in these regions (solar radiation, rainfall, soil) can efficiently support productive grazing systems that store carbon in the soil (Blanfort 2023), as shown by research in the French Amazon (Stahl et al. 2016, 2017). In Senegal, despite livestock's reputation for high GHG emissions per unit of product, research shows that pastoral areas can be carbon neutral by using an ecosystem assessment method that considers the entire use of the territory (Blanfort et al. 2023).

Conclusion

Livestock farming plays a complex role in climate change and food security, with its environmental impact varying across regions and production systems. While livestock contributes significantly to global GHG emissions, particularly methane, the environmental footprint is not uniform. A nuanced approach to evaluating these impacts is needed, considering diverse farming practices and the socio-economic functions of livestock.

Therefore, future research should focus on developing more refined and regionally tailored assessment methods to better understand the full scope of livestock's environmental impacts. In particular, it is necessary to produce more integrative measures and evaluation methods to better grasp the complex interactions between livestock farming and environmental factors, while integrating the multifunctional dimensions of livestock farming.

The aim is to contribute to science-based policies, right up to the international governance levels of the COPS of the UNFCCC and the United Nations Convention to Combat Desertification (UNCCD). The challenge for the future is to develop policies that support livestock farmers in the face of climate challenges, while guaranteeing food security and sustainable resource management.

The International Year of Rangelands and Pastoralists (IYRP), to be held in 2026, offers a tremendous opportunity to work towards these goals, to effectively integrate these issues into international commitments and climate financing. This will help to better integrate the role of pastoral systems in mitigation, adaptation and sustainable land management – aspects often underestimated in climate negotiations.

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Realising the opportunities and potential for pastoralist youth in rangelands

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Key words: pastoralist youth; rangelands; rangeland management; economic opportunities

Abstract

As pastoralist communities face a multitude of challenges that threaten their sustainability, engaging with youth in rangeland management is becoming increasingly important. This paper explores the opportunities that rangelands offer young people and the potential benefits of youth involvement in pastoralism. Drawing on existing cases and examples, we examine how youth participation in rangeland management contributes to socioeconomic development and ecological conservation. Pastoralist youth bring innovative approaches to traditional practices and integrate modern technologies with indigenous knowledge. Their adaptability and openness to new ideas can lead to more resilient pastoral systems and better rangeland management.

However, challenges remain in attracting and retaining youth in pastoral livelihoods. Addressing challenges such as land access, conversion and privatisation, and high entry barriers is essential for the viability of pastoral economies. Improving working conditions, strengthening labour rights, and ensuring succession planning and governance transition from elder pastoralists to the younger generation can attract more youth to pastoralism. We discuss potential strategies to overcome these barriers, including education programmes, policy support and economic incentives that recognise the multifunctional value of rangelands. Rangelands provide diverse opportunities for youth beyond herding along the value chain, including agribusiness ventures, eco-tourism and social protection projects. These opportunities present chances for young people to generate income, create jobs and contribute to the local and national economies. The greatest opportunities for change in pastoralist societies lie with the youth, who are often better formally educated and more in touch with emerging technologies and trends. By valuing and recognising the contributions of young pastoralists, we can explore innovative ideas and unlock the potential of rangelands in fostering sustainable development.

Introduction

Pastoralist communities are crucial in sustaining rangelands, encompassing over half of the Earth's terrestrial ecosystems (ILRI et al. 2021). These ecosystems sustain millions of people globally, particularly pastoralist communities, who depend on them for livestock grazing and cultural preservation. The livestock sector, predominantly supported by rangelands, accounts for over 50% of agricultural GDP in many African countries and provides critical sustenance and income for millions (FAO 2018). However, rangelands face significant challenges, including climate change-induced degradation, socioeconomic exclusion, and political and policy marginalisation (Briske et al. 2023). Pastoralist communities are at the heart of sustainable rangeland management, contributing significantly to local and national economies, and youth within these communities hold the key to their sustainability.

Youth represent a demographic group with the potential to integrate traditional practices with modern innovations and emerging technologies, fostering ecological balance and socioeconomic progress. However, these potential contributions are at risk as youth increasingly move away from pastoralism on account of limited economic opportunities, poor working conditions, and lack of access to education and land rights (Ancey et al. 2020). The disengagement of youth threatens the generational continuity of pastoralism, leading to the potential degradation of these ecosystems due to mismanagement and abandonment. Engaging youth in rangeland management offers a path to address these challenges in rangeland ecosystems by leveraging their adaptability, education and familiarity with emerging technologies. As rangelands play a crucial role in global food security, biodiversity conservation and carbon sequestration, empowering youth to re-engage with and innovate in rangeland management is urgently important (Holechek et al. 2020). This paper argues that addressing these socioeconomic and structural barriers is essential for realising the untapped potential of pastoralist youth to sustain and enhance the value of rangelands.

Methods

This study employed a literature review approach to investigate the role and potential opportunities for pastoralist youth in rangeland management. The review was conducted in several steps to ensure comprehensiveness and replicability. First, relevant sources were identified by searching academic databases, institutional repositories and online libraries. However, the review process revealed a significant scarcity of comprehensive, peer-reviewed studies and reports specifically addressing the role and contributions of pastoralist youth. This limitation necessitated reliance on grey literature, organisational reports and case studies. Specific journals, including *Rangeland Ecology & Management*, *The Rangeland Journal,* and *Rangelands*, were prioritised for their focus on rangeland ecology and pastoralism. Keywords such as "pastoralist youth," "youth," "rangeland management," "sustainable pastoralism," "youth empowerment," and "rangeland opportunities" were used during database searches, and only publications from the last two decades that explicitly addressed youth engagement in pastoralism, rangeland management strategies, or socioeconomic and policy dimensions were considered. Global, regional and local case studies and examples of youth engagement were selected. The selected studies were reviewed to extract data related to the research themes. The extracted data were categorised into economic diversification, technological integration and socio-political challenges affecting youth participation. A synthesis approach was applied to integrate findings across disciplines, providing a comprehensive understanding of the topic. Previously established review methodologies were referenced to ensure consistency and rigour, following guidelines outlined in earlier studies on pastoralism and rangeland sustainability (Turner et al. 2019, Scoones et al. 2013). This structured approach ensures that the findings are robust and grounded in diverse, high-quality sources.

Results

Rangelands offer a diverse range of opportunities for pastoralist youth. Beyond traditional herding, young pastoralists are increasingly engaging in agribusinesses, eco-tourism and value-chain activities like animal product processing and marketing. However, the findings indicate that they face significant opportunities and barriers in rangeland management. Key opportunities include diversification into agribusiness, where youth-led ventures such as dairy production, fodder cultivation and meat processing have demonstrated economic viability (FAO 2024). Ecotourism offers another avenue, particularly in biodiversity-rich rangelands. Initiatives such as community-run wildlife conservancies in Namibia have enabled young pastoralists to generate income while contributing to conservation efforts (Naidoo et al. 2016, Schiffer 2004). Youth can integrate ecotourism and biodiversity conservation with pastoral livelihoods by guiding tourists and conducting educational programmes about pastoralist practices, which generate income and foster cultural preservation and environmental awareness.

In Mongolia, young pastoralists are increasingly adopting digital tools to manage livestock and grazing patterns in response to overgrazing and climate change challenges. For example, herders use mobile phones for weather forecasts, livestock market prices and emergency alerts (Baival et al. 2012). Digital platforms such as the AfriScout app provide geospatial data to optimise grazing routes, while mobile banking services facilitate financial inclusion for young herders (SPARC 2013). Young pastoralists have also been instrumental in reviving community-based herding systems, known as *Nukhurlul*, which promote equitable resource sharing and sustainable grazing (Upton 2008). Educational initiatives, such as the Pastoralist Field Schools supported by the FAO, equip youth with skills to manage rangelands sustainably (Khisa et al. 2013). In the arid rangelands of Australia, Aboriginal youth are engaging in land stewardship programmes, and the Ranger Programs employ youth to manage invasive species, conduct controlled burns and monitor biodiversity, demonstrating the effectiveness of blending Indigenous and modern practices (Altman et al. 2012, Department of Climate Change, Energy, the Environment and Water 2021, Young et al. 2008). Thus, indigenous youth can actively participate in sustainable grazing and landscape restoration initiatives while raising awareness about their way of life. In Europe, shepherd and shepherdess schools are important for preserving pastoralism and herding traditions while equipping a new generation of herders with skills for extensive livestock farming (Bindi 2024, Escuela de Pastoras 2024). These institutions provide comprehensive training that integrates traditional herding and contemporary practices, empowering rural communities with extensive livestock farming and providing solutions to climate change as guardians of the ecosystems and managers of landscapes.

Despite these opportunities, systemic challenges persist. Limited access to land and insecure tenure rights disproportionately affect youth, reducing their ability to sustain livelihoods and engage with pastoralism, primarily due to land privatisation and encroachment (Archambault 2014). Additionally, the high costs of land and infrastructure limit entry into pastoralism. Climate variability exacerbates these challenges, increasing vulnerability to droughts and resource scarcity. A lack of reliable data and information on pastoralist youth further exacerbates this issue, making it difficult to design targeted interventions and support mechanisms. Youth engagement in pastoralist activities significantly contributes to the economic sustainability of rangeland-dependent communities. Young pastoralists bring diversification to traditional livelihoods, creating new revenue streams and job opportunities.

Discussion

The role of pastoralist youth is pivotal to the future of rangeland management. Their capacity to merge indigenous knowledge with modern technologies creates opportunities for innovation and resilience. However, enabling this requires targeted interventions, such as securing land rights through legal frameworks and community governance models that can reduce marginalisation. Educational reforms and initiatives that include technical training and indigenous knowledge systems can prepare youth for leadership roles in rangeland management.

Pastoralist youth have a unique ability to innovate within traditional systems, positioning them as drivers of sustainable development in rangelands. By integrating indigenous knowledge with modern technologies, youth can enhance resource-use efficiency and ecological resilience. The role of education and programmes like FAO's Pastoralist Field Schools and Spain's shepherding schools have built the technical and managerial capacity of young herders, enabling them to adopt climate-smart practices and engage in governance (Escuela de Pastoras 2024, FAO 2017, Khisa et al. 2013). Securing land rights through inclusive tenure policies and policy interventions is fundamental to addressing the barriers to youth participation and empowering youth engagement in pastoralism. Economic incentives, such as microcredit schemes and cooperatives tailored for livestock production and animal product price regulation, can lower financial barriers and create market access. Collaborative governance models that include youth in decision-making ensure that their voices shape the future of rangelands.

Enhancing land-tenure security is fundamental to advancing youth participation in pastoralist livelihoods and ensuring sustainable rangeland management. Secure land rights empower youth by providing stable access to grazing areas, reducing resource-use conflicts, creating space for infrastructure and value chain activities, and lowering entry barriers for new pastoralists. Policies formalising community land ownership, such as the Community Land Act in Kenya, offer a replicable framework for addressing tenure insecurity among pastoralist youth (Government of Kenya 2016). Integrating participatory governance models, where youth take active part in land management decisions, can further enhance tenure security. International organisations like the International Land Coalition advocate for inclusive land-tenure policies that combine customary practices with legal recognition to accommodate the unique needs of pastoralist communities. Financial incentives, such as subsidies for land registration and microcredit programmes for land development, can also reduce economic barriers to land ownership. By prioritising these policies, governments and development partners can unlock the potential of youth to contribute to sustainable rangeland management, ensuring the long-term viability of pastoral systems.

While the role of pastoralist youth is gaining recognition, a significant gap remains in the availability of data and information about their contributions and challenges. This lack of accessible, comprehensive research and online resources has hindered the development of targeted policies and interventions for pastoralist youth. However, efforts such as the International Year of Rangelands and Pastoralists (IYRP) have begun to spotlight these issues, catalysing global attention and dialogue on youth and other emerging issues. Despite this momentum, the scarcity of detailed data on pastoralists including the youth remains frustrating, as it limits the ability of stakeholders to understand and support their transformative potential in rangeland management fully. To bridge this gap, participatory and transdisciplinary research involving pastoralist youth is essential. Such approaches would ensure that the voices and experiences of youth are directly integrated into data collection and analysis, leading to more effective, evidence-based interventions and policies.

The potential for pastoralist youth extends beyond economic contributions. Their involvement in governance, education and technology development can drive systemic change, ensuring that rangelands remain productive and resilient. Communities and policymakers can secure these critical ecosystems' ecological and socioeconomic sustainability by investing in their capacities. The future resilience of rangelands is intrinsically linked to youth engagement. Their innovative spirit and technological fluency can maintain pastoralism as a viable and sustainable livelihood, balancing ecological conservation with economic development.

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Pastoralist women's initiatives in self-organisation and co-innovation for a sustainable future

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Key words: women herders; endogenous development; local knowledge; transdisciplinary research

Abstract

On rangelands, which cover over half the Earth's land surface, pastoralists produce food and other products from livestock. Not only have rangelands and pastoralists received less investment in research and development; often, women's critical roles in pastoral systems are overlooked or undermined by development interventions. There are only a few examples where herdswomen and rangeland scientists have worked together to jointly understand the rangelands and possible futures.

The United Nations declared 2026 as the International Year of Rangelands and Pastoralists (IYRP). This paper draws on own experiences of members of the IYRP Working Group on Pastoralism and Gender (WG)[18] in their work with pastoralist women as well as from a desk study, which is underway, of publications and grey literature related to pastoralist women's initiatives in endogenous development and co-innovation, in self-organisation to have more influence in public spheres, and in the women's collaboration with scientists.

The paper brings some findings from this desk study, here specifically related to experiences in Argentina, Hungary, India, Eastern Africa and Spain, which will be used in the lead-up to and during the IYRP2026 to raise awareness globally about the strengths and potentials of pastoralist women. The findings will also feed into a global gathering of women pastoralists and researchers, designed to bring together their respective knowledge systems and intensify transdisciplinary collaboration in research and development in the rangelands.

Introduction

On rangelands covering over half the Earth's land surface, pastoralists produce food and other products from livestock (UNCCD 2024). About half of the pastoralists can be assumed to be women and girls. Not only have rangelands and pastoralists received less investment in research and development (Johnsen et al. 2019); often, women's critical roles in pastoral systems are overlooked or undermined by development interventions (Hodgson

[18] The Working Group on Pastoralism & Gender is one of several Working Groups of the IYRP Global Alliance.

2000, Wangui 2008, Yurco 2024). Despite having been highlighted for decades in development cooperation, gender issues are still often overlooked in rangeland and pastoralist development interventions.

The United Nations has declared 2026 as the International Year of Rangelands and Pastoralists (IYRP). In the lead-up to 2026, the IYRP Working Group on Pastoralism & Gender (WG) seeks to generate better understanding of gender issues related to rangelands and pastoralism, to advance gender equity regarding access to resources and inclusion in decision-making about pastoral management and governance issues, and to give greater visibility and voice to pastoralist women and girls at subnational, national, regional and global level. It also seeks to bring together knowledge systems of women pastoralists and scientists and to intensify transdisciplinary collaboration in research and development in the rangelands.

In all pastoralist societies, women play crucial roles in livestock husbandry and rangeland management. Their knowledge, expertise and labour related to animals, plants and water are essential to pastoralism, as is their work caring for homes and families and cultivating good social relationships within and between communities (e.g. Fernández-Giménez et al. 2024). Their roles in building social capital and ensuring the sustainable use and sharing of resources within the family and community help to maintain social cohesion and to navigate potential crises for pastoralists' survival. Pastoralist women are also keepers of the cultural heritage of pastoralism, ensuring that this vital knowledge, including ethnoveterinary knowledge, is shared in the community – particularly from women to women and girls – and thus passed on to younger generations.

Pastoralist societies throughout the world differ as to who can purchase, inherit or otherwise gain access to livestock; who decides about livestock management; who sells animals and their products; and who controls the income from sales. Most pastoralist women do not have the same opportunity as men to gain access to production resources such as livestock, land, credit, technologies and services.

In decision-making processes above the family level, pastoralist women often have only indirect ways of influencing decisions through male members of the community, instead of participating directly and meaningfully in decision-making entities themselves. Development initiatives and community governance institutions are often designed in ways that constrain pastoralist women from taking active part in addition to their productive (e.g. livestock care) and reproductive (e.g. childbearing and childcare, homemaking, care of the elderly) labour. These continuing obstructions to equity restrict women's potential and critically important contributions to development.

However, in many areas, pastoralist women are taking their own initiatives to deal with new problems and opportunities. For example, in Isiolo County in northern Kenya, some Somali women who were trading individually in camel milk formed the Anolei Women's Camel Dairy Cooperative for collecting, processing and selling the milk. They expanded local sales of dairy products into larger and further-reaching operations, as far as Nairobi 270 km away. Development agencies then provided support to these women by strengthening their business analytical capacities and helping them to reduce milk wastage and to add value to the milk products through joint market research and consumer-awareness activities (Po et al. 2023). Research in Eastern Africa showed that pastoralist women are more willing than men to experiment with options for commercial enterprises and diversification and are more likely to form groups to reduce risk and increase profits, although they have greater difficulties than men to access credit and assets (Stites 2024).

Methods

The almost 60 members of the WG, who come from various countries across the world, are collecting and analysing examples where pastoralist women have taken initiatives to form their own groups at national and regional level so as to improve their social, economic and political status. Likewise, the WG members are collecting and analysing examples of pastoralist women's own socio-economic initiatives on an individual or community basis and their collaboration with scientists in processes of transdisciplinary research and development, building on the women's initiatives. The examples are related mainly to the knowledge and innovation of pastoralist women in livestock production, animal healthcare, managing natural resources and governance of rangelands. These examples are drawn from the WG members' own experiences working with pastoralist women as well as from the above-mentioned inventory, which is still underway, of publications and grey literature related to pastoralist women's initiatives. These examples are to be used in the lead-up to and during the IYRP in 2026 to raise awareness globally about the strengths and potentials of pastoralist women. Further analysis will reveal how local initiatives can be supported and pastoralist women can exert more influence on decisions about research and development in the rangelands.

Results

The examples gathered from the different countries and pastoralist communities are diverse. Thus far, there are only a few examples where herdswomen and rangeland scientists have worked together to jointly understand the rangelands and possible futures. In the Argentine Puna, pastoralist women have collaborated with scientists to explore "mutual breeding" that integrates animals, people and the rangelands (Quiroga et al 2018). In India, the Van Gujjar, and Dhangar communities are working with ecologists and other scientists to understand better how rangelands function and are threatened and what needs to be done for their sustainable management (Anthra 2024). Some herdswomen are forming organisations to make their voices heard in policy dialogue and public events, also about research, and engaging in transdisciplinary research, e.g.in Hungary and Spain (Lelea etc 2024).

In 2010, about 100 women from over 30 countries met in Mera village in Gujarat State, India, in a Global Gathering of Women Pastoralist (IYRP). In their Mera Declaration, they called for recognition of their professionalism as women pastoralists and of pastoral mobility as a basic right. They demanded better access to land and other productive resources, markets, technologies, information and services, and incorporation of their expertise in interventions aimed at sustainable rangeland management. The Pastoral Women's Alliance that emerged from this event now includes about 3000 women. Another global gathering, Mera+15, is planned in 2025 to assess what has changed since the 2010 gathering.

Also in other countries, pastoralist women have taken initiatives to form national or subnational networks, such as the Pastoral Women's Council in Tanzania (PWC) and *Ganaderas en Red* (GER / Women Pastoralists Network) in Spain, with 200 members. In 2021, *Nők a pásztorságban* (Women in Pastoralism) was formed in Hungary with the aim of mutual help and knowledge sharing. Its members (now over 60 in number) also take part in festivals, events and international conferences. The women in such networks meet in person and virtually, exchange knowledge and learn from each other. This helps them overcome social isolation, nurtures pride in their identity and empowers them to work together towards sustainable development of their communities (Lelea et al. 2024).

In Argentina in 2006, the "Gender Area" of *Red Puna* (an Indigenous higher-level organisation in northwest Argentina) was formed to improve women's self-care and influence, combat domestic violence and help women achieve greater economic independence, e.g. through producing handicrafts made of llama fibre. For this purpose, the Indigenous women formed a subgroup *Las Artesanas* (Women Artisans). Women technicians, extensionists and researchers supported the entire process. The *Las Artesanas* members (now 120 women and 5 men) share their experiences and opportunities with new members and other women's organisations (Martínez 2013). Also in the Argentine Puna, pastoralist women and researchers share knowledge on grazing management and "mutual breeding" based on integrating animals, people and the environment. This work valorises women's knowledge and skills in managing herds and the relationships between livestock, pasture and the watershed, seeking to strengthen sustainability of the entire ecosystem (Quiroga Mendiola et al. 2018).

Amongst several pastoralist communities in India, when men left the community to seek jobs outside of pastoralism, the women dealt with this change by starting to manage the herds themselves, in addition to their regular tasks of caring for offspring and processing milk into different products for sale (Ghotge 2020). The *Van*

Gujjar Yuva Sanghatan (VGYS / Van Gujjar Youth Movement) – a group of young male and female Van Gujjar buffalo herders in the lower Himalayas – came together to address the challenges they face. The young women in this group have realised that formal education is needed to be able to navigate a future for themselves and their animals. Further south in Maharashtra State, women from the Dhangar pastoralist community are working with the team at the Indian NGO Anthra to understand the rapid changes in their ecosystems and the impact of climate change on their livestock and their livelihoods (Anthra 2024).

Women pastoralists in Europe, Africa and Asia are also using their networks to raise wider awareness in the general public and to influence policymakers by creatively conveying their messages through various media, including song and film, also participatory video (e.g. Maasai women in Tanzania: https://www.youtube.com/watch?v=BRvRRxoDggQ).

Pastoralism, especially highly mobile forms of it, makes collective action, organisation and even meetings difficult; however, modern technology in the form of mobile phones and apps have facilitated sharing and exchange. For example, in Spain, GER members use a communication tool called Slack, a free app installed on their mobile phones, to communicate and share knowledge. This group also brought out a cookbook of local recipes and uses songs, podcasts, films and social media to share messages about themselves and the work they do (cf. *Ganaderas en Red*).

Discussion and implications

There are many examples around the world that pastoralist women are organising themselves and innovating, also in collaboration with other research and development actors. The examples underline that cooperation and coexistence are important elements for pastoralist livelihoods, whether it be with the rangeland vegetation and landscape, with wildlife, with other communities living in and using the same natural resources, with research and development actors or with the State.

Women pastoralists have shown themselves to be passionate advocates for rangelands and pastoralism, defending pastoralists' mobility and land rights in the face of rangeland appropriation, commodification and conversion to other uses. Lack of formal education, health and social services suited for mobile pastoralists disproportionately impacts on the women and girls. Governments often justify initiatives to settle pastoralists with arguments about providing better services, yet pastoralists know that staying in one place reduces livestock productivity, degrades rangelands and water-points, and raises vulnerability to climate extremes, thus increasing poverty and compromising sustainability. Women pastoralists therefore call for services adapted to their mobile lifestyles.

Many of the women's organisations have given women a chance to develop new skills, take pride in their role as pastoralists and gain confidence to reach for their dreams. It is necessary to reinforce pastoralist women's efforts to advocate at all governance levels by supporting women-only and women-led groups to further strengthen women's confidence and capacities, educating women leaders and creating leadership opportunities for them, and funding their participation in international policy processes. Support is needed for pastoralist women's networks and international gatherings and for incorporating these networks into all initiatives related to rangelands and pastoralism, including those related to the IYRP 2026. It is also important to integrate pastoralist women into transdisciplinary action research and to build their capacities to carry out their own research on pastoralism and rangeland issues, building on their own specific knowledge, innovations and initiatives.

Pastoral animal husbandry, far from becoming obsolete in the face of industrial food systems, continues to thrive worldwide and is gradually becoming recognised as a more sustainable alternative to interventions in rangeland areas that require high levels of inputs based on fossil fuels. The knowledge-intensive practices of mobile pastoralists – men and women – make use of spatially and temporally variable vegetation and hold promise for a climate-friendly future. Pastoralist women's tasks are changing, largely due to their initiatives to address emerging problems and opportunities. The women are making deliberate efforts to increase their voice and influence also beyond their communities. It is time to make their vital traditional and new roles more visible so that they are better recognised in their own countries and globally and can contribute even more to wellbeing.

There is much to be learned from pastoralist women about their ability and determination to care for their animals, their families and the land that supports them; about their ability to face adversity and come together in innovative ways to face new challenges and grasp new opportunities; about their contribution to peace-keeping among multiple stakeholders in land use; and about their desire to continue as pastoralists and advocate for their way of life within their country and globally. These and more examples will be used in the lead-up to and during the IYRP in 2026 to raise awareness about the strengths and potentials of pastoralist women. Further analysis of pastoralist women's initiatives will reveal ways in which these can be meaningfully supported and ways in which pastoralist women can exert more influence on decisions regarding research and development in the rangelands.

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IYRP Session 2 - Co-design, partnerships & incorporating traditional knowledge for more enduring rangeland outcomes (RISGs

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The adaptive systemic approach: equitable co-design and partnerships for sustainable multi-use rangelands in Tanzania, Ethiopia, and South Africa

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Key words: complex social-ecological systems; rangeland co-operation; strategic adaptive management.

Abstract

Building effective equitable partnerships and implementing co-designed projects and/or interventions to sustain multi-use rangelands, takes time, sustained commitment, and resources. There are pitfalls. Teams in three African countries used the collaboratively developed Adaptive Systemic Approach (ASA) to navigate these processes. We present a summary of the ASA and findings from its application. Key ASA strengths included: partnership building; enabling co-design; and capacity building through transformative social learning (explicitly respecting and integrating different knowledge forms: academic, practice-based, indigenous). We identify pitfalls: inadequate capacity building across academic disciplines, patchy facilitation skills, process discontinuities (e.g. changing representative participants), inattention to language and translation, power imbalances, and experiences of disrespect. We present adaptations to mitigate pitfalls. In all three contexts we aimed to move towards increased capacity for participatory governance, and an increased likelihood of improved rangeland condition and sustainable livelihoods. 1) The Great Ruaha River catchment (Tanzania), exemplifies challenges related to unequal water resources sharing, and ongoing contestation among competing water users, including communal livestock farmers, crop farmers and other community members. ASA engagements included these marginalised groups, addressed longstanding power imbalances, and set the groundwork for future collaborations. 2) Current vegetation cover in the Upper Blue Nile River basin (Ethiopia) reflects a complex interplay of human activities including grazing, cultivation, and selective fodder cutting; interwoven with the influences of climate, soil, and geology. A long-term restoration initiative in the Aba Gerima and Debre Yaqob catchments focusses on managing vegetation cover and the balance of woody plants and grasses. Using the ASA, communities in the two catchments co-developed strategies for rangeland and livelihood sustainability. 3) In the Tsitsa River catchment (South Africa) the appointment of eco-rangers, and early steps towards agreements for rotational grazing of multi-owned herds, in the degraded free-range communal rangeland, emerged from participatory ASA processes.

Introduction

Across Africa, rangelands are used by people with livestock for cultural, economic and food production purposes (Homewood 2004). As competition for rangeland use increases, contestation emerges (Samuels et al. 2021). It takes time, sustained commitment, and resources to build effective equitable partnerships and implement co-designed projects and/or interventions that catalyse change towards social justice and ecological sustainability - social-ecological justice (Wolff et al. 2019). There are pitfalls. We consider contexts in three African countries, two where livestock grazing has impacted vegetation cover, rangeland health and livelihoods, and one where livestock owners are scapegoated for water scarcity problems. In each context we applied the Adaptive Systemic Approach (ASA)(Palmer et al. 2023, Palmer and Tanner 2024). We qualitatively evaluated the indicators: partnership building; enabling co-design; effective communication; and developing participatory governance capacity and capabilities through transformative social learning. We discuss the implications of practising the ASA in rangeland management and restoration.

Methods

The Adaptive Systemic Approach (Palmer et al. 2023) (Figure 1) emerged from the literature on Adaptive Management (Allen and Garmestani 2015), the emergence of Strategic Adaptive Management (SAM) (Rogers and Luton 2011), and practice in the Tsitsa River catchment (Cockburn et al, 2018) - that included participatory monitoring, evaluation, reflection, and learning (Rosenberg and Kotschy 2020).

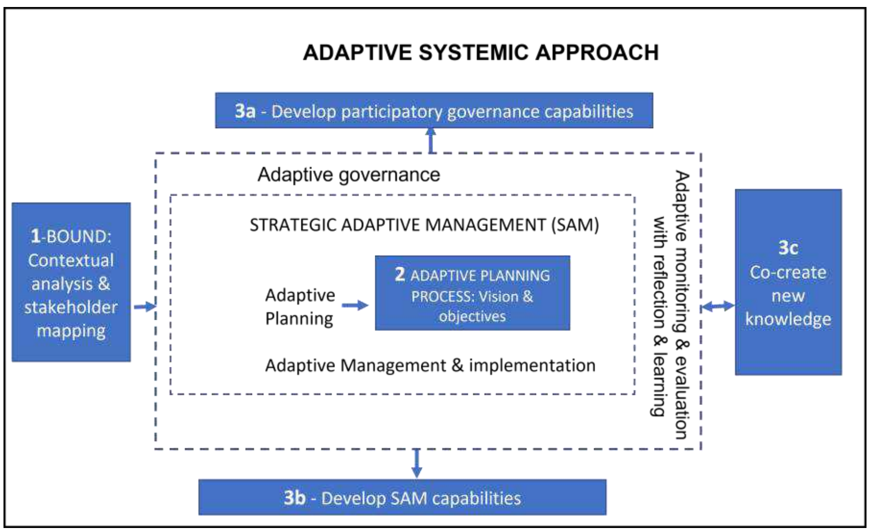

Figure 1. The Adaptive Systemic Approach (ASA) (1-3) begins with a contextual analysis termed “Bound” because systems have porous boundaries, influencing and being influenced by neighbouring systems. The Bound phase **(1)** includes early stakeholder mapping and engagement. Strategic Adaptive Management (SAM) was built on the tradition of adaptive management, with strategy conferred by an Adaptive Planning Process (APP) **(2)**. When the ASA was developed, SAM did not include governance, or monitoring and evaluation with reflection and learning. The first participatory ASA event is a facilitated SAM Adaptive Planning Process (APP) workshop **(2)**, where stakeholders experience participation, and begin a journey of participatory governance capability development **(3a)**. The APP gives rise to an objectives hierarchy – the blueprint for strategically and adaptively managing a system. SAM can be used to manage a problem being faced collectively by stakeholders, and also in the management of their home institutions. The ASA initiates the development of SAM capabilities **(3b)**. Concurrently, additional research into the collective problem may be undertaken, and in all participatory engagement stakeholders learn from each other (transformative social learning) – fostering the ongoing co-creation of new knowledge **(3c)**. Adaptive monitoring and evaluation, with reflection and learning is applied in each of the ASA activities, including facilitation planning and debriefing.

The full ASA was applied in Tanzania and Ethiopia. In South Africa, it was applied in the earlier Tsitsa River catchment forum (Cockburn et al. 2018). Detailed engagement data are curated at the Institute for Water Research, Rhodes University, South Africa. Here, we qualitatively assessed the key features of ASA practice claimed by Palmer et al. (2023): *Partnership building, Developing participatory governance capacity and capabilities, Transformative social learning and Enabling co-design;* in the three country-based case studies. Outcome achievement was judged as 1) minimal, 2) moderate, or 3) substantive.

Results

Tanzania: Ruaha River catchment in the Rufiji River basin

The Ruaha River catchment, Tanzania, is characterised by inequitable water sharing, and ongoing conflict among competing water users that include expanding towns, large- and small-scale farmers in the Usangu plains; pastoralists and fisherfolk in seasonal wetlands and in the Ihefu permanent swamps; and the wildlife ecosystems of the Ruaha National Park. The Ruaha River also sustains electricity production at the Mtera and Kidatu hydropower plants, with new hydropower development planned. Among these, small-holder irrigation and mobile pastoralists were blamed for reduced streamflow.

Partnership building, Developing participatory governance capacity and capabilities, and Transformative social learning were moderate among the wide spectrum of participating stakeholders. Analysis of participant reflections indicated intractable power differences despite evident co-learning and knowledge exchange among stakeholders. Continued application of the ASA would aim for slow trust-building, and data sharing to demonstrate the level of inequity, and the low level of threat from smaller resource users, in comparison to large-scale agriculture and hydropower. In the Ruaha, water-use conflict is more intense than rangeland-use conflict for livestock owners, and delinking grazing impact from water use would be helpful. *Enabling co-design* was minimal in the timeframe of the research engagement.

Ethiopia: Aba Gerima and Debre Yacob sub-catchments in the Upper Nile River basin

Landscape restoration activities, with restricted grazing and delivery of rangeland forage by "cut and carry" enabled livestock production and rangeland recovery (Feoli et al. 2002). Restoration practices were more rigorously maintained in Aba Gerima. The ASA Adaptive Planning Process workshop enabled the two catchment communities to meet, collaborate and learn from each other. They co-developed a vision and objectives that included a renewed commitment to cut and carry, to support livestock and rangeland improvement in both sub-catchments.

Partnership building, Developing participatory governance capacity and capabilities, Transformative social learning and Enabling co-design were all substantive at the scale of communities in the two sub-catchments interacting with each other and with researchers. These indicators were progressed in the preparation for, and facilitation of the Adaptive Planning Process workshop. Clear objectives for community livestock and landscape restoration and sustainable management were agreed. Progress in all these indicators was minimal at the scale of community-government engagement. The most immediate reason was the civil conflict in the region. However, researcher-government engagement was slow, and deepening research-government relationships, and extending these to include communities, would have required more extensive trust-building and communities travelling to the capital, Addis Ababa, for a "learning words" process prior to government engagement (Palmer et al. 2022, Palmer and Tanner 2024).

In engaged, transdisciplinary sustainability research, time frames are crucial (Palmer and Tanner 2024). Aba Gerima and Debre Yacob catchment had been the focus of Ethiopian research engagement over decades, and the success of landscape restoration was already evident (Feoli et al. 2002). The three-year ASA project came in as a facilitated intervention to encourage and renew sustainable pastoral grazing when cut and carry efforts had flagged in one of the catchments. It effectively catalysed renewed sustainability practice.

South Africa: Tsitsa River catchment in the Mzimvubu River basin

The Tsitsa River catchment is a strategic water resource in South Africa. However, historical land-use practice has resulted in extensive erosion and vegetation cover loss which threaten the effectiveness of any dam development (Powell et al. 2018). Water resource development needs motivated investment in landscape restoration. The seven-year Tsitsa Project (Cockburn et al. 2018) constellated many of the ASA elements and the Tsitsa River catchment was a learning catchment for the Tanzanian and Ethiopian cases.

Partnership building, Developing participatory governance capacity and capabilities (Palmer et al 2022), Transformative social learning (Weaver et al. 2023) and Enabling co-design (Fry et al 2024) were substantive. The research had time to facilitate the development of community livelihoods, with a focus establishing nurseries to grow the plants used in landscape restoration, and the employment of eco-rangers to control free-range livestock movement. This is an alternative to the "cut and carry" methods used in Ethiopia. The timeframe of the Tsitsa catchment intervention was not long enough to measure vegetation cover increases, so the appointment of the eco-rangers was the measurable impact on the rangeland of the engaged research.

Discussion

The ASA provides natural and social scientists with the conceptual and practice tools to effectively engage with natural resource users (like pastoralists) and managers, civil society, powerful private enterprise, and government agencies, with the purpose of moving rangelands towards social-ecological justice and sustainability. However, the reality of engaged transdisciplinary work is hard (Palmer and Tanner 2024). As we advocate for rangeland researchers, managers, and governments to use the ASA, we highlight one lesson from all our experience: the fundamental importance of epistemic justice – fairness in relation to knowing. The two core aspects of epistemic justice in transdisciplinary participatory engagements are, that all participants i) experience being equally and well respected, and ii) have sufficient understanding and vocabulary to both understand and contribute to participatory knowledge exchange. Engagement planning and facilitation style are key in achieving this. Early engagement in the Tsitsa River catchment revealed that while facilitation skills such as eliciting input from participants randomly (rather than preferencing those with higher perceived status or power) and writing participant input on sheets that everyone could see, in exactly the words used, resulted in experiences of being respected. It was harder to build equitable knowledge and vocabulary, and respect for a range of knowledge forms. Knowledge was unevenly held and respected. In the Ruaha and Tsitsa River catchments formally educated participants were impatient, and discounted the value of local knowledge, while local communities needed time, were sensitive to disrespect and could be easily silenced. It was hard to overcome entrenched gender and racial prejudice. The development of the Learning Words processes in the Tsitsa project (Palmer et al. 2022) was crucial: stakeholder participants who are residents in the landscape meet with researchers the day before a general stakeholder workshop. Their local knowledge is elicited, and they are exposed to how deep their knowledge is, and that other stakeholders know far less. They are encouraged to share their knowledge in the engagement to come. Researchers then introduce any specialist vocabulary likely to be used the following day. Very often residents understand the concept – but may have a different set of words – for example not all languages have a direct word for "catchment" or "landscape. Learning Words workshops need to be routinely incorporated into the ASA process. In all our case studies engagement with local communities was undertaken in their local language, with translation for participants who only spoke English. (A sound colonialism push-back.) Adaptation to the pitfalls of practising the ASA included working to expose both specialist natural and social scientists to foundational ASA concepts such as complex social-ecological systems, transdisciplinarity and transformative social learning. We exposed the depth of gap between the social and natural sciences and the need for work on conceptual similarities with different vocabulary, methodological differences, and engendering sufficient respect for researchers to take the time collaborate effectively. We exposed the need for training in epistemic justice-sensitive facilitation.

Inclusion of epistemic justice, the methods of Learning Words, and the wider framework of the ASA can contribute to several *IYRP themes*: The ASA provides a purposeful mechanism for *connectivity* and building social-ecological *resilience.* The ASA focuses on building a shared fair, sustainable future and supports *biodiversity* retention of the *ecosystem services* related to *soils, water and land-use*. Learning Words workshops forefront *indigenous and local knowledge,* and ASA facilitation methods enable fair inclusion of *women and youth*. It is vital to understand that sustainable rangeland restoration and management involves respectful engagement. Above all, to recognise that engagement processes take time, and that respect and trust building are the foundational levels of transformation.

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Respectful publication of traditional herders' ecological knowledge

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Key words: collaboration, participatory research, knowledge co-production, traditional grazing, traditional herders, publication ethics

Abstract

Knowledge partnership between traditional herders/pastoralists and researchers is vital for adapting to rapid socio-ecological changes. Respect can efficiently help these partnerships as we need trust, time and dedication to bridge scientific and traditional knowledge systems. The three authors of this contribution have been closely working together since 2009, and beyond co-producing scientific papers and media articles they are experimenting with various other adequate and respectful types of ”publications” to share herders' traditional ecological knowledge with scientists, diverse stakeholders and the wide public. In this paper, we share some of the experiences of our long-term collaboration and motivate others to experiment with and prepare diverse types of publications.

Introduction

Indigenous, traditional and local ecological knowledge is increasingly respected and collaborations between traditional knowledge holders (TKHs) and scientists are now widespread. Scientists usually publish their research results in scientific papers and, in the case of social sciences, often in scientific books. But do we know who read these publications? And what readers get and understand from the traditional knowledge of TKHs documented in these publications? Will they bring the desired change, especially improvement, in the life of TKHs?

Experience shows that scientific papers and books do have, but only a limited power to change people's behaviour. Alternative ways of publications are needed to reach more people and more efficiently.

In this paper we aimed to summarize the experiences of a herder family and an academic researcher about the benefits and challenges of alternative ways of publishing (sharing, teaching) traditional ecological knowledge.

Positionality

László Sáfián is a traditional herder coming from a seven-generation herder family. He has been working with Zsolt Molnár since 2009, teaching each other and testing diverse ways of collaborations, and co-production of knowledge and publications. Ibolya Sáfiánné is a traditional shepherdess, born into a herder family. She is the leader of the Hungarian Women Herders Group. Zsolt Molnár is a botanist, ethnoecologist working with traditional herders and farmers in Central Europe since 2000, and in Mongolia, Iran and Kenya since 2016. He was not born into a herder family.

Methods
This work is based on 15 years of collaboration between a herder family and a scientist. All data and conclusions below are based on our own experiences. The paper was designed and prepared together by the three authors, first in Hungarian (the mother tongue of the authors) and then translated into English. Many of the mentioned publications are also available in English, because one of the aims of the knowledge co-production between the authors was to share herders' traditional knowledge abroad, to put Hungarian herders on the global map of science on pastoralism.

Results
In most cases the design and the preparation of publications was led by the scientist (or outsiders, like journalists and film makers). Partly because the publications appeared in the scientific sphere, especially at the beginning. The TKH partners were not experienced on how to work in these unfamiliar settings. However, with time, the design turned more and more into co-design, and the preparation became also increasingly a co-production. Recently, publications were led by the herders themselves (see Sáfiánné et al. 2024, and journal and radio reports).

Our experience shows that many herders simply hate, as they express it, or at least feel very uncomfortable, being interviewed by journalists, participating in scientific works, but even they feel and know the benefits of these '*tortures*': "*People see and understand our life much better.*" Herders tend to be patient even in situations that are far beyond their comfort zone, especially if they experience reciprocal patience and respect from the other side.

Table 1 Various forms of publication of herders' traditional ecological knowledge for traditional knowledge holders (TKHs) themselves, for scientists and the wider public based on the experiences of the authors of this paper

Scientific publications	**Films, media and conferences**		**Exhibitions and other**
Scientific papers (high-ranked, English)	Short documentary films (English)	Media articles (English)	Exhibitions (photo)
Other non-local language papers, book chapters	Short documentary films (local language)	Media articles (local language)	Exhibitions (complex)
Books (English, multi-lingual)	Slow films (English)	Agricultural journal articles	Field discussions at the knowledge holder's place
Books (local language)	Slow films (local language)	Conference presentations (local language)	Field discussions at other knowledge holders' places
Local language scientific papers	Radio reports	Conference presentations in English/abroad	Facebook pages
Reports (e.g. IPBES, CBD, IYRP)	Podcasts	Online discussions (long presentations)	Teaching course (in person)
	Short TV reports		
	Talk shows		

- High-ranked papers can bring high respect for TKHs, especially when later they meet readers (academics, professors) at international conferences. Real co-authorship in scientific papers was achieved first by co-producing the results and discussion sections of the papers, and later by co-designing the whole research process.
- Short films, radio and TV reports prepared by outsiders can be challenging (even frustrating) for herders because uncareful journalists can strengthen misleading and unrespectful stereotypes and

misunderstanding. We found that experienced TKHs can help journalists to learn respectful and decolonial behaviours and approaches, slow down the preparation of the product and give a chance to TKHs to check the product for technical correctness and respectfulness before the publication. The success of these deep and respectful reports and articles can be unexpectedly big.

- Longer films and content rich, colourful books increase the chances of sharing traditional knowledge and can lead to respectful and adequate inclusion of local TEK in policies but also in cross-cultural scientific reviews. When TKHs see themselves in films and books, this increases their self-confidence, and they become aware of the value of their knowledge. Herders argue that with books their knowledge gets a chance to survive longer.
- After some less successful attempts with publishing traditional knowledge in culturally less appropriate forms, we designed and made a three hours long slow film. This film became an unexpected success. Viewers not only enjoyed watching the film and having a deeper than ever insight into herders' knowledge but many of them expressed later to the herder that they learnt a lot and they use the learnt knowledge in their everyday herding. The storyline of the film is very simple: an ”uncut” video about an afternoon-long, herder dog-assisted herding of 300 sheep on a patchy semi-natural pasture made with two cameras and a drone. Later, the first author narrated the whole film by answering the questions of the researcher. The Hungarian version of the film has >730 000 views (December 2024), and >115 000 viewers watched the whole film.
- Conferences are a big challenge for TKHs. To lessen stress, for local language conferences we developed a dialogue-based presentation style, where the herder(ess) answers the researcher's questions (agreed upon before), while at foreign conferences the herder(ess) speaks in her/his mother tounge while the slides have rich English content.
- Personal encounters are missing in most forms of publications. Online seminars turned out to be a useful tool for cross-continental 'virtual personal' discussions. Students got a chance to ask their personal questions after or during the 1-1.5 hours long presentations. Herders were also enthusiastic what and how foreign students asked from them.
- Personal visits by scientists to TKHs' pastures and families can help build bridges between cultures and between scientists and TKHs. Experiencing TKHs' life in their own environment gives a chance to scientists to cross the boundary line between the scientific and traditional knowledge systems. In our case, many of these scientists watched the slow films in advance, which helped them ask respectful, adequate and specific questions while on the pasture. Personal visits by a TKH to like-minded people and herders abroad, especially to other continents helps them understand their own culture, increase the understanding of the value of their knowledge. Cross-cultural similarities of how to care for the livestock and what challenges others have help TKHs (reciprocally) to overcome the feeling of loneliness with their problems.
- Facebook is a great opportunity for TKHs to network, even internationally (cf. automatic translations). Having photo and video cameras in the mobile phones helps THKs to document their world themselves and share them directly without any liaison person. This is a new and great opportunity to share (publish) ideas, feelings, knowledge, stories, challenges directly. The group of Hungarian Women Herders especially expressed their happiness of having a closed FB group where they can freely share their everyday stories with other women working in pastoralism.

Discussion

Alternative publications are often still in the experimental stage, but it is clear that publishing traditional ecological knowledge not only in scientific papers and books is crucial to reach diverse stakeholders and potential partners. Herders argue that with these publications, they feel the increased respect towards knowledgeable herders both from the public and from scientists and conservationists. They also became aware of the crucial importance of finding new ways of intergenerational knowledge transmission of their knowledge.

IYRP (the UN International Year of Rangelands and Pastoralist, 2026) could efficiently help promote awareness raising around the issues of pastoral people, especially their adaptive knowledge, role of women and prospects of pastoral youth, as these have vital role in the future of pastoralism. As the number of herders decrease, they get more isolated, thus networking through IYRP could be a key mechanism for developing a better future for pastoral people.

Acknowledgements
Experience shows that there is a lot to learn by European TKHs and scientists from Indigenous Peoples and their allies, how collaborations and common publications can work under various circumtances. We are grateful for our Indigenous partners for their teachings. This work is supported by the Horizon Europe BIOTraCes project (101081923).

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Extending the boundaries in rangeland management to include the soil microbiome

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How grazing management influences biocrust community composition in the Northern Territory rangelands

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Key words: biocrust, community composition, rangelands, grazing management

Abstract
Biological soil crusts are an important indicator of the long-term productivity of grazed landscapes. Healthy biocrust communities can improve soil fertility by increasing soil stability, enhancing moisture retention, as well as facilitating both carbon and nitrogen cycling and fixation. The Rain Ready Rangelands project, funded through the Australian Government Future Drought Fund analysed biocrust health on three producer demonstration sites in central Australian woodlands and shrublands and the Barkly Tablelands Mitchell grass regions of the Northern Territory. In this paper we focus on a producer demonstration site located approximately 250 km northwest of Alice Springs in tall open Acacia shrublands with deep red earths, sandy red earths, red clayey sands and deep sandy loams over mixed short grasses.

Samples were collected under varying grazing intensities (with distance from water and inside vs. outside cattle exclosures) and with different grazing management (current vs. recommended grazing management). To detect the functional contribution of these communities baseline samples were collected and analysed for biocrust species composition, total carbon and nitrogen and DNA analysis. 16S rRNA marker gene sequencing was used to profile bacterial community diversity along grazing gradients from watering points, and inside and outside cattle exclosures.

Bacterial community composition shifted significantly with distance from water at the central Australian sites. Diversity was highest at the most disturbed site 50 meters from the water point at one of these locations, while community composition had not diverged inside vs. outside newly established exclosures after the first year. Changes in total carbon and total nitrogen were observed only with distance from water, with enhanced C and N adjacent waterpoints compared to all other distances. The ecological implications of these changes are being further investigated. We plan to monitor these sites through time to see if alternative management regimes and cattle exclusion results in different trajectories in biocrust community composition and function.

Introduction
This research took place in the Alice Springs region of the Northern Territory. As a part of a broader project called Rain Ready Rangelands, we established a Paddock Challenge demonstration site on a large cattle station covering

over 2700 km^2. We aimed to illustrate the benefits of positive grazing management strategies such as adjusting stocking rates to safe carrying capacity on land condition by measuring vegetation and biocrust communities across sites.

Biological soil crusts, also known as biocrusts are often referred to as the 'living skin' of the soil surface (Weber et al. 2022). Inhabiting the upper centimetres of soil between and under vegetation in dryland and savannah ecosystems, biocrusts play a central role in primary production. Biocrusts functional influence on soil fertility and plant growth can provide us with an indicator of how management can promote drought resilient soils (Eldridge and Delgado-Baquerizo 2017; Williams et al. 2021). Hence, we measured biocrust responses to grazing intensity and management through sampling biocrusts, and soil C and N.

To ensure long term productivity of grazed landscapes, sufficient replenishment of nitrogen is required. Nitrogen accounts for a large proportion of the soil-derived nutrients that pastures require. Among other functions, cyanobacteria, bacteria and other microorganisms that make up biocrusts have the capacity to fix nitrogen and cycle nutrients (Belnap 2003).

Environmental DNA sequencing of 16S rRNA gene, at terrestrial field sites identifies bacteria at the genus and species levels, providing detailed information about overall composition and abundance of microbial communities. There was no current knowledge in this region of biocrust communities and the effects of trampling by livestock. Thus, we set out to discover the diversity of biocrusts and their associated microbial communities. As management entails very large areas in a climate controlled by low rainfall, we designed this component to encompass the landscape scale effects at a micro-scale.

Methods

Samples were collected in April 2023 along two transect lines north and south of 2 long established bores (permanent ground water supplies for livestock). Samples were collected from deep red earths, sandy red earths, red clayey sands and deep sandy loams. Biocrust samples were collected from three land systems: Bushy Park (Broad alluvial drainage floors and floodplains with deep red earths), Kanandra (coarse textured brown alluvial plains of deep sandy loams and sandy read earths) and Sandover (Flat or gently undulating desert floodplains and levees with red clayey sands and deep sandy loams) (Perry et. al. 1962 & Grant 1983R). Pastures were dominated by mixed short grasses and forbs including E*nneapogon polyphyllus* (Oatgrass), *Aristida contorta* (Kerosene grass) and *Eragrostis kennedyae* (Lovegrass).

The exclosure was erected in a representative area of productive country, aiming to explore differences between the paddock/watered area treatment versus no grazing. The fenced cattle exclosure was located 1 km from a Bore. Biocrust monitoring sites were strategically located along transects at varying distances from a watering point (50 m, 500 m, 1-2 km, 6 km). Three types of biocrust samples were collected for DNA, C and N and biocrust microcosms.

Quadrats (n =3) were randomly placed on the ground at each distance from water and photographed. DNA samples were collected using a 50 mL Falcon Tube and a spatula. In each Falcon Tube 3 sub samples of the top 1 cm of soil were collected and combined (n=3 per quadrat). Equipment was cleaned with alcohol wipes between each sample. Total C and N samples were prepared by using a spatula to collect three subsamples 10 x 10 x 5 cm depth (n=3 per quadrat). Biocrust microcosms were collated by collecting 4 surface subsamples using a spatula and placed in a petri dish (n= 3 per quadrat). This methodology was repeated twice at each site, giving us three composite samples of each type from every site location (n=12 per site).

Environmental DNA was extracted using the Qiagen DNeasy® PowerSoil Kit. Amplicon sequencing of the 16S rRNA gene was amplified by polymerase chain reaction (PCR) using the primers799F (5'-

AACMGGATTAGATACCCKG-3') and 1193R (5'-ACGTCATCCCCACCTTCC-3') (Lane, 1991) for bacteria profiling, and sequenced using the MiSeq System (Illumina) platform. The taxonomy for the 16S rRNA gene reads from sequencing was assigned using blastn from QIIME2 against the SILVA (v138.1) (Quast et al. 2012) database.

Total carbon (C) and total nitrogen (N) in soil samples was performed using the Elementar Vario Macro cube analyzer in CN mode at UQ lab….

Results

Distance from water effect on Central Australian biocrust microbial communities

The composition of biocrust communities varied with distance from water (PERMANOVA R^2=65%, F=10.9, P<0.001), although alpha diversity remained consistent. The community composition at a distance of 50 meters from the water was significantly different (P < 0.001) from all other distances (Figure 1).

Although not statistically significant, the 6 km biocrust communities did separate out from all other distances, whereas samples from between 500 m and 1-2 km from water showed significant overlap in composition (Fig. 1). In total, 60 operational taxonomic units (OTUs) were identified with a relative abundance greater than 1% in the biocrust bacterial community. ANOVA analysis (p < 0.05) on the relative abundance revealed that 47 of these 60 OTUs exhibited significant changes based on their distance from the water.

The biocrust composition was represented by members of the Acidobacteriota, Actinobacteriota, Armatimonadota, Chloroflexota, Firmicutes, and Proteobacteria. From a general overview, several members of the Acidobacteriota and Chloroflexota, were reduced in their relative abundance at 50 m from water, in contrast to several members of Firmicutes that increased their relative abundance at the shortest distance from water.

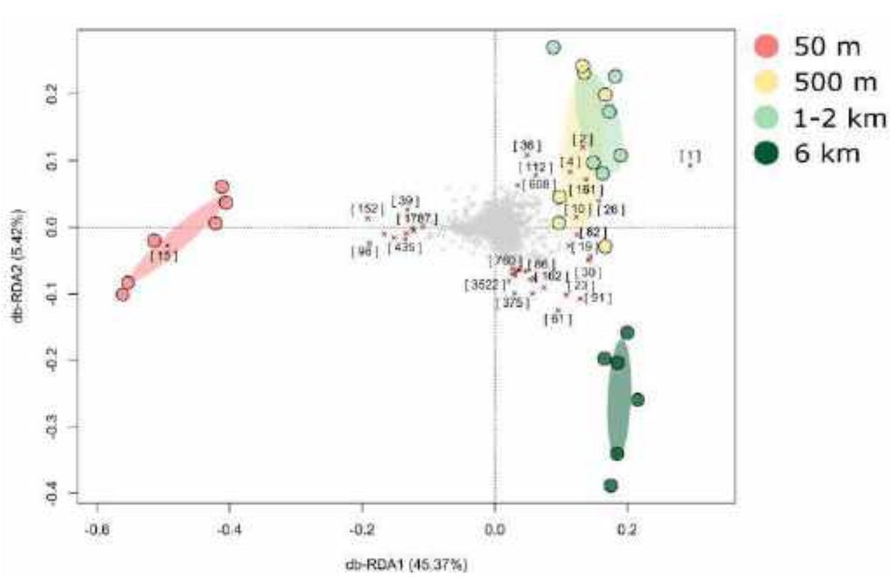

Figure 1. Separation of biocrust community composition between 50 m and 6 km from water clearly evident in Distance-based Redundancy Analysis (db-RDA) ordination plot. Constraint by distance as per PERMANOVA analysis. Discriminating OTUs are shown in brackets.

Distance from water effect on total C, total N, and C:N ratio

Total nitrogen and carbon (but not C:N ratio) varied with distance from water and at 50 m they were both more than double the levels found at all other distances (Table 1, Figure 2).

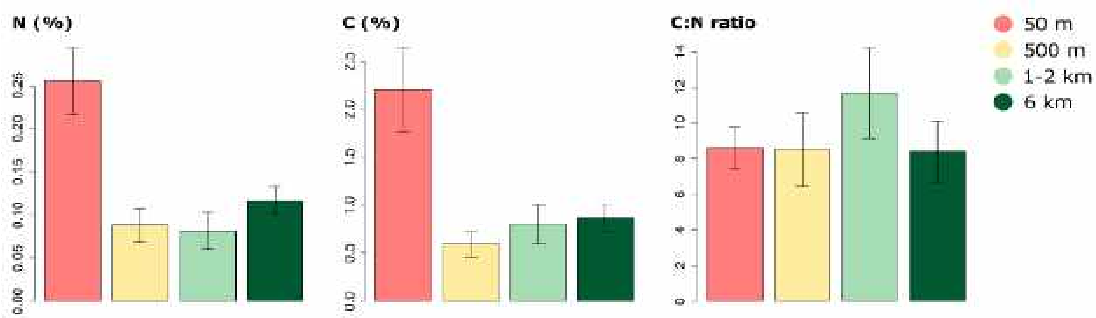

Figure 2: Bar graph of total carbon (%), total nitrogen (%), and C:N ratio by distance from water (50 m, 500 m, 1-2 km and 6 km). Error bars represent standard errors

Table 1. Total carbon (%), total nitrogen (%), and C:N ratio by distance from water (50 m, 500 m, 1–2 km and 6 km). Means and Standard Deviation, different letters represent significant differences as per post hoc analysis ($P < 0.05$)

Distance	Total Nitrogen (%) Mean SD	Total Carbon (%) Mean SD	C:N ratio Mean SD
Mount Denison			
50 m	0.26 ± 0.09 b	2.21 ± 1.06 b	8.57 ± 2.86 a
500 m	0.09 ± 0.05 a	0.60 ± 0.33 a	8.51 ± 4.98 a
1-2 km	0.08 ± 0.05 a	0.80 ± 0.51 a	11.66 ± 6.20 a
6 km	0.12 ± 0.04 a	0.87 ± 0.34 a	8.39 ± 4.22 a

Effect of excluding grazing on biocrusts

The exclosure effect (inside versus outside) on alpha diversity and composition was evaluated across all sites. There was no effect of the first year of exclosure on alpha diversity (Shannon's index) and composition (results not shown).

Discussion

The biocrust microbial community in extensive grazed rangeland paddocks was relatively stable in its composition and diversity with the exception of heavily trampled high use areas immediately adjacent waters.

The study on biocrust community composition found an increase in the relative abundances of several Firmicutes populations at the closest distance from the water points (50 m). While Firmicutes are known as plant growth-promoting bacteria (Amaresan et al. 2020), they have also been found to effectively remove ammonium and total nitrogen from wastewater (Yue et al. 2024), which is possibly related to the increased N content at the 50 m point from water.

The higher levels of total C and N at the water points are likely due to animal manure and urine inputs, as cattle often congregate and camp close to the water points. The animals graze out several kilometres daily, harvesting resources as they graze pastures and browse from the surrounding paddock. The stocking density and time spent were highest closest to water, leading to a translocation of resources to campsites and water points, which accumulates these resources from long distances into a smaller site closer to the water (Augustine et al. 2013). Given that only the heaviest grazing and trampling impacts immediately within the 50 m vicinity of stock water points had differences in C and N, it is unsurprising that exclosures surrounded by moderate to low grazing had little impact on soil C and N.

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Monitoring pre- and post-fire changes in land cover including biocrusts using high resolution satellite imagery in a grazed tropical savanna

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Key words: Monitoring ground cover, biocrusts, rangelands, savanna

Abstract

Biocrusts play a pivotal role as ecosystem engineers, mitigating soil erosion, enhancing soil stability, and enriching nitrogen availability in rangelands. In northern Australian savannas, prescribed fires are a common land management strategy. However, fire impacts biocrust function, making it important to monitor biocrust cover to assess ecosystem health and guide sustainable land management practices. In this study, we investigated land cover with a focus on biocrusts, before and after prescribed fire events at Victoria River Research Station in the Northern Territory.

A 2.6 km^2 patch situated more than 2 km from water in the north-west corner of a 14.7 km^2 paddock was burnt in October 2022. Cattle were left in the paddock both during and after the fire. High-resolution PlanetScope imagery was used to track changes in land cover between July 2022 and June 2023. Reference sites that included bare soil, biocrusts (95% coverage) and vegetative cover (grass, shrubs and trees), were collected in the field. Crust Index was employed to discriminate between land cover classes. Using supervised classification with a random tree classifier, we achieved 90% accuracy in identifying these land cover classes across multiple time points.

Post-fire, early wet season, biocrust cover decreased by 10.8%, from 67 ha pre-burn to 39 ha, partially due to an increase of 10% in vegetation cover (189 ha to 215 ha). Grass canopies had obscured the biocrusts underneath them. Bare soil areas expanded by 20%, from 7.9 ha to 9.7 ha, likely due to cattle preferentially utilising the burnt areas post fire during the following wet season. These findings underscore the importance of monitoring and adaptive strategies such as spelling paddocks from grazing post fire, essential for sustainable and resilient ecosystems.

Introduction

Australian rangelands cover vast areas across the country and are essential components of the nation's environmental, societal, and industrial dynamics. However, these landscapes are under increasing pressure from climate change and degradation, which threaten native vegetation, diminish landscape functionality, and cause local extinctions of various biota, including shifts in fungal and bacterial community structures (Hodgkinson & Wang, 2020). Biocrusts are unique and diverse communities of microorganisms, including bacteria, cyanobacteria, fungi, algae, lichens, mosses, and liverworts, that inhabit the soil surface and its upper layers. These biocrusts are predominantly found in regions with limited water availability and sparse vegetation cover (Weber et al., 2022). Occupying much of the soil surface in rangelands, biocrusts play a critical role as ecosystem engineers by mitigating soil erosion, enhancing soil stability, and enriching nitrogen availability. Disturbance factors such as fire and grazing significantly influence these biocrusts (Belnap & Eldridge, 2001).

In the Australian rangelands, prescribed fire is commonly used as a tool to manage vegetation density and regeneration (Nielsen et al., 2020). However, fire impacts biodiversity, including biocrusts, which provide several ecosystem services, such as reducing soil erosion and replenishing nutrients. Therefore, monitoring land cover changes, including biocrust distribution during prescribed fire events, is crucial for assessing ecosystem health and informing decision-making for sustainable rangeland management practices.

Remote sensing is essential tool for monitoring land cover and land use changes, and is a popular tool among agriculturalists and rangeland ecologists (Wabnitz et al., 2008). Detection and mapping for regional distribution of biocrust can be implemented using remote sensing with different platforms, spaceborne, Airborne, and Unmanned Aerial Vehicles (UAVs) (Rieser et al., 2021). Utilising satellite imagery offers a variety of benefits, primarily in its ability to generate a comprehensive temporal range of data. This capability allows for the quantification of both spatial and temporal changes within specific regions.

Multispectral satellite with high spatial resolution is considered to detect biocrust for large scale areas. Several studies have revealed that numerous species face limitations in producing detectable spectral signatures (Baxter et al., 2021). Biocrust's spectral signature resembles both soil and vegetation due to the dynamic states of microphytes that only actively photosynthesise when moist. This results in biocrusts appearing soil-like when dry and exhibiting a vegetation appearance when wet, and engaged in photosynthesis (Rozenstein & Adamowski, 2017).

To address this complexity, specialised methodologies have been developed, including the Crust Index, which utilises the normalised difference between red and blue spectral bands to detect cyanobacteria-dominated biocrusts (Karnieli, 1997). This approach leverages the unique reflectance properties of cyanobacteria, distinguished by the presence of the phycobilin pigment, which strongly reflects in the blue spectral region compared to sandy substrates (Karnieli & Sarafis, 1996).

In northern Australian rangelands, research on biocrust distribution and its response to prescribed fire remains limited. In this study we investigated land cover changes, including biocrust dynamics, before and after prescribed fire events, using high-spatial-resolution imagery from PlanetScope (3 m resolution). Cyanobacteria-dominated biocrusts, known to be prevalent in northern Australian rangelands (Williams et al., 2014), were analysed using the Crust Index to elucidate their spatial distribution and response to fire-driven disturbances. This research contributes to bridging knowledge gaps in biocrust area distribution and informs sustainable land management practices in the rangelands.

Methods

The study was conducted over a 2.6 km^2 area located at the Victoria River Research Station, Northern Territory, Australia. A prescribed fire event was carried out in October 2022, with cattle remaining in the paddock both during and after the fire. Reference data were collected in the field to establish baseline conditions for land cover classes, including bare soil, biocrusts (95% coverage), and vegetation (comprising grass, shrubs, and trees). High-resolution imagery from PlanetScope (3 m spatial resolution) was employed to monitor land cover dynamics over the study period, spanning from July 2022 to June 2023.

The Crust Index was applied to differentiate land cover classes, particularly for detecting cyanobacteria-dominated biocrusts (Karnieli, 1997). A supervised classification approach using a random tree classifier was implemented to categorize the land cover into predefined classes. This method achieved an overall classification accuracy of 90%, effectively capturing temporal changes across multiple observation points.

Results

In this research, the spectral analysis is crucial in evaluating land cover changes employing crust index (Fig 1). The fire event significantly altered land cover dynamics within the study site, which included four primary classes: vegetation, bare soil, and biocrusts. The vegetation cover expanded from 189.27 hectares before the fire event during the dry season (July–September 2022) to 215 hectares after the fire event in the post-wet season (April–June 2023). Biocrusts exhibited a pronounced seasonal pattern, with coverage peaking at 67.18 hectares pre-fire and declining to 39.07 hectares post-fire. Conversely, bare soil areas increased from 7.9 hectares before the fire to 9.7 hectares following the fire in the post-wet season.

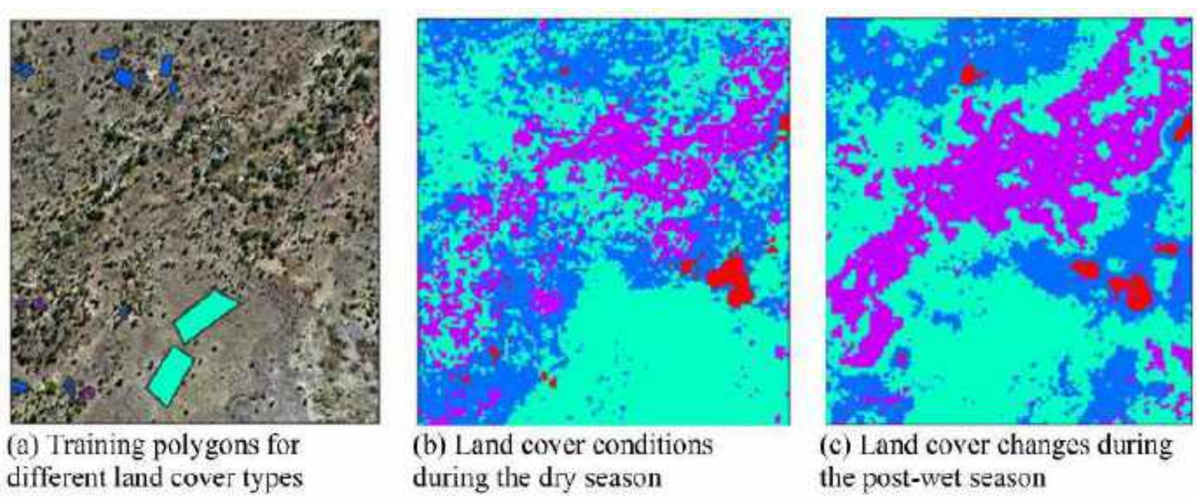

Figure 1. Seasonal land cover changes: (a) Training polygons for different land cover types: blue represents biocrusts, light green indicates grass, purple denotes trees and shrubs, and red corresponds to bare, degraded soil. The Crust Index effectively discriminated biocrusts from vegetation and bare soil during (b) the dry season (pre-fire) and (c) the post-wet season (post-fire).

Discussion

Post-fire rainfall introduced challenges in accurately capturing the spectral signatures of biocrusts, as increased vegetation cover overshadowed biocrust reflectance (Swe et al., 2023). Our findings underscored the discriminative capabilities of the Crust Index in capturing the spectral response differences among individual classes in every season. The pronounced recovery of vegetation—particularly grasses, trees, and shrubs—after the fire was driven by consistent rainfall, highlighting the resilience of rangeland flora to disturbance events. Bare soil areas expanded by 20%, likely due to livestock preferentially grazing in burned regions during the subsequent wet season. These findings highlight the complex interactions between fire, rainfall, and land cover dynamics in rangeland ecosystems. They also underscore the importance of post-fire management strategies, such as resting paddocks from grazing, to allow the recovery of vegetation and biocrust communities.

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Dust to Crust: Rangeland regeneration through biocrust inoculation of Mitchell grass (Astrebla lappacea (Lindl.) Domin)

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Key words: biological soil crust; bio-priming; germination; grasslands

Abstract

Biocrusts are a living complex of microscopic organisms (cyanobacteria, bacteria, fungi, algae, lichens, liverworts, mosses) that cover the upper soil between vascular vegetation in arid and semi-arid rangelands. As providers of ecosystem services, they are a nature-based solution for landscape regeneration, but site- and species-specific knowledge is often missing. We tested the hypothesis that biocrusts differ in their effect on grass germination. Our focus was Mitchell grasslands with tussock grass *Astrebla lappacea* because degraded semi-arid western Queensland requires effective regeneration techniques. We used characteristic descriptions of biocrusts in testing the effects of biocrust as soil surface or as separate seed inoculum on germination success in glasshouse and laboratory experiments. Germinations increased slightly on a biocrust surface compared to a sand-only control. Although differences were not statistically significant, germination was greater than in sand in 71.4% of inoculum treatments and rate was significantly faster in one-third of treatments. With promising early findings, we conclude that biocrusts can improve germination of *A. lappacea*, with optimisation in next-steps research such as inoculum field experiments across landscapes. Biocrusts hold promise as a nature-based solution to address the global problem of degraded rangelands.

Introduction

Mitchell grasslands are dominated in their natural state by *Astrebla* tussock grasses and cover about 57 million hectares of Australia's rangelands ("Mitchell Grasslands", 2021). *Astrebla lappacea* (Lindl.) Domin. (Curly Mitchell grass) is one of four abundant *Astrebla* species. It is a highly desirable perennial grass that provides ecosystem stability, having a 20 to 30-year life span and considerable drought tolerance (Lambert et al., 1990). Death of *Astrebla* tussocks is accentuated by heavy grazing during drought, which causes the problematic colonisation of annual grasses in the interstitial spaces when *Astrebla* cover is reduced (Orr & Phelps, 2013). Regeneration techniques are required to successfully and cost-effectively restore these landscapes. Focussing on nature-based solutions, we studied the role of biocrusts in the target grasslands. Biocrusts provide a multitude of ecosystem services including stabilising soils, carbon and nitrogen fixation and cycling, and water cycling (Weber et al., 2016). Biocrusts influence vascular plant establishment due to their position in the upper soil layer and surface where seeds are dispersed (Bowker et al., 2022; Weber et al., 2016). However, plant germination responses to biocrusts are variable and are site- and species-specific (Havrilla et al., 2019; Peter et al., 2016). Research into the effects of biocrust surfaces and inoculums on the germination of other species has been conducted (Bowker et al., 2022; Jiménez-González et al., 2022; Muñoz-Rojas et al., 2018; Peter et al., 2016; Serpe et al., 2006) with mixed findings. To fill knowledge gaps relating to Mitchell grasslands, we explored the interactions of biocrusts and *A. lappacea* seed, and tested in a first step how different types of biocrusts affect germination success. This study aimed to test two hypotheses:

1. Biocrusts enhance germination of *A. lappacea.*
2. Differently developed biocrusts have different effects on germination of *A. lappacea*.

Methods

Biocrusts were collected from 21 sites across western Queensland between April and May 2024. Mean annual rainfall varies across the region between 380 and 530 mm. The wettest months are November to March with 70% of annual rainfall (Climate Data Online, 2024). Sites spanned nine land types and consisted of intact, open woodlands and grasslands to degraded areas with low or no ground cover and soil erosion. Spatulas were used to collect the top 5 mm of soil surfaces with biocrust. *A. lappacea* seed was collected from wild populations near Julia Creek (141.7442°E, 20.6909°S) in May 2024, dried and stored at room temperature. Germination tests using a sub-sample of 20 naked caryopses were undertaken in a Thermoline Scientific STAR700 Climatron with LED lights set at 12 hourly diurnal cycles (32°C day, 25°C night). The number of seeds that had germinated (5 mm radicle visible) were counted over 30 days.

Glasshouse pot trials were conducted to test effects biocrust have when on the soil surface. Naked *A. lappacea* caryopses were imbibed in water for 18 hours. Three replicates for each of 21 biocrust sites plus a sand control were randomly allocated to pots and the surface covered by biocrust. One soaked seed was sown ~5 mm. Bottom-up watering was used and water availability reflected wet-dry cycles. Mean counts of pasture grass germination were used for analyses. Biocrust inoculum trials were conducted to determine whether differently developed biocrust affect germination of *A. lappacea* differently when applied directly to seed. The top 2 mm of each biocrust sample was passed through a sieve (~0.5 mm). Sieved biocrust (1.5 g) was combined with 1mL of DI water to create a separate inoculant for 21 samples. Sand was used for a control. Six *A. lappacea* naked caryopses were immersed in each inoculant and the control then sealed in Petri dishes using parafilm. Petri dishes were placed in the climatron. Equal volumes of DI water were used throughout the experiment to moisten inoculants. The number of germinated seeds were counted over 29 days. Germinated seeds were those meeting Internation Seed Testing Association guidelines (International Seed Testing Association, 2013).

One-way ANOVA with a Kruskal-Wallis test for non-parametric data tested whether germination with biocrust, compared with a sand control, was significantly different. Spearman's rho was used to determine effect size of correlations between biocrust characteristics and germination. A generalised logistic model with time as a covariate was fit for proportional data to extrapolate germination rates with biocrust inoculum. Significance was determined by examining the 95% confidence intervals of odds ratios and whether one was between the lower and upper confidence interval. Jamovi (The Jamovi Project, 2024) was used for statistical analysis.

Results

Experiment 1: Effects of biocrust surface on seed germination

Mean counts of all pasture grass germination, including seeds already in the seedbank and sown A. lappacea, were analysed. Emergence of seedlings was greater than the control in 47.6% of treatments and 33.3% of treatments had germination equal to the control. Correlations between biocrusts characteristics and germination were analysed (Figure 1). Significant correlations ($p<0.05$) were observed between germination and both water availability in land types biocrusts were sourced from, and crust colour.

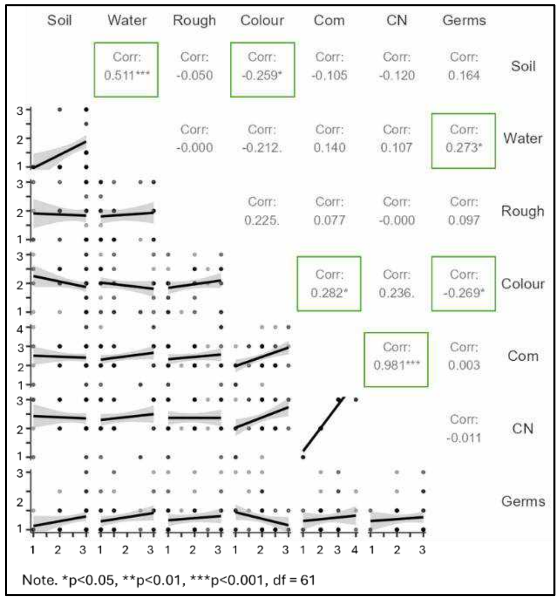

Figure 1. Correlation between biocrust characteristics and germination of pasture grasses in surface trials (Spearman's, asterisks indicate significance). Axes numbers represent classifications: Soil (1= Shallow, gravelly or sandy, 2= Texture contrast, 3= Heavy clay); Water (1= Low availability, 2= Moderate, 3= High); Roughness (1= Smooth, few pores, 2= Few pores, raised surface, 3= Rough due to liverworts, mosses or lichens); Colour (1= Light to intermediate, 2= Dark, 3= Green); Community (1= Light cyanobacteria, 2= Intermediate cyanobacteria, 3= Dark cyanobacteria with lichens, liverworts and/or mosses, 4= Dark dominated by lichens, liverworts and/or mosses); Carbon and Nitrogen (0= Bare ground, 1= Some organic matter/litter, little biocrust, 2= Light to intermediate cyanobacterial biocrust, 3= Dark cyanobacterial biocrust or dark biocrust with lichens, liverworts and/or mosses)

Experiment 2: Effects of biocrust inoculum on seed germination

Germination tests in paper towel revealed that 5% of *A. lappacea* seeds from the sub-sample germinated. Emergence was greater than or equal to the non-insulated control in 71.4% of biocrust inoculum from the 21 treatment sites. When data was extrapolated using a generalised logistic model, for treatments with increasing probability of germinating over time, one-third of sites were significantly faster compared to the control. Treatment sites grouped by land type revealed 77.8% of land types reached greater than 50% germination within the 30-day testing period. Community composition affected mean germination. Germination was greatest with light cyanobacterial inoculum (58.33 ± 35.36%). Intermediate cyanobacterial had 36.36 ± 19.46% and dark cyanobacterial crust with liverworts, mosses and lichens had 42.86 ± 16.27%. Dark biocrust dominated by liverworts, mosses and lichens had equal germination to the control (16.67%). Whilst cyanobacterial biocrust inoculum enhanced germination, mean germination for various biocrust communities was not significantly different to the control in these experimental conditions ($p>0.05$).

Discussion

In this study we aimed to develop an understanding of how biocrust and A. lappacea interact and determine whether biocrusts at various successional stages affect seed germination differently. Germination of the studied seeds was 5%. Naked A. lappacea caryopses usually have around 90% germination rate when dormancy is not a barrier (D. Phelps, personal communication, October 16, 2024). In our study, seed was harvested in May and experiments performed in August, so dormancy is a likely reason for the low germination rates in preliminary germination tests. Despite this, we found some support for our hypothesis that biocrusts affect germination. One way biocrust may enhance germination is through improved water relations. There is conjecture over effects of biocrust on water capture, movement and retention. Like our findings, others (Canton et al., 2020; Ming et al., *2024) found that cyanobacterial biocrusts decreased run-off and retained water for longer than bare soils, especially in upper layers. Adessi et al., (2018) attributed increased water retention to extracellular polymeric substances (EPS); there is agreement that EPS contributes to better soil structure, aeration and water infiltration. In our study, soil texture influenced water availability as the sand control had higher evaporative rates (NP observations), resulting in poorer biocrust development, and reduced water retention. With less water available in the sand control, germination rates were lower than biocrust treatments.*

We also found some evidence to support the hypothesis that differently developed biocrusts affect germination differently. Significant differences in germination in our experiments are likely due to differences in biocrust colour. Biocrusts are generally darker than the parent material they grow on and exhibit lower albedo, especially biocrusts with organisms like cyanobacteria that contain more chlorophyll and UV protecting pigments such as scytonemin (Kidron et al., 2022). Higher albedo associated with light cyanobacterial biocrusts likely accounted for increased germination in our experiments (Fig.1). *We discovered that germination success was enhanced to varying degrees when seeds were primed with biocrust inoculum. This supports previous studies that have demonstrated that 'bio-priming' seeds with cyanobacteria enhanced germination in some species native to Western Australia (Chua et al., 2020; Muñoz-Rojas et al., 2018). In our study, the number of germinations may have been lower in some land types, but the speed at which germination occurred was higher. This would have the potential for seed to germinate and establish before water runs out. Biocrust enhanced germination rates for 71.4% of site inoculums and, for most treatments, inoculum-seed mixture remained moist, so water availability was probably not a barrier for germination in those with lower rates. Our observations are supported by studies where no significant difference in water retention was observed when induced biocrusts were ground up rather than being left intact (Colica et al., 2014). We found effects of biocrust inoculums were site-specific and this is consistent with findings of other studies (*Havrilla et al., 2019; Peter et al., 2016).

Overall, biocrust enhanced germination of *A. lappacea*, although not significantly, and minor differences in germination were observed for differently developed biocrusts in the context of this study. Conclusions are based on limited data and replications as few biocrust samples were available so should be considered preliminary in this field of research. Additionally, identification of genera or species was outside the scope of this study and more testing for inoculums is recommended. Given the effects of biocrust are site- and species-specific, further research into the effects of biocrusts on germination of *A. lappacea* in field experiments is essential for development of effective nature-based solutions to rangeland regeneration.

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Should we burn or bust the biocrusts: an overview of biocrust management in the Australian rangelands.

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Key words: Biocrusts; Savanna; Fire; Grazing; Rangelands

Abstract

The biocrust microbiome that occupies the surfaces of rangeland soils globally are key contributors to carbon sequestration, nutrient cycling and sustain vegetation cover. Previously, research in northern Australia has demonstrated N inputs from biocrusts of 5 kg/ha seasonally that accounts for approximately one sixth to half of the annual pasture N demand. Biocrusts are important indicators of rangeland health, and we address how management actions can facilitate their survival under climatic extremes.

We explored the resilience of biocrusts to fire and grazing at two long-term research sites at Kidman Springs (NT) and Wambiana (QLD), respectively. At Kidman Springs in our first DNA analysis (metabarcoding) we examined the recovery of biocrusts after one year of burning, on plots 2 and 4 year prescribed burning regimes, carried out late dry season. Biocrusts were resilient to fire and recovered in the first wet season with no grazing pressure, as there were no differences in composition between the control and late 2- and 4-year burns. However, DNA analysis from nearby grazing exclosures showed that after 60 years of no cattle grazing, biocrust composition had significantly diverged from grazed areas. Furthermore, in our second DNA analysis (metagenomics) we included samples from 2, 4 and 6 years prescribed fires, burnt early and late in the dry season, and we collected samples at the dry and wet season, demonstrating that there was significant variation in biocrust bacterial composition between all fire treatments and soil types. Bacterial genes responsible for nitrogen fixation were sensitive indicators, that responded to seasonal conditions. Biocrusts also had significantly more nitrogen and carbon than bare degraded soil.

At Wambiana, moderate stocking rates maintained good land condition and strengthened nitrogen fixation potential of biocrusts. Key indices of landscape function including biocrust cover were informed by land condition and climatic conditions. Moderate stocking rates combined with wet season rotational spelling on average every

three years also facilitated nutrient cycling. Recently, we have shown that discrimination of biocrusts using satellite imagery is a feasible monitoring tool on a landscape scale. We can track changes in ground cover including biocrusts both spatially and temporally. Bare ground covered with biocrusts are sensitive indicators of landscape function.

Introduction

Tropical and dry savannas in Northern Australia are one of the largest intact mixed grass-woodland ecosystems globally. They cover >17% of Australia (tropical savanna, 1.9 million km^2, subtropical savanna, 272,000 km^2), where 99% remains as native vegetation of which >65% is grazed native vegetation, and ~35% are conservation zones or natural vegetation (DCCEEW, 2024.). They contribute to 12% of the existing tropical savannas in good environmental condition, and its conservation value is of global significance (Woinarski et al., 2007). The vegetation is diverse, from the eucalypt-dominated woodland to open woodland, shrubland and tussock grassland. The savanna structure is shaped by anthropogenic activity, herbivores, and fire (Cowley et al., 2014). Beef production in Northern Australia contributes $17.6 billion to the economy, carrying over 60% of the total herd of the Australian cattle industry. While most grazing lands are in good condition, a combination of drought, overstocking and intense selection for preferred land types has led to significant degradation in many areas. Fires are also common in these savanna landscapes and can cause changes in ecosystem characteristics such as physiological function, species composition and structure at multiple scales from leaf to landscape (Barger et al., 2016; Cowley et al., 2014).

Recent studies have highlighted the importance of biocrusts across these landscapes (Chilton et al., 2022; Williams et al., 2014) where cyanobacteria dominated biocrusts are estimated to cover 617,000 km^2 (~28%) of the soil surfaces (Fig. 1a), (Williams and Driscoll 2012, unpublished data). Biocrusts form an expansive protective cover on the soil surface (Fig. 1c-d), and serve important ecological functions including soil stabilization, nitrogen fixation and carbon cycling (Williams et al., 2018, Williams et al., 2014, Elbert et al., 2012). These microbial communities are dominated by a diverse suite of cyanobacteria and liverworts, together with micro-lichens, mosses, bacteria, algae, and fungi (Williams et al., 2014). Nitrogen fixation by cyanobacteria and other diazotrophic bacteria provides a direct source of bioavailable N for plants that fluctuates seasonally (Williams et al., 2018, Barger et al., 2016). Loss of biocrust cover (Fig, 1d) results in erosion and degradation of critical soil resources (Eldridge and Delgado-Baquerizo, 2017).

Biocrusts, are important post-fire to boost plant-available nutrient pools in savannas globally, although are less well understood in the context of fire in Australian savannas (Weber et al., 2016; Williams et al., 2018). Recovery of biocrusts post-fire varies with fire regime, locality, time since fire, biocrust community type, and broader geographic range (Palmer et al., 2020, Weber et al., 2016). The impact of fire on biocrusts depends on fire intensity, frequency, and patchiness (Johansen, 2001). In the Great Basin (USA) interactive effects of fire and cattle grazing on biocrust communities, can mediate the effects of invasive grass species and regulate site resistance to invasive species and future fires (Condon and Pyke, 2018). In the northern Australian savanna, we quantified how biocrusts responded to fire and grazing.

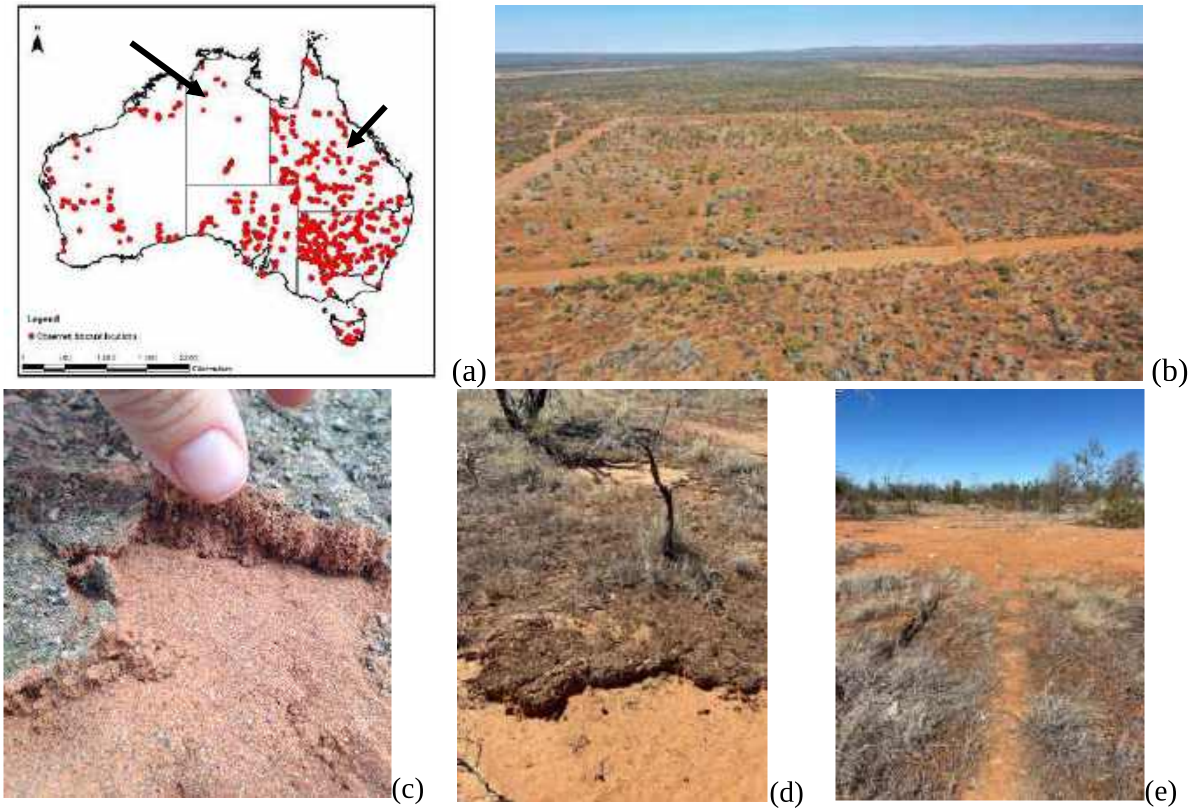

Figure 1 (a) Current survey points recording the presence of biocrusts across Australia compiled from published works and authors' unpublished data (arrow indicates Kidman Springs (left) and Wambiana (right), (b) Kidman Springs fire plots on calcarosols, (c,d) examples of biocrust (state 1) securing the ground cover with erosion caused by cattle 'camps' and water washing the degraded areas away, (e) results of erosion and compaction with no biocrust and ongoing trampling (state 2).

Background

At Victoria River Research Station (VRRS) in the Northern Territory, a cattle station at Kidman Springs, biocrusts have been subject to long-term fire trials for 30 years (1994–2024), with fire intervals of no fire (controls), 2, 4 or 6-yearly burning and season, early (June) or late (October) dry season (Cowley et al., 2014). Since 2013, wet season resting from grazing followed the two-yearly burns but were applied to all treatments. The fire plots (Fig. 1b) are set across two soil types (calcarosol and vertosol) and divided into 16 x 160 m x 160 m square plots, separated by fire breaks. On each soil type there are two replicated plots for each treatment and four unburnt control plots. At VRRS there were two 50-year cattle exclosures approximately 20 ha in size (Bastin et al., 2003) where we compared grazed and ungrazed biocrust diversity for sites that had no regular fire regimes (Vega-Cofre et al., 2023). Separately, in October 2022, a late burn was carried out across a heterogenous 2.6 km^2 Conkerberry paddock containing patches of grass, sparse cover and degraded areas (Fig. 1c-e.). Planet Scope imagery (3 m resolution, 8 MS bands) was used to determine the effect of fire and grazing on biocrust cover pre- and post-fire events (Myint Swe et al., these proceedings). Biocrust cover was substantiated by ground-truthing. Cattle were fitted with tracking collars and left to graze over the course of the following wet season.

The overall aims of these research projects were to provide in-depth studies of the effects of fire and grazing management at a local and commercial scale. This was intended to demonstrate the benefits of burning at the right time, and to contrast the effect of carrying stock post-fire with wet season resting. Additional research took place at the long term Wambiana grazing trial, Charters Towers, Qld, (1997–2023) where the impacts of heavy stocking, moderate stocking and moderate stocking with rotational wet season spelling (resting) on biocrusts were assessed.

Our central aims in the above studies were to determine pasture and biocrust recovery post-disturbance that would result in healthy soils and sustainable levels of ground cover. In doing so we can provide an accurate and rapid assessment of degradation events and post-disturbance monitoring of ground cover recovery at several levels. In turn we can provide support for land managers to sustainably manage Australia's extensive northern savanna. We discuss recent international research together with preliminary findings to understand the importance of biocrusts in the Australian rangelands.

Biocrusts, indicators of soil health

Where biocrusts exist in the rangelands they are both a protection against erosion as well as a useful indicator of soil health, cover and therefore stability and soil function or its potential (Aye et al., 2024). Moreover, biocrusts remain a relatively intact form that can be measured during both periods of stability and climate extremes such as drought. Based on a global drylands' dataset, Chen et al. (2020) found biocrusts formed alternative stable states:

1. Biocrust cover, ~80%; vascular cover, ≤10%, balance bare unprotected soil
2. Biocrust and vascular cover, ≤10%, balance bare unprotected soil
3. Vascular plants (vascular cover, >50%; biocrust cover, ~50%

At Kidman Springs evidence of these states were found across much of the 2.6 km^2 burnt Conkerberry paddock (e.g. Fig. 1c-d). Game camera records from the following wet season (W. Williams, unpublished data) showed the gradual degradation of new grass plants, biocrusts, and ongoing erosion of the soil surface with a further estimated 20% loss in functional integrity (Than Myint Swe et al., this publication), likely caused by ongoing cattle trampling, exacerbated by a significant loss of carbon and nitrogen in degraded areas (W. Williams unpublished data). Our results reflect many other studies that demonstrate the loss of resources that occurs with the loss of biocrusts (Zhang, 2024).

The effects of fire and grazing on biocrust communities and the subsequent influence these factors have on nutrient cycling and pasture quality is highly relevant for land management on grazing properties in northern Australia (Vega-Cofre et al., 2023). In this 2017 study, Vega-Cofre and coworkers found there were significant effects of grazing on bacterial community composition in the vertosol soils that were generally associated with increased cyanobacterial taxa in the 0–1 cm. Our findings demonstrated that the presence of livestock in rangelands increased the proportional representation of cyanobacteria whereas they were not strongly impacted by fire management (Vega-Cofre et al., 2023). Further analyses showed many cyanobacteria and bacteria were associated with nitrogen fixation and cycling. In the more frequently burned sites (early and late season 2-years, both soil types), there were significant impacts of fire management on the overall composition of bacterial communities (unpublished results).

At the Wambiana trial, biocrust cover was highest in the moderate stocking with rotational wet season spelling treatment. Here biocrust cover was dominated by cyanobacteria that bound soil particles, reduced erosion, sequestered carbon, fixed nitrogen, and improved soil fertility (Büdel et al., 2018; Williams et al., 2018). The results emphasised the advantages of wet season spelling combined with moderate stocking rates adjusted seasonally, as effective management strategies in these landscapes (Williams et al., 2021).

Challenges include extreme rainfall variability, intensified drought, and inherently nutrient-poor soils. In drought-prone environments, monitoring the presence and integrity of biocrusts connects landscape function and soil health. Biocrusts that protect and enrich the soil will support long-term ecosystem integrity and economic profitability of cattle production in rangelands (Williams et al., 2021).

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Harnessing private sector finance for large-scale rangeland restoration through sustainable livestock value chains including the development of a rangelands stewardship certification scheme and standard

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Building a global Rangelands Data Platform: Safeguarding rangelands through data-driven decision making

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Key words: Rangelands, data platform, restoration, biodiversity, decision-making,

Abstract

Rangelands, spanning over half of Earth's land, include ecosystems like grasslands, deserts, savannas, and mountains. They support biodiversity, vital ecosystem services, and the livelihoods of pastoralists, livestock keepers, and farmers. However, rangelands face threats from agriculture, mining, urbanization, and infrastructure expansion, leading to land degradation and increased pressure from rising livestock product demand.

The global Rangelands Data Platform addresses these challenges by serving as a repository for rangeland data, supporting informed decision-making on their management, protection, and restoration. Accessible to the public, the platform raises awareness, supports scientific research, and guides investments in sustainable practices.

By providing data for global advocacy and community resilience, the platform contributes to initiatives like the UN Decade on Ecosystem Restoration and promotes the sustainable use of rangelands. This effort ensures the preservation of their ecosystem services and cultural heritage for millions worldwide.

Introduction

Rangelands, covering over half of Earth's terrestrial surface (Reid et al., 2014), are diverse ecosystems that include grasslands, deserts, savannas, tundra, woodlands, wetlands, and mountainous areas. These landscapes support biodiversity, provide essential ecosystem services, and contribute to food security and poverty alleviation for millions worldwide (Asner et al., 2004). Approximately 91% of rangelands are extensive, characterized by open landscapes with minimal boundaries and limited crop agriculture, while 9% are mixed-use areas combining grazing with cultivation. Communities such as pastoralists, hunter-gatherers, and crop farmers rely on rangelands for livestock production, cultural heritage, and socio-economic activities.

Despite their global importance, rangelands face growing pressures from urban expansion, large-scale agriculture, mining, and climate change. These challenges contribute to land degradation, affecting 25-35% of rangelands globally, and reduce their ability to provide critical ecosystem services. Addressing these threats requires effective governance, restoration, and sustainable management practices. International efforts, such as the UN Decade of

Ecosystem Restoration and the declaration of 2026 as the International Year of Rangelands and Pastoralists, underscore the urgency of protecting these ecosystems.

To address these challenges, the "Sustainable Investments for Large-Scale Rangeland Restoration" (STELARR) project was launched in 2023. Funded by the Global Environment Facility (GEF), STELARR aims to reverse rangeland degradation, enhance productivity, and reduce poverty through sustainable livestock value chains. The initiative prioritizes inclusive benefits for women and youth, fostering resilient livelihoods and economic opportunities. It reinvests profits from sustainable livestock practices directly into rangeland restoration, creating a self-sustaining model for long-term environmental and economic benefits.

Central to STELARR's mission is the development of a global rangelands data platform, led by the International Livestock Research Institute (ILRI) in collaboration with GMV and Vizzuality. This platform serves as a comprehensive repository for rangeland data, enabling the collection, sharing, and analysis of critical information. It supports policymakers, scientists, and local communities in making informed decisions and promotes evidence-based strategies for sustainable management. By highlighting the ecological, economic, and cultural value of rangelands, the platform facilitates targeted investments, monitors changes, and enhances awareness at local, national, and global scales, ensuring the long-term health and sustainability of rangelands worldwide.

Methods

The development of the Rangelands Data Platform employs an iterative methodology that combines user-centred design (UCD) principles with agile practices to meet stakeholder needs and align with the STELARR project's goals. It begins with a discovery phase that gathers and analyses information across business, design, scientific, and technical domains. This phase evolves iteratively, incorporating new insights to ensure the platform remains adaptable.

Business discovery is central to this phase, defining governance structures, identifying stakeholders, and setting objectives and use cases. It also maps needs, analyses existing initiatives, establishes metrics for success, and identifies potential risks. Five key user groups are prioritized: remote sensing and GIS experts, climate and ecosystem management professionals, land management and conservation specialists, community-based approach experts, and agriculture and livestock managers. Their feedback shapes user profiles, use cases, and platform features, ensuring relevance, transparency, and trust.

The design phase adheres to UCD principles, engaging stakeholders to refine platform features through workshops, discovery sessions, and prototype testing. Accessibility is a priority, making the platform inclusive for technical and non-technical users, even those with limited digital literacy or connectivity. Iterative development ensures adaptability to evolving needs.

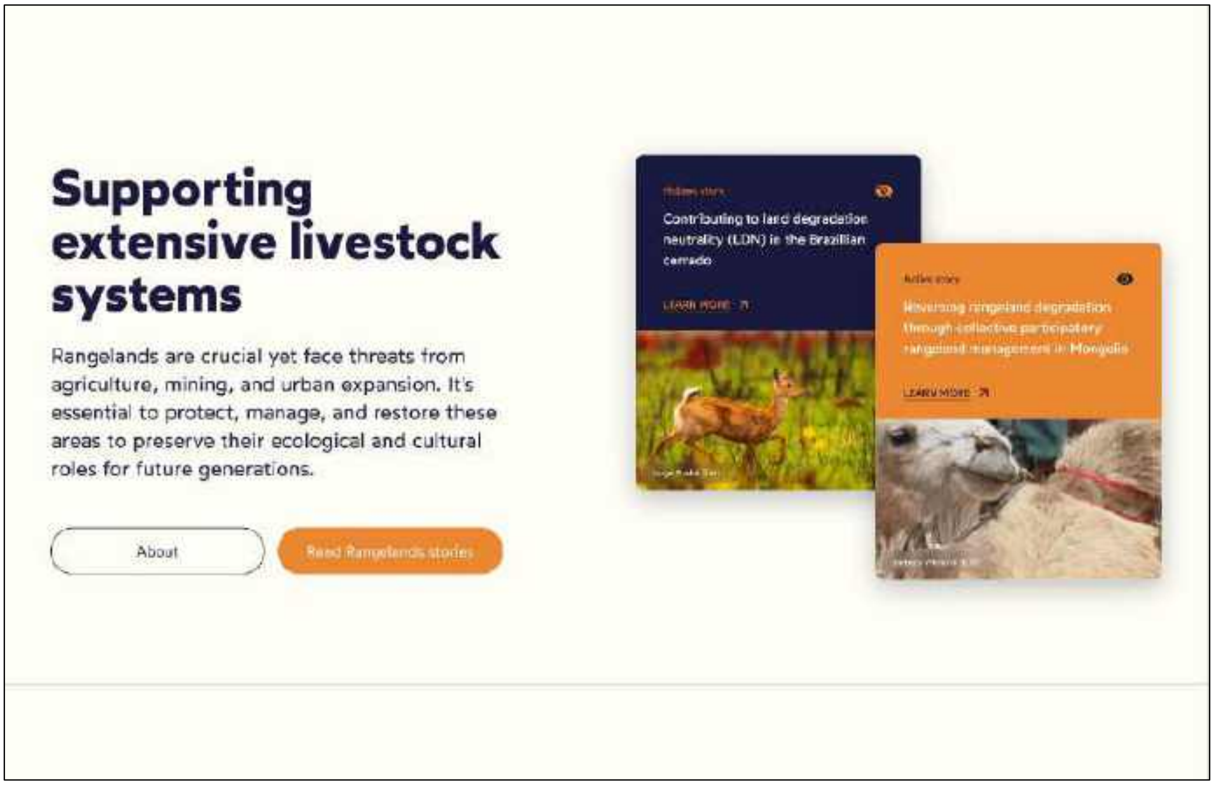

Figure 1 Screenshot of a section of the Rangelands Data Platform landing page.

Simultaneously, the data and technical discovery phases address the platform's data ecosystem, infrastructure, and architecture. Data discovery evaluates existing datasets, identifies gaps, and proposes new sources, while technical discovery focuses on infrastructure, tools, and sustainability strategies. It addresses data formats, processing needs, and storage solutions, mitigating risks to ensure reliable performance in areas with limited connectivity.

Agile methodology underpins development, enabling flexibility and responsiveness. Iterative, time-boxed sprints deliver functional features regularly, guided by continuous stakeholder feedback. A cross-functional team of data scientists, designers, and developers prioritizes a backlog of features and ensures efficient delivery through continuous integration, rigorous testing, and adaptive planning. Post-sprint retrospectives refine processes and align the platform with STELARR's objectives, ensuring it meets diverse user needs.

This structured approach guarantees a user-centric, adaptable, and sustainable platform that addresses the challenges and priorities of rangeland management while remaining aligned with STELARR's broader goals.

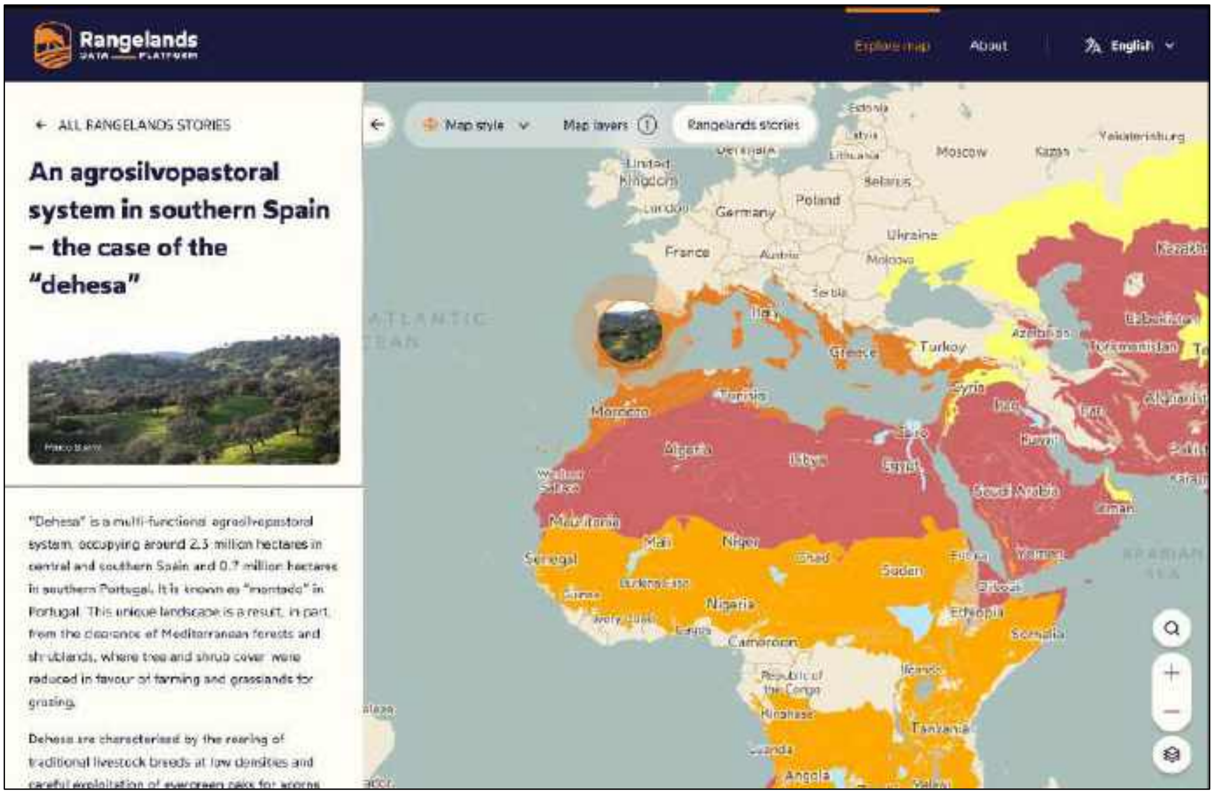

Figure 2 Screenshot of a rangeland story featured on the Rangelands Data Platform.

Results

The Rangelands Data Platform integrates diverse geospatial and contextual datasets within a scalable framework, facilitating comprehensive analysis of rangeland ecosystems. It currently incorporates datasets addressing ecological, productive, and contextual dimensions, with a flexible architecture designed for continuous expansion based on stakeholder feedback and emerging needs. The platform also features case studies that illustrate how changes in rangelands impact local communities, livestock, and natural resources, while showcasing efforts to protect rangelands, wildlife, and the livelihoods dependent on these ecosystems and extensive livestock systems.

The platform is built upon a foundational dataset that defines global rangeland systems by selecting seven of fourteen biomes or rangeland types, based on World Wildlife Fund's (WWF) classification of terrestrial ecoregions, as defined in the ecoregions layer by Dinerstein et al. (2017). This dataset serves as a spatial mask, enabling users to visualize and explore data specific to rangelands, with the ability to filter by individual biomes or their constituent ecoregions. Building on this foundation, the platform incorporates a range of ecological datasets, such as time-series net primary productivity (NPP) data from Moderate Resolution Imaging Spectroradiometer (MODIS) to capture vegetation dynamics, the Anthropogenic Biomes of the World dataset from Socioeconomic Data and Applications Center (SEDAC) to highlight human impacts on ecosystems, and the World Dryland Areas dataset from UNEP-WCMC to define global dryland boundaries. Additionally, datasets on tree cover loss and tree cover gain from Global Forest Watch provide insights into changes in forest cover over time. Other contextual datasets further enrich the platform, offering valuable information on conservation priorities, threatened species, surface water extent, livestock systems and density, population distribution, pastoralist communities, and indigenous territories. As the platform evolves, the collection of datasets will continue to grow based on ongoing stakeholder feedback, providing a robust foundation for analysing the ecological, productive, and social dimensions of rangelands.

Figure 3 Screenshot of the Rangelands Data Platform, displaying the ecoregions within the rangeland systems and the Net Primary Productivity (NPP) for the year 2001.

The platform's technical infrastructure is designed for efficient data processing and seamless visualization, enhancing user interaction with diverse datasets. Vector datasets are processed using Python, converted into MBTiles, and hosted on Mapbox to ensure optimized performance. Raster layers are retrieved from Google Earth Engine and processed within Google Cloud Functions, where they are dynamically styled and transformed. This allows the creation of new layers, such as NPP change (calculated from the first and last years of the time series) and total livestock density (aggregating the number of animals per grid cell). The cloud-based processing approach ensures the platform can efficiently handle large datasets and generate real-time, customized visualizations. The system leverages Google Cloud Platform, with containerized applications managing the frontend, backend, and data workflows. Terraform automates resource provisioning for scalability, while Cloud SQL supports relational data storage. Strapi is employed to manage metadata and style configurations for both vector and raster layers, enabling easy updates. Key statistics, such as rangeland metrics, are embedded within the corresponding Mapbox layers, enabling the frontend to retrieve and present this information to users in an interactive and accessible format.

By combining this robust technical foundation with a diverse and expanding set of datasets and case studies, the Rangelands Data Platform offers a flexible, scalable resource for advancing the understanding and management of rangelands. Its ability to incorporate new tools and datasets, driven by ongoing stakeholder feedback, ensures that the platform remains relevant and adaptable to evolving research and policy needs.

Discussion and outlook

The rangelands data platform is design to become a transformative tool for rangeland management, driven by continuous stakeholder interaction and technological advancements. It aims to meet the diverse needs of policymakers, scientists, local communities, and conservationists.

Regular consultations and feedback sessions have been crucial in developing the current version, providing insights into the specific needs of different user groups. However, many more will still be necessary to fully address the platform's goal. Training programs and workshops are also expected to enhance stakeholders' capacity to utilize the platform effectively.

Future developments will enhance the platform's capabilities by incorporating more localized data and success stories on rangelands restoration, improving analytics, and fostering greater collaboration among stakeholders. Continuous improvement through stakeholder engagement and technological innovation will ensure the platform remains a vital resource for sustainable rangeland management.

In conclusion, the rangelands data platform represents a significant advancement in rangeland conservation. Its evolution and stakeholder interaction position it as an indispensable tool for promoting sustainable practices, enhancing biodiversity, and supporting resilient livelihoods. As it grows and adapts, it will play a crucial role in achieving global rangeland conservation and sustainable development goals.

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The need for a global rangeland health monitoring framework

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Abstract

Globally, rangelands contribute to biodiversity (above- and below-ground), climate change adaptation and mitigation, ecosystem restoration, wildlife habitat and human well-being. However, these critically important ecosystems are degrading at unprecedented rates, due to lack of investment and awareness. Further limiting these investments are the vast knowledge gaps on the status of rangeland health, including the ability to reliably measure the impact of rangeland restoration interventions on key indicators of ecosystem health. We propose that building and implementing a global rangeland monitoring framework, aimed to build consistent datasets, will enable the comparison of management practices across diverse systems, track the efficacy of interventions over time, and provide the evidence-base to inform policy and practice. In addition, we see an additional benefit of such a system is the contribution to the various standards around value chains from rangeland systems, ultimately providing additional income to pastoralists and value chain actors. Within the STELLAR (Sustainable Investments for Large-scale Rangeland Restoration) project, we have conducted a review of standards and their associated monitoring frameworks across the rangeland value chains in the Americas, Central Asia, and Africa. We collated the variables and indicators within each framework and found wide disparities in indicators monitored, monitoring techniques, and assumptions made. Variations in how data are collected and which variables are included demonstrated a lack of consistency across frameworks. For example, the Land Degradation Surveillance Framework (LDSF) is a comprehensive field based method that collects multiple indicators of soil health, land degradation and vegetation diversity, but does not include local knowledge or socio-economic variables. We call for a framework that combines systematic field-based assessments, with citizen science and remote sensing to deliver accurate assessments of rangeland health indicators at scales relevant to stakeholders (pastoralists, value chain actors, land managers, standards experts, and policy makers) and to track interventions over time.

Introduction

Rangelands are incredibly vast ecosystems and provide multiple critical ecosystem services and livelihoods for millions of people. Yet, rangelands are highly degraded, with soil erosion being dominant in dryland systems (Vågen and Winowiecki, 2019). Therefore, there is an urgent need for rangeland restoration efforts. A significant obstacle to attracting private investment in rangeland restoration, as Burrows (2024) points out, is the absence of reliable and straightforward performance indicators. Livestock value chain development (LVCD) offers a promising pathway for driving investment and improving rangeland management. By involving actors across the livestock value chain - including the commercial sector - LVCD can help establish sustainable and climate-resilient systems. This involves directing investments toward the resource base (rangelands) to enhance productivity and enable targeted restoration efforts. Furthermore, LVCD can build international momentum for rangeland restoration through collaboration among key stakeholders, alliances, and evidence-based approaches. However, the lack of globally validated standards, tools, and frameworks for assessing restoration progress has hindered effective scaling of robust value chain models, particularly in developing nations.

Ecological monitoring involves tracking changes in ecosystems by measuring specific variables and indicators across space and time. Indicators are measurable attributes of an ecosystem that provide critical insights into its health and functionality (Suter 2001). These indicators can either directly quantify significant ecosystem attributes or services - such as vegetation biomass as an indicator of productivity - or indirectly measure elements correlated with processes or features that are more challenging to assess directly. An ecological monitoring framework offers a systematic approach to observing, evaluating, and interpreting ecosystem conditions and their dynamics over time. Its primary purpose is to enhance the understanding of ecological processes, identify changes or trends, and support informed management decisions (Schlesinger and Bernhardt 2013).

To address these gaps, we aim to co-develop a comprehensive framework for monitoring rangeland health that can be applied across various value chains and landscapes.

Methods

A first step in this development process was to conduct an extensive review of existing monitoring frameworks. An initial review assessed 30 monitoring frameworks, including 15 connected to sustainability standards, 11 based on field methodologies, and five relying on remote-sensing techniques. Additionally, a review of 65 publications - across topics of rangelands, grasslands, savannas, restoration, degradation, drylands, monitoring, and surveillance - was conducted to identify current practices and best approaches in rangeland monitoring. This review assessed 59 biophysical and 18 socioeconomic indicators across the frameworks. To assess the frameworks, we rated them based on the number of indicators assessed under the following categories: 1) Soil health; 2) Vegetation; 3) Hydrology; 4) Landscape Level; 5) Faunal Diversity; 6) Community Indicators; 7) Ease of Implementation; and 8) Data Collection and Integration. If a framework had five or more variables measured under each category, it was scored high. We also conducted interviews with key informants, including standard developers and commercial sector representatives, to better understand practical challenges and priorities for LVCD investment. Further, a consultation workshop on the proposed global rangelands monitoring framework and indicators was held with representation of 22 organizations to provide feedback and suggestions.

Results

The results of this review illustrated that no one monitoring framework adequately covered all aspects of socio-economic, biodiversity, and animal health and diversity. While some frameworks were excellent in biophysical indicators and ease of implementation (the Land Degradation Surveillance Framework (LDSF), others were strong in the socio-economic and community indicators (Sustainable Fibre Alliance) (Table 1). Furthermore, there was little overlap in indicators, making it difficult to use data from different frameworks to compare and assess rangeland health. However, from the 59 biophysical indicators and the 18 socio-economic indicators assessed we narrowed down to a list of 10 biophysical indicators and 12 socio-economic indicators, see below. These indicators were narrowed down through a multi-step process including: 1) Assessing whether the indicators adhered to the SMART indicator framework (Specific, Measurable, Attainable, Relevant, and Timebound); 2) Multi-stakeholder consultation workshops; and 3)Key informant interviews. This process will continue through the next six months to finalize the list.

Biophysical Indicators
Soil: Soil organic carbon content, soil compaction, soil erosion prevalence, bare ground cover
Vegetation : Annual primary productivity, herbaceous cover, woody cover
Biodiversity: diversity and density of grasses, forbs, woody vegetation
Hydrology: soil-water infiltration capacity

Socioeconomic indicators
Rangeland Enterprise: Rate of return on investment, palatable forage cover, livestock density/health, presence of a feasible management plan, governance structure, secure land tenure
Community Livelihoods: Income inequality, local ecological knowledge utilized, education, employment diversity

Table 1: An evaluation of 11 rangeland health frameworks according to the number and type of soil, vegetation, hydrological, biodiversity, landscape, and community indicators, and the framework's ease of implementation and infrastructural integration. Dark green represents the highest rating, followed by light green, yellow, and pale red representing the lowest rating.

Monitoring Framework	Soil Indicators	Vegetation Indicators	Hydrological Indicators	Landscape Indicators	Faunal Biodiversity	Community Indicators	Ease of Implementation	Data Collection and Integration
AusPlots								
ILRI Participatory Rangeland Management								
IUCN Land Health Monitoring								
Landscape Functional Analysis								
LDSF – Rangeland Health Module								
MARAS								
Rangeland Baseline Master Protocol								
Sustainable Fibre Alliance								
USDA-ARS								
Veld Management								
Western Australia RMS								

Discussion

There is a clear need for a comprehensive monitoring framework that combines globally relevant, validated indicators while also capturing the unique nuances of local contexts. This framework should generate reliable evidence of the impacts of restoration activities and support investments in sustainable rangeland value chains. We recommend integrating robust field-based methods with citizen science and remote sensing technologies. This combination will allow for the establishment of accurate baselines and facilitate long-term monitoring of key biophysical indicators, all while providing geo-referenced data on the location and types of actual interventions taking place on the ground. Such an approach would provide the necessary evidence to support adaptive management, guide policy decisions, and attract further investment in sustainable rangeland management.

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Mobilizing luxury brands' value added as investment in rangelands

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Key words: Rangelands; Luxury; Restoration; Brands; Private Sector.

Abstract

Rangelands generate a multitude of products and services. Some pass into value chains delivering branded luxury products. Luxury value chains are stakeholders in rangeland restoration. The juxtaposition of their perceived excess and exclusivity with the harshness of subsistence production in adverse environments is widely recognised. Luxury also conveys uniqueness, quality and provenance. Ongoing efforts at "fast fashion" and "affordable luxury", have demonstrable impacts on rangelands. In the STELARR (Sustainable Investments for Large-scale Rangeland Restoration) project we argue that product differentiation using rangelands' provenance is established across products as diverse as meat, cosmetics and clothing. We identify models for luxury brands' investment in rangelands directly and investigate the entry points available for that investment. Context for these models' operation includes rapidly developing functionality of standards and certification relating actions in the rangelands to sustainability indicators and onwards to support claims at the retail level. Technology that enables information capture, transmission and visualisation offers opportunities for product differentiation and a product story that supports a luxury price. Global trade's move to products' verified sustainability credentials offers a convergence of value chain actor's interests and capabilities. Owners of luxury brands then have the opportunity both to advance and support their own claims by appropriate investment in rangelands; and to exclude competition all along the value chain from brands not achieving the markups associated with luxury sales. Seven investment models are identified, with entry points for deal structures to engage luxury value chains. Across the Americas, Central Asia, and Africa we identify on-going initiatives that enable the investment models, including the Rangeland Stewardship Council, and industry- and national-level actions, on the interface between sustainability and value chains. We call for a broader embrace of value chain development which aligns the high retail margins of luxury brands with the incentive to invest in rangelands.

Introduction

Rangelands support numerous value chains which deliver food, fibre and industrial products within and beyond the rangelands' geographic reach. Rangelands also deliver ecosystem services across a variety of spatial, functional and organisational contexts to deliver public and private goods (Fisher, Turner, & Morling, 2009). From the concept of "Land Value Chains" (Raschio, 2017), networks extending into international markets enable rangeland products to be sold and re-sold, transformed and marketed far from their rangeland origins. Some rangeland products find their way into luxury value chains. The current study identifies and examines links between the value added and branding of these products, and the rangelands.

The mobilisation of sustainability is not a new concept for delivery of value addition in supply chains and social development outcomes. Rangelands have in the past successfully attracted investment into value chains (De Groot et al., 2013; Ferwerda, 2015), including programs for Payments for Environmental Services (PES) which have had a variety of orientations around environmental degradation (Pappagallo, 2018), but have occurred at limited scale.

Method

This paper is a synthesis of current knowledge on the connection between luxury brands and rangelands, to identify models and entry points for investment by brand owners under the STELARR (Sustainable Investments for Large-scale Rangeland Restoration) project.

Results

Estimates of the extent of degradation of the World's rangelands vary, but up to one third of their area is reckoned to be either degraded or under threat of degradation (Herrera Calvo, 2024), with some estimates much higher (Ding et al., 2017). Rangeland degradation has numerous symptoms, causes and consequences, both public and private. Knight and Overbeck (2021) conclude that restoration cost estimates per hectare are highly variable and context specific but can extend to the tens of thousands of dollars.

Rangeland preservation is widely acknowledged as requiring a convergence of stakeholder interest supported by organisational models and community. The STELARR project addresses rangeland restoration, for which associated models are less well documented. Pastoralists' enterprises and associated value chain and environmental actors might represent a convergence of stakeholder interest (Reij et al., 2020; Shames & Scherr, 2020), but cost levels are such that Leake (2021) remarks on "a significant need for restoration … that can seldom be paid for by the land manager or farmer of that land".

Opportunities for value chain-related financing of rangeland restoration have been examined by Teno (2022) in the context of the large scale Great Green Wall initiative. Recognition of business more generally as a stakeholder in rangeland restoration is taken up in UNCCD's business sector engagement strategy (Voigt, 2013). The STELARR project sets out to design, demonstrate and support rangelands' products and provenance as a basis for luxury brands' investment in rangelands directly, and at the landscape scale which has evaded investments at the level of value chains. Enhanced mobility of communications and preferences across national and cultural boundaries have produced a recent "democratisation of luxury" which has enhanced access to luxury.

This access has affected the rangelands: the much discussed "cashmere crisis" is presented by some as the increased demand (often in blends and in lower quality products) implicating animal welfare and overgrazing (Darbalaeva et al., 2023; Lauesen, 2019). Jones and Jones (2018) describe "sustainable luxury", and an "ideological product", mobilised to include employment conduct and conditions, animal welfare and other sustainability concerns by Cavender (2018) to state that brands express "core values" through their stance on sustainability, but despite luxury brands' embrace of information technology as a means of communicating with consumers, they do not use these channels to "tell a story" featuring sustainability. Further, provenance plays a significant role in branding: cashmere's provenance and its associated "heritage" and "spiritual home" are central to customers' perception of a cashmere brand (Collins & Weiss, 2015). "Product integrity", "craftsmanship" and "relationship to place" are also central to cashmere marketing (McLaren-Hankin, 2013), as are "authenticity, heritage and craftsmanship" (Towers, Perry, & Chen, 2013). However, these communications of provenance refer to the place of manufacture, and not the place of origin of raw materials: the rangelands.

Value chains exhibit differing relationships to their rangelands resource base, and stakeholder systems reflect this. Mobility of pastoralists requires particular resource governance forms; customary access and non-private ownership requires others; grazing and cultivation pressure across public/private boundaries accentuate pressure on public rangelands and on the bodies administering them. The demanding logistics and quality requirements of luxury products impose high costs along these lengthy value chains. Beyond storytelling, certification and standards are playing a role. Some 35% of global cashmere production, 42% of mohair and increasing proportions of luxury camelid fibres, are certified for sustainability, animal welfare and social functions (TextileExchange, 2023). Little peer-reviewed research reports on certification within the supply chain for high value brands, but a study of CSR actions by Towers et al. (2013) found that procedures were informal and based on trust, rather than documentation. Danka, Grochowska, and van Rijt (2017) identify barriers to use of certification as complexity of the supply chain, problems with traceability, and a lack of universally accepted standards. Further, they have limited informational links to unified guidelines on land degradation neutrality (Chasek et al., 2019).

Discussion and conclusions

Luxury brands increasingly extol their sustainability credentials in publicly available reports featuring targets and verification procedures. Mixed farm production systems, and a plethora of product standards and certifications, have provided a limited foundation for investment in rangeland restoration related to single products' value chains. Textile Exchange certification and its promotion throughout the South African mohair industry, broad based standards for cashmere, and whole-of-chain initiatives in fine wool, have all developed over time. In different settings, precisely targeted sourcing arrangements for high valued beef branded as promoting rangelands (Lerma, Díaz Baca, & Burkart, 2023), and the vicuna species-preserving actions of luxury fibre brands in the Andes (CITES, 2019) have also played a role.

With regard to land-based investment such as rangeland restoration, clear benefits to investors have been elusive, even where tightly geographically defined (Bourne, Muller, de Villiers, Alam, & Hole, 2017). The best-known large scale private sector engagement program is "Business4Land", from which projected private sector benefits (drawn from several sources) are presented in table 1.

Table 1. Private sector incentives for rangeland investments

Private sector benefit	Mechanism
Risk mitigation	Improved delivery of both environmental services and marketable products and raw materials Access to scarce or unique raw materials
Enhanced productivity	Production generated from concentration of effort on several aspects of productivity (sustainable intensification)
Corporate responsibility	As able to be demonstrated along value chains
Brand value	Product differentiation based on credible claims Identification with International Year of Rangelands and Pastoralists Inclusion of rangelands and pastoralists in product provenance
Innovation in processes	Improved focus based on reliable volumes and qualities of product Scale of operation
New markets	Attracting new consumers to differentiated products. Carbon markets
Regulatory compliance	Addressing local, national or international requirements for access to resources, raw materials and markets
Government incentives	Tax and resource access incentives Climate related incentives

Source: Authors' compilation; (Herrera Calvo, 2024)

From the juxtapositions of luxury, sustainability and issues of high value branding, several models emerge which provide entry points for investment in rangeland restoration by the owners of high value brands. several are proposed as a source of finance for rangeland restoration:

- location-based investments (planting, soil and water management) which facilitate access to raw material supply from that location and support from communities and policy actors
- brand promotion by social investments (schools, community assets)
- attachment of brand identity to investments in rangelands which support endangered species
- strategic partnerships with high profile actors in rangeland conservation

Information flows are central to this process, and along with associated stakeholder actions, are presented in annex 1. Synthesis of reporting on high value apparel brands using rangelands-based natural fibres reveals difficulties in recording of investments, quantification of baselines and progress in rangeland productivity, and the establishment of value chain performance metrics which reconcile public and private benefits.

At the pastoralist level, mixed enterprises and multiple uses of rangelands across varied landscapes obviates the need for holistic rangeland standards rather than a 20th Century- product and process standards. A Rangeland Standard is under development in association with the STELARR project. Data and its collection and curation has represented a barrier to change by value chain actors including policy makers, resource managers, as well as the owners of high value brands investing in rangelands' restoration. An information platform combining remote sensing with ground-based verification is under development in association with the STELARR project. is targeting three luxury value chains for investment by high value brand owners, using a variety of entry points: cashmere in Mongolia and Afghanistan; mohair in South Africa; and vicuna in Peru and Argentina.

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IYRP films on pastoralism and biodiversity conservation

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Promoting pyric herbivory and mixed species grazing for enhancing livestock production from rangelands in the Great Plains – An integrated research–education–extension endeavor

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A disturbance triangle: The case for the interactive role of prairie dogs with fire and ungulate grazing in the Great Plains

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Key words: Biodiversity, Burrowing mammal, Grassland, Pyric-herbivory, Rangeland

Abstract

Global biodiversity declines have been hastened by the suppression of once-widespread disturbance regimes. In recent decades, restoration of the fire-grazing interaction has helped address these declines in the North American Great Plains. Conversely, relatively little attention has been paid to another historically ubiquitous disturbance agent -- the black-tailed prairie dog (*Cynomys ludovicianus*). While some research exists on the interaction between large ungulates and prairie dogs, scant work recognizes the triangle of historical and current interactions among large ungulates, fire, and prairie dogs, and research on interaction between the latter two disturbances is especially rare. Upon reviewing the literature, 34 sources discussed the fire-prairie dog interaction, but only one empirically tested the direct effect of prairie dogs on fire. Despite this research gap, historical fire patterns, current fire management activities, and unpublished data indicate prairie dogs likely reduce wildfire spread and/or intensity. We advocate for a paradigm shift in Great Plains rangeland management that considers prairie dogs as the third corner of a "disturbance triangle," and further exploration of these more complex disturbance interactions worldwide

Introduction

Most grassland and shrubland ecosystems evolved in the context of various interacting disturbances (Fuhlendorf and Engle 2001). The periodicity, spatial extent, and intensity of disturbances helped shaped the floral and faunal composition of these systems; thus, systematic suppression or alteration of historical disturbances during the past few centuries has led to decreased biodiversity and ecosystem health in myriad rangelands (Truett et al. 2001, Garnett et al. 2010). In the North American Great Plains, European settlement has coincided with reduced fire frequencies, novel grazing patterns of ungulates, and large-scale conversion of grasslands to row crop agriculture (Fuhlendorf et al. 2012; Augustine et al. 2021). Altered disturbance regimes on remaining grassland patches facilitate encroachment of woody species and homogenized herbaceous structure further contributing to biodiversity reduction (Ratajczak et al. 2016).

Accordingly, restoration of historic disturbances and their interaction has become a major goal of rangeland ecologists and conservation biologists alike (Sayre et al. 2013). While the ranges of native large herbivores including bison and elk (*Cervus canadensis*) have contracted since European settlement and fire has been long-suppressed, the fire-grazing interaction has been mimicked using domestic livestock and native grazers like bison on both public and private rangelands via patch-burn grazing, with evidence that this management approach can support both livestock and biodiversity goals (Fuhlendorf et al. 2009). Despite progress towards the reintegration of fire and grazing as interacting disturbances, most grassland management paradigms continue to ignore another interacting disturbance that was historically ubiquitous across the Great Plains: burrowing mammals, and specifically, the black-tailed prairie dog (*Cynomys ludovicianus*).

As a keystone species, black-tailed prairie dogs are an important prey item for numerous avian and mammalian predators including the endangered black-footed ferret (*Mustela nigripes;* Hoogland 2006). Prairie dogs are also ecosystem engineers, living live in dense colonies with hundreds or thousands of individuals that together consume vegetation and actively clip it to optimize predator visibility (Hoogland 2006). Their digging and shrub clipping helps to aerate soil and reduce the rate of woody encroachment (e.g., Barth et al. 2014), burrows provide habitat for rattlesnakes (*Crotalus* spp.) and burrowing owls (*Athene cunicularia*), and the short, sparse vegetation structure they generate is ideal for the imperiled mountain plover (*Charadrius montanus;* Duchardt et al. 2019). This same engineering that provides so many ecosystem benefits can also reduce forage availability for livestock in certain contexts (Augustine and Derner 2021). This conflict is largely responsible for eradication programs that have reduced current prairie dog populations sizes to 5% of historical estimates (Miller et al. 1994). While there is evidence that prairie dogs can negatively affect livestock production, recent research indicates that this conflict may be contingent on factors like interannual precipitation variability (Connell et al. 2019, Augustine and Derner 2021). Moreover, forage *quality* is often greater on colonies because prairie dogs maintain vegetation at an early phenological state and can shift species composition towards more nutritious plants (e.g., Connell et al. 2019).

While researchers and managers have acknowledged relationships between fire and grazers (e.g. Fuhlendorf and Engle 2001), and between grazers and prairie dogs (e.g., Augustine and Derner 2021), less consideration has been given to the other side of this triangle: prairie dogs and fire; few studies exist on impacts of fire on prairie dogs, and we are unaware of any experimental studies demonstrating the effects of prairie dog ecosystem engineering on fire behaviour. To address this knowledge gap, we 1) review the literature on influence of fire on prairie dogs and prairie dogs on fire and 2) propose a framework by which to consider the historic role of prairie dogs within the fire-grazing interaction.

Methods and Results

We hypothesized that fire would have a similar influence on prairie dogs as grazing, facilitating expansion of prairie dogs into burned areas (+). Conversely, because prairie dogs not only remove biomass like other grazers but also lead to soil disturbance, we expected a suppressive effect of prairie dogs on fire (-) (Fig. 1). To better understand both sides of the fire-prairie dog interaction, we reviewed the primary literature using Google Scholar and Academic Search Premier. We conducted our Google Scholar search between 20–23 October 2023 using ["prairie dog" OR "Cynomys"] and "fire", which returned 10,900 hits. We exhausted all 100 pages that Google Scholar generates (1,000 hits) on 23 October 2023. We completed the Academic Search Premier search on 25 November 2023 using the same search terms, which returned 758 hits. We reviewed titles for relevance then searched for the terms: "fire", "burn", and "fuel" within each relevant source. If a source contained any of these keywords, we downloaded the source for a subsequent full review, which yielded 98 documents. Upon review, we deemed 38 of these resources as relevant; 34 addressed the fire → prairie dog interaction either theoretically or empirically. Most of these resources (n = 29, 85.3%) merely discussed the directional effect of fire on prairie dogs; text referencing fire influences on prairie dogs predominantly appeared in introduction, discussion, and management implications. A small portion (n = 5, 14.7%) of the literature empirically explored the effects of fire on prairie dogs, with overwhelming support for a positive effect of fire on prairie dogs, mainly by facilitating expansion into burned areas (e.g., Milne-Laux and Sweitzer 2006, Augustine et al. 2007).

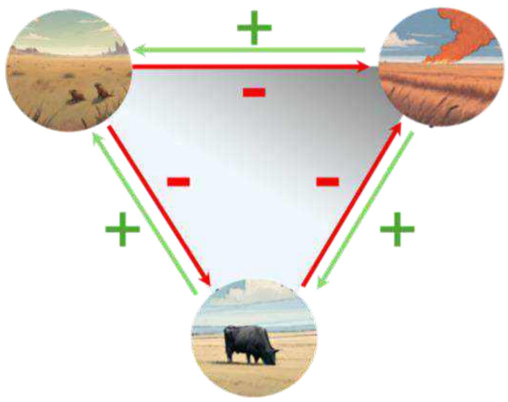

Fig. 1. Proposed disturbance triangle between fire, ungulate grazing, and prairie dogs within the Great Plains of North America.

Few sources discussed, let alone tested, the prairie dog → fire interaction. Only 6 sources mentioned this potential interaction, typically by identifying prairie dogs as potential engineers of fire breaks without direct supporting citations (or in some cases, citing resources which themselves made statements without supporting research citations). Only one source, a dissertation (Strawn 1995), empirically tested the effects of prairie dogs on fire, and found a 20% reduction in fire coverage on burned prairie dog colony as compared to an adjacent area that was also burned, although this was tested somewhat indirectly with burn tiles and with mixed efficacy (personal communication, S. Strawn). Strawn (1995) also indirectly explored the effect of fire on prairie dogs and tested the prairie dog-grazing interaction, finding support for positive interactions between prairie dogs and grazers.

Where the literature is incomplete, scientists often turn to natural history to begin considering mechanisms; such first steps are crucial in identifying future research need. Potential evidence for prairie dogs reducing fire intensity or size can first be found in historical fire return intervals. Although we know of no dataset that would facilitate modeling these dynamics directly, abnormally small or infrequent fires relative to predicted frequencies could be interpreted as an indication of the role of prairie dogs. For instance, Porensky et al. (2018) highlighted the incongruity of fire-intolerant big sagebrush (*Artemisia tridentata*) persisting in portions of northeastern Wyoming, where fire-free intervals were estimated at ~7 years (Perryman and Laycock 2000). Researchers posited several potential factors leading to discontinuity of fuels, including disturbance caused by prairie dogs (Porensky et al. 2018).

More direct observations of the role of prairie dogs in influencing fire exist. The Anderson Creek Wildfire was the largest recorded fire in Kansas history, burning across 161,774 ha in 2016. Many structures were destroyed, and hundreds of livestock were killed, but on one ranch the losses were not so steep. Free-roaming bison on the Z-bar Ranch were observed moving to prairie dog towns during the fire. The fire did not carry across the colony, and all bison survived (Browning and Browning 2016, Magnus McCaffery, Turner Ranches, personal communication). Based on discussions with managers, it also appears that prairie dogs are taken into consideration when crafting burn plans, either as a means of "catching" (helping to limit) fire (David Lucas, Fish and Wildlife Service), or as a hindrance to fire spread in more arid systems (Ana Davidson, Colorado Natural History Program).

Discussion

While potential interactions between fire and prairie dogs appear straightforward, we found little evidence in the literature of previous research focused on this relationship. Little is known about the effect of prairie dogs on fire, barring a few references in the literature, and only one empirically-based dissertation chapter. The lack of research on how prairie dogs influence fire extends to other taxa as well, highlighted by a recent review (Foster et al. 2020). Therein, authors highlight the effect of animals on fire regimes are often overlooked, and studies incorporating the effect of fauna typically focus on mega-herbivores. However, prairie dogs consume and clip vegetation, reducing fuel availability and altering vertical structure. Prolonged occupation of a colony is associated with altered vegetation composition favoring annual forbs, often with a drastically reduced shrub component relative to the surrounding area (e.g., Duchardt et al. 2019); as a result, they also influence the composition of fuels, drastically reducing the availability of coarse fuels that would burn hotter and longer. Together with increased annual forb cover, burrowing activities increase bare ground, reducing fuel continuity. Despite a lack of empirical research, anecdotal evidence from numerous fires on the Great Plains supports this hypothesis.

We encourage a paradigm shift towards this multi-disturbance model not only because it appears to be more is more ecologically accurate, but also because it could be increasingly important for future management of these imperiled systems. Management on remaining rangelands in the Great Plains must necessarily factor in economic considerations; therefore, we do not expect every pasture or property within native prairie dog range to contain prairie dogs. Indeed, this would not have been the case historically and would be infeasible now. However, as our understanding of ecological processes grows, so should our management toolbox. Rangeland biodiversity in the Great Plains was not historically maintained by just fire and bison grazing, and we do managers a disservice by ignoring the unique ecosystem services that prairie dogs can provide. These include a potentially effective approach to address woody encroachment, one of the largest threats to portions of the Great Plains (Morford et al. 2022).

The fire-suppressive force of prairie dogs may be important for wildfire management in the future. By reducing woody encroachment and fuel availability, prairie dogs have been observed to reduce fire effects locally, as in bison herd survival on the Z-bar ranch fire, and more broadly in terms of fire spread on the Marshall, Wildcat Creek, and Gilbert Ranch fires. Nevertheless, these interactions have yet to be empirically tested. A better understanding of these dynamics is crucial, given fire frequency has nearly quadrupled in the Great Plains in the past decade, relative to the 1980s and 1990s (Iglesias et al. 2022) with more frequent megafires in the southern plains (Shore 2019).

Further research is needed on how prairie dogs influence fire behaviour in prescribed burns and wildfires. Further investigation of manager perceptions of prairie dogs in the context of fire may also be informative. We hope that continued research and discussion may do for the fire-prairie dog interaction, and the disturbance triangle as a whole, what we have observed with the fire-grazing interaction over the past 25 years. Although the restoration of any historical disturbance is dependent on both ecological and social context, much work has already been done to educate the public on the important ecological services these diverse disturbances can provide in grassland and rangeland ecosystems. Although incorporating prairie dogs into the grassland disturbance paradigm may be an uphill battle, we hope that this is at least a first step in that direction facilitated by a broader understanding of fire dynamics.

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Promoting rangeland literacy through development of agents of change and high-impact education resources

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Key words: agents of change; educator cohorts; high-impact learning resources; rangeland literacy

Abstract

The sustainability of Great Plains rangelands and their ecosystem services is under threat by woody plant encroachment and climate change. Restoring coupled fire and grazing processes through pyric herbivory and mixed species grazing can effectively support rangeland ecosystem function, services, and resilience, but the adoption and public and policy support of these practices have been limited. The aim of the Educator Cohorts of the Prairie Project was to develop agents of change in secondary and undergraduate education through faculty and curricular development and action research to promote rangeland literacy. We organized three 2-year Educator Cohorts each of which starting with an intensive summer workshop focused on current science of rangeland ecology and ecosystem services as well as current learning science and high-impact pedagogy. It was followed by monthly online meetings and individual consultations focused on professional development, community building, and supporting participants in design, implementation, and assessment of their projects. Our work on developing rangeland literacy had four foci: (1) fire and grazing are fundamental processes of rangelands, (2) ecosystem services of rangelands are essential for all, (3) woody encroachment negatively impact these ecosystem services, and (4) pyric herbivory and mixed species grazing are effective climate-smart practices for sustaining rangelands and their ecosystem services. Cohort participants developed high-impact learning modules/lesson plans related to fire and grazing, implemented them in their own classes, assessed the impact on student learning, and presented their work and findings in professional or education conferences to engage peer educators to promote awareness and facilitate adoption to broaden the impact. Pre- and post-surveys of the students in the classrooms of the cohort participants and project team members have shown significant changes in knowledge and attitudes related to rangeland literacy, especially the roles of fire and grazing in sustaining rangelands and their ecosystem services.

Introduction

The Great Plains rangelands are a cornerstone of U.S. livestock production, biodiversity, and other ecosystem services, including water regulation, carbon storage, and wildlife habitat (Wilcox et al. 2022). However, these landscapes are under severe stress due to woody plant encroachment and increasing frequency and intensity of droughts and wildfires associated with climate change, which collectively diminish the rangelands' capacity to sustain these ecosystem services (Derner et al. 2018). Woody plant encroachment, in particular, has transformed millions of acres of open grasslands into woodlands, reducing forage availability and biodiversity (Archer et al. 2017).

Two promising approaches to counter these threats are pyric herbivory, a management strategy that integrates fire and grazing to create a heterogeneous landscape (Fuhlendorf et al. 2009), and mixed species grazing with cattle, goats and/or sheep. They have been proven as effective climate-smart practices that can reduce woody plant encroachment, impact of drought, and the risk of wildfire while increasing livestock production (Wilcox et al. 2022). Despite their efficacy, adoption of pyric herbivory and mixed species grazing remains low due to misconceptions, cultural resistance, and a lack of public and policy support.

Recognizing the role of education in addressing these barriers, the Prairie Project launched its Educator Cohorts Program designed to cultivate agents of change in secondary and undergraduate educational institutions through faculty development, curriculum enhancement, action research, and peer engagement. It emphasizes the development, implementation and dissemination of high-impact educational resources that include the key concepts of pyric herbivory and mixed-species grazing for sustainable rangeland management. It aims to empower educators as agents of change and equipping them with the knowledge and tools needed to foster rangeland literacy among secondary and undergraduate students. In addition to rural audiences, the Educator Cohorts Program intentionally targeted urban and suburban audiences, who represent the majority of policymakers and voters in the Great Plains region, seeking to build broad-based support for sustainable rangeland management.

Methods

Each of the Educator Cohorts spanned two years, with three staggered cohorts implemented to allow one year of overlap between them. The participants of the cohorts were educators from middle and high schools as well as colleges who were offered benefits such as travel support, stipends, and opportunities for continuing education or graduate credits. There were three main components of the cohorts' activities:

Summer workshop - Each cohort started with an intensive summer workshop and all cohort participants were required to attend this six-day workshop led by experienced facilitators from the Prairie Project's Education and Extension (E&E) team. During the workshop, the participants explored (1) the current science and practice of pyric herbivory and mixed-species grazing and how these affect the sustainability of rangelands and their ecosystem services in the Great Plains region, and (2) the current learning science and active learning pedagogies (peer instruction, case studies, authentic inquiries, citizen science projects, etc.). They then (3) participated in field tours of Prairie Project's research and demonstration ranches and met with researchers, extension specialists, and ranch managers to discuss and observe the research and management practices. Each participant (4) designed a learning module or inquiry project specifically tailored to their own class, as well as an associated assessment for assessing the impact of the module on student learning.

Implementation and assessment - During the following fall and spring semesters, participants refined and implemented their learning modules or projects and conducted assessment research of student learning. A collaborative learning community, comprising facilitators and cohort peers, provided ongoing support through (1) monthly online meetings to share progress, reflect on successes and challenges, and brainstorm solutions as well as (2) one-on-one consultations with facilitators for personalized guidance in module implementation and assessment research.

Broader engagement - In the second year, participants presented their curriculum designs, implementation strategies, and research findings at professional conferences and outreach events. These presentations aimed to inspire peer educators to adapt these learning modules and resources, professionals and ranch managers, while also recruiting participants for future cohorts. Potential venues include the Society for Range Management and Ecological Society of America meetings, the National Center for Case Study Teaching in Science conference, the Life Discovery–Doing Science Biology Education Conference, and the Lilly Conference on College and University Teaching.

The work of the educator cohort focused on developing ***rangeland literacy*** which had four key components: (1) fire and grazing are fundamental processes of rangelands, (2) ecosystem services of rangelands are essential for all, (3) woody encroachment negatively impact these ecosystem services, and (4) pyric herbivory and mixed species grazing are effective practices for sustaining rangelands and their ecosystem services. A survey focused on rangeland literacy was developed and all cohort participants administered this survey before and after the implementations of their learning modules, in addition to any other assessments they used, to assess student learning gains in rangeland literacy.

Results

High-impact learning module development and implementation

Over 30 participants of the Educator Cohorts have developed effective learning modules and projects in both secondary and high-education settings. They employed diverse approaches of high-impact pedagogies, from active and experiential learning, case studies, game-based learning, technology-enhanced learning, free response questions (FRQ), authentic inquiries, and course-based undergraduate research experiences (CURE). Many of them incorporated the use of Prairie Protector game developed by the Prairie Project team and/or the Rangland Analysis Platform (RAP) along with other activities to engage students and develop deeper understanding and place-based relevancy. All participants developed effective assessments, both formative and summative, for and of their students learning.

Impact on student learning

Preliminary results from the pre and post surveys have shown significant positive impact of the education modules and projects on rangeland literacy of the students. For example, through an inquiry project focused on fire and grazing, significant changes occurred in student understanding of the effect of woody plant encroachment on both livestock production and biodiversity (Fig. 1a, b), rangelands providing ecosystem services to both rural and urban residents (Fig. 1c, d), and the importance of fire in rangelands and its suppression leading to woody encroachment (Fig. 1e, f).

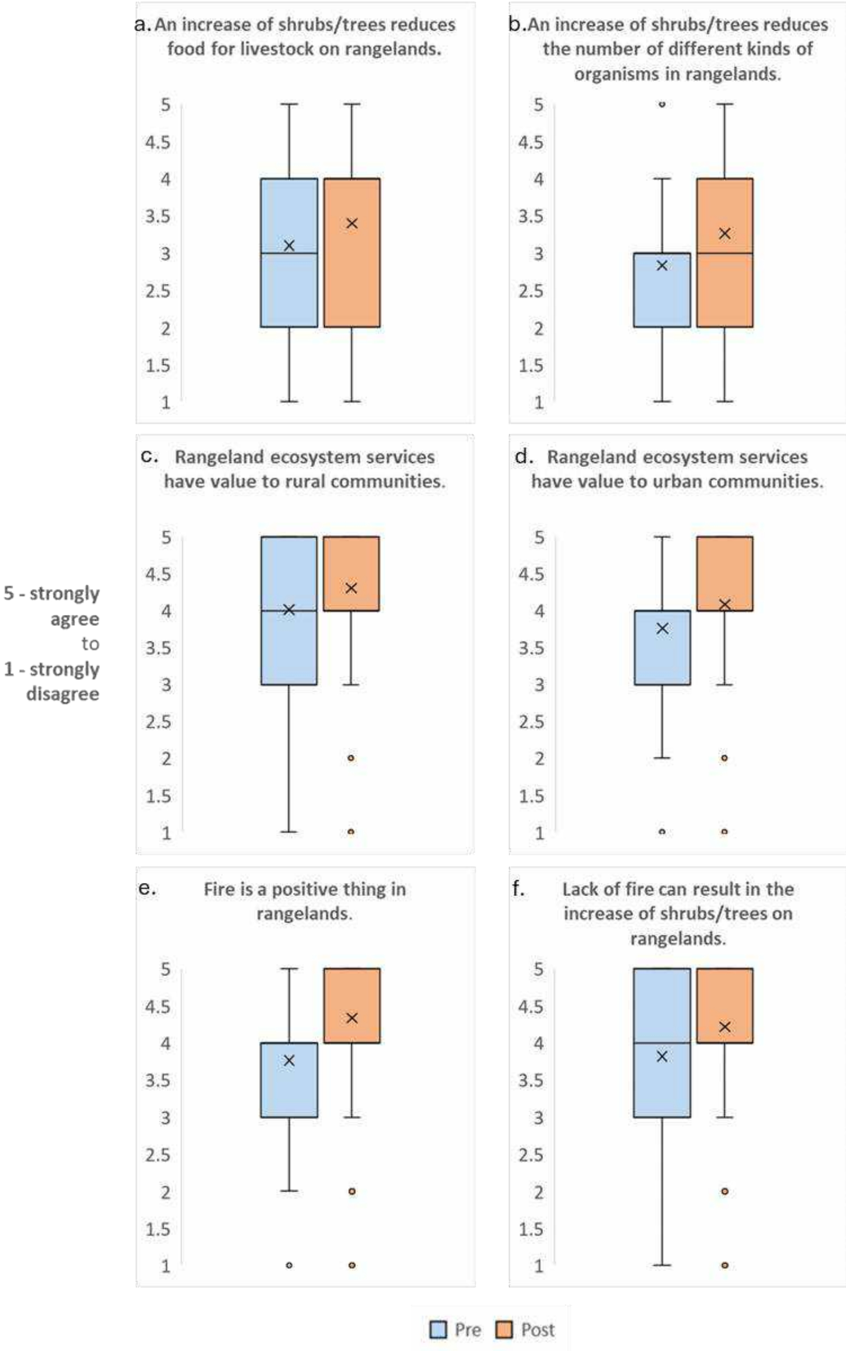

Figure 1. Pre- and post-survey results showing changes in student rangeland literacy.

Engaging peers as agents of change

The Educator Cohort participants has presented their work, often in collaboration with the Prairie Project E&E team members, in national and international conference in science and education, such as the Society for Range Management annual meetings, Ecological Society of America annual meetings, the Wildlife Society conference, National Science Teaching Association conferences, Advanced Placement Annual Conference, National Association of Biology Teachers conference, and the Lily Conference. Several of the participants have also presented, some together with their students, in regional conferences such as Nebraska Summit on Math and Science Education, Nebraska Association of Teachers of Science meeting, Oklahoma Academy of Science conference, Texas Chapter Wildlife Society meeting, Texas Society for Ecological Restoration conference.

Prairie Project E&E team members and the cohort participants have also collaborated in organizing symposium/organized sessions featuring our E&E work, including a symposium, an Ignite session, and a workshop at the SRM annual meetings, an organized session at ESA annual meeting, an organized session at the AP Annual Conference, and an educator workshop in Austin Texas.

Discussion

The Prairie Project Educator Cohorts have successfully developed agents of change who are advancing rangeland literacy and fostering support for climate-smart management practices. The educators' work has led to significant improvement in their students' rangeland literacy, and they have become effective advocates of rangeland literacy and high-impact pedagogy with their peers. By combining ecological science with innovative education strategies, the program provides a scalable model for addressing complex environmental challenges. Challenges remain, including the need to scale the program to reach more educators and students and to secure sustained funding for long-term impact. Future initiatives should prioritize policy engagement, broader dissemination of resources, and the integration of new technologies to enhance learning experiences. Continued investment in such initiatives will be critical for ensuring the sustainability of rangelands and their vital ecosystem services.

Acknowledgements

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Developing teachers and faculty to be change agents promoting the value of rangelands: impacts of the Prairie Project Educator Cohorts

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Key words: teacher; faculty; training; development; rangeland literacy

Abstract

Creating spaces and opportunities for teachers and faculty to become agents of change is central to promoting public understanding of the ecological and societal values of sustainable rangeland production and ecosystem services. One promising effort was the Prairie Project Educator Cohorts, which targeted the four domains of Clarke & Hollingsworth's (2002) Interconnected Model of Teacher Professional Growth. Housed within the overall Prairie Project (a federally funded grant collaboration between Texas A&M, Oklahoma State, and the University of Nebraska, Lincoln), the program trained educators from grades 6-16 on the threats to grasslands and effective management solutions. Participants from schools across TX, OK, and NE learned about pyric herbivory and mixed-species grazing during a summer workshop and field tour, then incorporated their new knowledge into a course of their choice during that fall or spring. A team of Extension professionals and teaching experts from the three collaborating universities led monthly online cohort meetings and were assigned to each educator as mentors. To assess the effectiveness of the Educator Cohorts, a summative qualitative evaluation was conducted. Data were collected through focus groups and individual interviews conducted over Zoom, and observations during cohort meetings. Thematic analysis was employed using an inductive approach to analyse the data. Findings revealed that the educators had significant advances in their knowledge of pyric herbivory, multi-species grazing, and the severity of the impact of woody plant encroachment. They also expressed that they were able to create powerful research-driven learning experiences for their students. Additionally, educators served as agents of change by sharing their instructional materials with their colleagues and supervisors and their new knowledge with friends and family who managed land. These data provide evidence that a comprehensive cohort program be an effective approach to professional development programming for educators that ultimately increases the rangeland literacy of their students.

Introduction

Empowering educators to be agents of change is an important way to get future generations interested and engaged in rangelands. Educators have a significant impact on their students' awareness of and orientation toward science (Keller et al. 2017). Equally, they have the ability to disseminate information horizontally to their peers within the profession (Supovitz et al. 2010). With experience and expertise, educators can be opinion leaders in their fields through sharing novel recommendations and innovative ideas (Fairman and Mackenzie 2015). Thus, creating spaces and opportunities for teachers and faculty to become agents of change is central to promoting rangelands and related best management practices. The aim of this study was to investigate the experiences of instructors who completed the Prairie Project Educator Cohorts - a two-year professional development program for K-12 teachers and higher education faculty from schools across Texas, Oklahoma, and Nebraska.

Housed within the Prairie Project (a federally funded grant collaboration between Texas A&M University, Oklahoma State University, and the University of Nebraska, Lincoln), the program trained teachers and faculty about the science of rangelands with an emphasis on the threats to the land and management solutions to overcome them. In the first year of the program, educators learned about pyric herbivory, mixed-species grazing, and high impact teaching strategies during a virtual summer workshop. The technical content was delivered by Prairie Project research scientists who the educators later got to meet in-person through a multi-state field tour.

Next, the educators incorporated their new knowledge into their curriculum via an active learning strategy of their choice. The lessons they created ranged from interrupted case studies to collecting data in the field and creating public service announcements. For support, each educator was assigned two mentors from a team of Extension professionals and teaching experts from the three collaborating universities. Further assistance was provided by the mentors through monthly online cohort meetings that included continuous education. In the second year, each educator led one monthly meeting to share about the design, implementation, and evaluation of their classroom project. Educators were required to give a similar presentation at a conference or professional setting of their choice. The educators received funding for travel and classroom supplies, and a stipend.

The conceptual framework for this study combines two existing theories and a model. The first theory is the theory of teacher change (Wayne et al. 2008), which focuses on teachers changing their knowledge or behaviour as the result of participating in specific activities. The second is the theory of instruction (Wayne et al. 2008), which promotes that teachers make changes based on increases in their knowledge. Both of these theories are leveraged in the Prairie Project Educator Cohort program. These theories align well with Clarke & Hollingsworth's (2002) Interconnected Model of Teacher Professional Growth.

Methods

This study employed a phenomenological research design, specifically existential phenomenology, to examine the perspectives of the educators who completed the Prairie Project Educator Cohort program. This qualitative research approach involved seeking detailed descriptions and interpretations from participants to understand the meaning of their lived experiences.

The sample population consisted of all the K-12 teachers and higher education faculty who completed any of three cohorts of the program (Cohort 1 2020-2022; Cohort 2 2021-2023; Cohort 3 2022-2024). Twenty six educators participated in the study (eight men and 18 women). The grade level breakdown was one middle school teacher, 12 high school teachers, and 13 faculty members. No other demographic information was captured.

Data were collected through two focus groups (one conducted in May 2022; the other in June 2024), and 16 individual semi-structured interviews completed between 2023 and 2024. Both the focus groups and interviews were conducted and recorded via Zoom and varied in length between 45 minutes and 90 minutes long. The same questions were used for the focus groups and individual interviews and included prompts such as: "how and why did you choose the instructional strategies for your lesson?", "how did your students react to the lesson?", "how have you shared your instructional materials beyond our official Prairie Project outlets?", and "in what ways did the Prairie Project contribute to your ability to serve as an agent of change?".

The focus groups and interviews were transcribed verbatim through online audio to text converters. An undergraduate student worker then listened to each recording while reading the corresponding transcript to correct any errors.

Evaluation coding (Rallis & Rossman, 2003) was used to analyse the transcripts to examine the significance of the Prairie Project Educator Cohort program. As noted by Saldaña (2016), evaluation coding can consist of multiple coding methods as the data analysis has to align with the structure of the program evaluation. Two members of the project staff were involved with coding. Independent and collaborative coding took place to create a codebook and gain confidence in the consistency of how the codebook was being applied. The codes were then organized into themes. Theme identification was an inductive, reflexive process that occurred over multiple meetings through critical discussion.

Results

Four overarching themes were identified from the dataset: educator development, educator takeaways, agent of change, and program feedback.

Educator Development

The first theme focused on changes in skills, knowledge, and attitude among the educators. Even though most of the educators were familiar with grasslands and rangelands, their specific knowledge of prescribed fire, patch burn grazing, and multispecies grazing increased through their participation in the cohort program. Two quotes captured many of the sentiments in this theme. One educator shared, "I think the biggest impact would just be more knowledge on something I thought I knew a lot about". Another said, "Good stuff. Yeah. I didn't have a lot of information on [mixed-species grazing]. That was all pretty new knowledge for me". The educators either thought they knew quite a bit about the topics and they were able to learn significantly more from us, or they learned something new and were enthusiastic about it.

The educators also expressed that their teaching (content delivery, classroom management, etc.) was impacted by their experience. One person described a "lightbulb moment" she had when a speaker said that it was important to make sure that they were not teaching to themselves and their learning preferences, and to keep their focus on being student-centred. The educator said she began to reflect on how she taught in the past and then made adjustments to make her classroom more inclusive to the different ways students learn. She claimed, "it made me a little bit more empathetic, which is a good thing to me as a teacher...it probably helps me make my classroom more inclusive".

Educator Takeaways

The second theme focused on educator gains that were not related to personal growth. Besides being equipped with new knowledge and resources, a big takeaway for the educators was the community they developed both among themselves and with the program facilitators. One educator remarked, "And so it just gives me another group of people that I've met and been able to engage with and could call colleagues, basically at some at some level. It may not be that you're engaging with them regularly. But if I were to email anybody, Oh, yeah, I'm happy to help, or, you know, like, that's the that's the general sentiment across the group yet. you know. So I think it really built another new collaborative group of people which is fantastic".

On a related note, others appreciated the respectful and encouraging environment that was created. One teacher said, "Hearing from other teachers and faculty that they were dealing with that as well was kind of nice to make me maybe not think I was the only one that was struggling with that". The monthly cohort meetings became a brave space for educators to share successes and challenges with each other.

Agent of Change

The third theme highlighted the ways educators acted as agents of change regarding rangeland science and best management practices. This included how they shared their new knowledge and the curriculum items they created with others beyond the program requirements. A faculty member shared, "I've shared the unit with…a plant taxonomist here that teaches biogeography actually. And she was really interested…I've shared some of the information in passing our Dean as a former plant taxonomist as well." Others were agents of change in their personal networks. An educator stated, "My understanding of rangeland management changed a lot during this process, and you know that was great for me from the education standpoint. But still, personally raising cattle and having some very good friends that have some pretty big operations up in the northern part of the state, you know, just being able to pass that information on to them. And when they've got questions, they can kind of lean on me a little bit more".

Program Feedback

The fourth theme encompassed reflections on the program components had a significant impact, as well as ideas for program improvement. Most of the educators expressed that they valued being able to have resources that connected students to local relevant science and something students could see within their neighbourhoods. A teacher said, "just cool to be part of something region wide...it was useful for the students. I think it helped with engagement for them to see that the topic we're talking about are really important throughout the whole Great Plains“. Another teacher shared how one of her students enthusiastically told her, "this it legit, Miss!" as he was able to understand the real-world application of what they had just learned in the classroom.

Additionally, the educators appreciated the autonomy they had to create their lessons. One person remarked, "I thought that was one of the real strengths of the program. And it wasn't really prescriptive which I think opened up creativity and allowed us to, in some cases, use some of our own strengths in that project".

The most common piece of program feedback was that the educators wished they had more opportunities to meet and collaborate in-person with each other. However, a couple of educators also noted that while they would have liked to have spent more time together in-person, that it would not have been feasible due to the demands of the academic year.

Discussion/Conclusions/Implications

These findings align with the growing body of literature that emphasizes the importance of professional development that enhances content knowledge and fosters a supportive community of practice. In the first theme underscores the importance of continuous learning in professional development programs. Additionally, the reported changes in teaching strategies highlight the program's influence on pedagogy and suggests that such programs should not only focus on content knowledge but also support educators in adopting reflective and adaptive teaching practices that enhance student engagement and learning outcomes (as proposed in the conceptual framework).

The sense of community described in the second theme is consistent with research on professional learning communities. The ability to reach out to fellow educators and facilitators for advice or support not only enhanced participants' sense of belonging, but also contributed to a culture of ongoing professional dialogue. This sense of camaraderie and mutual support may serve as a catalyst for sustaining the changes in teaching practices initiated by the program.

The third theme illustrates the broader impact of teacher training programs, where educators extend their influence beyond their classrooms and contribute to the community at large. The educators' roles as agents of change underscore the importance of equipping them with not only content knowledge but also the confidence and resources to share that knowledge with others.

One of the most notable positive aspects was the opportunity to connect students with local science, which helped make the content more tangible and engaging for learners. This finding supports the idea that placing educational content within a local context can enhance its relevance and foster greater student interest.

Overall, the findings from this study suggest that the cohort program had a profound impact on educators' professional development; educators were empowered to become agents of change. Future program improvements should focus on enhancing opportunities for in-person collaboration while maintaining the flexibility and autonomy that educators found valuable.

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Comodity production increased with mixed-species grazing and pyric herbivory

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Key words: Angora goat; cattle; patch burn grazing

Abstract

Woody plant encroachment (WPE) is a global problem to which browsing herbivory and pyric herbivory are potential sustainable solutions. This study aimed to compare the efficacy of goat browsing and prescribed fire to mitigate WPE on rangelands in different seral states. The effect of browsing and fire in a 2 x 2 factorial design was investigated on rangelands in different seral states, namely woodland, savanna, and grassland. The different seral states were created by mechanically removing woody plants on 2 ha areas to a canopy cover of about 20% (savanna), 5% (grassland), or no removal (woodland). Three 2 ha areas, one in each seral state, were planned to be burned annually, but we were only able to burn in two years and those burns were not effective. Weaned calves were planned to graze for 10 months at a light-moderate stocking rate of 16 ha/AUY. However, because of drought, the average stocking rate was 28 ha/AUY. Angora wether goats grazed for 6 months at an average stocking rate of 20 ha/AUY resulting in a 230% higher stocking rate on multispecies compared to single species grazed pastures. Calf average daily gain (ADG) was higher (P=0.04) on the single species treatment than the mixed species grazing (0.46 vs. 0.54 kg/day, respectively). Because lighter calves have higher market value the economic difference was less than the difference in ADG. Over the three-year study Angora fleece weight averaged 2.4 kg/hd. The value of fleece production on mixed-species grazed pastures was USD 31.60/ha, resulting in a total value of production of USD 61.44/ha compared to USD 32.26 USD/ha on single species grazed pastures. The increased stocking rate due to mixed species grazing on this study was greater than reported in other studies co-grazing goats and cattle.

Introduction

Before the advent of mechanized agriculture, grasslands and savannas accounted for nearly 40% of the earth's surface; today, the remaining intact grasslands and savannas cover only a little over 20%. Rangelands are hotspots of wildlife biodiversity, large repositories of soil carbon, and source areas for clean and abundant water. In addition, they support most of the world's livestock production and are critical for pastoral societies as well as advanced commercial animal production. Despite their importance, grassland biomes are imperiled worldwide. As many as half of them have been converted to croplands or altered by afforestation. The remaining grassland biomes are being degraded by other factors, including invasive species and woody plant encroachment (WPE). The proliferation of trees and shrubs on rangelands is one of the most striking land-cover changes of the last 100–200 years. Since the 1940s, the range management community has aggressively worked to reverse woody proliferation, relying heavily on mechanical and chemical brush control, with the primary goal of increasing forage production for livestock. Enormous amounts of money, effort, and time have been spent on reversing WPE, but the results have generally been short-lived. Emerging research has identified some management strategies that are extremely promising, not only for maintaining livestock production across the Great Plains but even for increasing it. Examples include pyric herbivory and mixed-species grazing. Pyric herbivory can facilitate the use of prescribed fire by eliminating the need to rest pastures before and after the burn while simultaneously enhancing forage quality and increasing heterogeneity. Mixed species grazing by adding a browsing herbivore helps control woody species and increases animal production.

The objective of this research was to investigate the effect of mixed species grazing and pyric herbivory on WPE and their effect on livestock commodity production.

Methods

The experimental design is a 2 x 2 factorial of with or without pyric herbivory and mixed species grazing with goats. These treatments were conducted on four 48 ha pastures. In addition to the WPE management treatments, woody plant thinning treatments were done before implementing these treatments (Fig. 1). Woody plants were thinned to three levels of canopy cover removal, namely: control (woodland, i.e., no bush removal); savanna (woody plant removal to approximately 20% canopy cover); and grassland (woody plant removal to approximately 5% woody plant cover). These levels of brush control correspond to an Oak/Juniper Woodland Community, Midgrass/Oak/Mixed Brush Savannah, and Historical Climax Plant Community, respectively, in the NRCS Ecological Site Description (ESD) for Low Stony Hill (Site ID: R081BY337TX) the predominant ESD on the study site. Each thinning treatment was done on eight 2 ha blocks in a stratified random manner based on the two soil types present. The thinning treatments aimed to estimate the effect of different initial stages of WPE on the effectiveness of WPE management treatments.

Weaned calves were grazed on all four pastures shortly after weaning in October at a light moderate stocking rate of about 16 ha/Animal Unit Year (AUY), where an AU = 454 kg. Calf stocking rate was kept variable to achieve about a 40% utilization of key species and to try and maintain adequate fine fuel for the prescribed fire treatments. Freshly shorn Angora wether goats browsed from October through March, ie. spring shearing. Goats were planned to be stocked to achieve about a 90% increase in stocking rate compared to cattle only pastures. Animals were weighted on and off pasture, and mohair weighed at spring shearing. Grazing years spanned two calendar years and are referred to by the year when grazing ended.

Randomly selected 2 ha polygons in each of the three woody plant thinning treatments on the two pastures in the pyric herbivory treatment were planned to be burned every year. However, because of drought conditions and lack of fine fuels prescribed fires were only conducted in January 2022 and March 2024.

Because prescribed fires for the pyric herbivory treatment were not conducted as planned and were ineffective when conducted, calf weight gains were analysed only for the effect of grazing treatment and year with analysis of variance. The value of calf weight gain was calculated using local market reports to determine the difference between the values of similar size and class of calves at weaning and their value when removed from the pasture. The value of goat production was calculated from fleece weight and the price of mohair at local markets for each year less the cost of shearing (USD 5.00/hd).

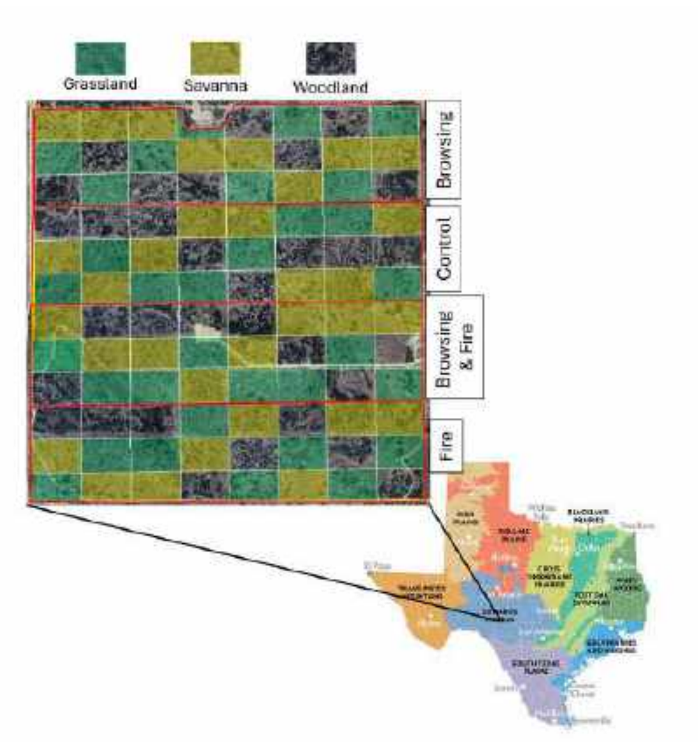

Figure 1. Study area showing 49 ha treatment pastures outlined in red and stratified and randomly distributed 2 ha areas cleared to 5% 20% or uncleared representing grassland, savanna, and woodland, respectively.

Results

During this study, precipitation was 70% of the average, and the calf stocking rate was adjusted to compensate for the deficiency in precipitation (Table 1). The adjustment in cattle stocking rate was done by removing animals sooner than planned. Cattle grazed for the planned duration in only one of the four years of the study and were not grazed in 2023 because of drought (61% of average precipitation). In contrast, goats grazed every year for the planned duration, but they were lighter than expected, resulting in a slightly lower stocking rate. Average stocking rates were over twice as high on the mix-species (12.2 ha/AUY) compared to the single species (28.5 ha/AUY) grazed pastures for the 3 years cattle grazed.

Table 1. Planned and actual stocking rates for during the study period. Years refer to the year grazing ended, and actual grazing spanned two calendar years, beginning in the fall and terminating in spring or summer.

	Planned	2021	2022	2023	2024
Precipitation (mm)	631	452	437	386	506
Calves					
Number	5	4	5	0	5
Body Wt. (kg)	328	265	320	-	320
Day on	Oct 1	Sep 23	Sep 19	-	Nov 1
No. Days on	300	189	302	-	182
ha/AUY	16	40	17	-	28
Goats					
Number	40	40	40	40	40
Body Wt. (kg)	63	43	50	50	51
Day on	Sep 15	Sep 23	Sep 30	Oct 27	Sep 14
No. Days on	182	190	181	166	179
ha/AUY	17	15	22	24	22

There were no grazing treatment x year interactions (*P*>0.21) for cattle performance metrics. As expected, the average daily gain (ADG) and gain/hd of calves in the single species grazing treatment were greater (P=0.09 and 0.04, respectively) than in the mixed species grazing treatment. The value of the weight gain on the single species treatment was also greater but not significantly. The value of the mohair produced doubled the per ha value of livestock products on the mixed species grazing treatment. The yearly differences in cattle weight gain reflected differences in precipitation.

Table 2. Effect of grazing treatment (single-species vs. mixed-species) and year on livestock production.

	Grazing Treatment			Year			
	Single	Mixed	P-value	2021	2022	2024	P-value
Average daily gain (kg)	0.54	0.46	0.09	0.45[a]	0.40[a]	0.65[b]	<0.01
Gain (kg/hd)	115	98	0.04	85	118	118	0.07
Value (USD/ha)	32.26	29.84	0.12	11.11[a]	35.24[b]	46.80[c]	<0.01
Mohair (kg)		2.4					
Value (USD/ha)		31.60					

Discussion

The two important results of this study were the small difference in cattle weight gain between mixed and single species grazed pastures, given that the stocking rate on mixed species grazed pasture was over twice as high as the single species grazed pasture, and the difficulty of conducting patch burn grazing in areas where annual precipitation is less than 650 mm. Cattle on the single species grazing treatment gained 17% more per head than cattle on the mixed species treatment. The increased stocking rate on the mixed species grazed pastures was much greater than previously reported in other studies. A general recommendation is that 2 breeding goats can be added for each cow without decreasing the stocking rate (Merkle et al. 2014). Animut (2008) calculated a theoretical increase in stocking rate of 60% by adding goats to single species cattle grazing. On an animal unit (AU) basis, those recommendations are equivalent to about 0.3 – 0.6 goat AU/cow AU; our replacement rate was 1.2 goat AU/cow AU or two - four times higher. The season of grazing was primarily responsible for the higher carrying capacity of goats in this study. Goats were grazed in the dormant season because this is the season when their potential impact on juniper encroachment is highest (Taylor 2008) and when their consumption of juniper is highest (Walker et al. 2013). Juniper is not a limiting forage on these rangelands and dormant season grazing minimizes diet overlap with cattle and thus minimizes the effect of the high stocking rate on cattle performance.

Per ha income from mohair production on the mixed species treatment was almost as much as the value of the gain on calves on the single species grazing treatment. This is a result of several factors: on an AUE basis, there were more goats than cattle and the high value of mohair that averaged about $3.80 USD/kg. Angora wether goats were used for this study because they require minimal management and are predator resistant. This makes them an easy class of livestock to incorporate into a cattle operation.

The lack of adequate fine fuel to conduct the planned prescribed burns and the fact that when the burns were conducted the continuity of fine fuel was insufficient to carry fires across the burn unit was a result of insufficient precipitation and soil disturbances caused by the mechanical removal of woody plants. Deferment for several years is recommended on rangelands in fair to poor condition to accumulate adequate fuel for an effective burn (Hanselka 2009). The inability to meet planned burning objectives indicates that patch burn grazing will be difficult to accomplish in areas with less than 650 mm of annual precipitation, unless pastures are in excellent condition.

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