Pastoralism
Research, Policy
and Practice

August 2026

The role of pastoral livestock and products in climate change

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ISSN 2041-7136
ISBN 978-2-8325-8473-6
DOI 10.3389/978-2-8325-8473-6

Livestock create greenhouse gases. But does pastoral livestock management have the same effects as more intensive management systems?

Raising livestock and consuming their products is increasingly being scrutinised as partly responsible for soaring greenhouse gas emissions and climate change. Since the landmark publication of "Livestock's Long Shadow" nearly twenty years ago (Steinfeld et al. 2006) [1] by the Food and Agriculture Organization of the United Nations, the attention of researchers, policy-makers, the media and the public has been drawn to many questions about the consequences of keeping domesticated animals. Data, research and opinions are proliferating as scientists, practitioners and advocates reach differing conclusions both about the problem and its solutions.

The stakes are important since positions taken by governments, international donor organisations and NGOs on these questions can shape support for the livestock sectors. Consumers are voting with their wallets by making choices about which livestock products to buy or avoid. The food and textile industries are responding with alternatives to livestock products, marketed as less climate damaging. These choices have consequences for livestock owners and could undermine economic opportunities for sustainable rangelands management.

This Special Issue aims to probe the debate by assessing livestock's role in climate change but differentiated according to types of livestock production systems. While there are numerous forms of livestock production, varying by environment, animal species, social relations, management methods and world regions, these can be generically grouped into two distinctive forms. The first form is intensive, characterised by greater reliance upon capital investment and technologies such as housing and fencing, which allows a denser population of animals per area and a faster animal growth reliant on high inputs such as feed and antibiotics. The second form is extensive (termed pastoralism), in which animals are predominantly grazed on open pastures with communal access, lower external inputs, and have a lower livestock population per land area.

The types of inputs and outputs of these two broadly dissimilar systems are well-studied by now. There are estimations of the impacts of each system on climate change. Evidence is accumulating that intensive livestock systems can have greater negative impacts than extensive systems for climate change. To assume that all livestock production systems have comparable harmful environmental effects for the climate may overlook beneficial effects of extensive systems.

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TYPE Special Issue Editorial
PUBLISHED 12 June 2026
DOI 10.3389/past.2026.16611

Editorial: The role of pastoral livestock and products in climate change: a complicated issue

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OPEN ACCESS

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RECEIVED 19 March 2026
REVISED 27 April 2026
ACCEPTED 29 May 2026
PUBLISHED 12 June 2026

CITATION
Marin A, Davies J, Flintan F, Kerven C and Singh R (2026) Editorial: The role of pastoral livestock and products in climate change: a complicated issue. *Pastoralism* 16:16611.
doi: 10.3389/past.2026.16611

KEYWORDS
climate change, development, emission intensity, pastoralism, tier 2

Editorial on the Special Issue
The role of pastoral livestock and products in climate change: a complicated issue

Introduction

There are a lot of livestock in the world. Different species and breeds are raised in many types of places and climates. First domesticated more than 10 thousand years ago, livestock have provided people with food, transport, clothing, artefacts and income through exchange. Certain livestock are deified and imbued with deep cultural values. Many people depend directly or indirectly on livestock, and enjoy consuming their products. Livestock transform landscapes and the ecology through their need for forage, feed and water, and just by walking. Current environmental narratives often portray livestock as a contributor to biodiversity loss and global warming, yet counter narratives highlight the role pastoral livestock systems have played in creating habitat, protecting bioidiversity and protecting carbon stocks. The studies in this Special Issue delve into questions about which kinds of impacts livestock are having on climate change, by evaluating why, how and where these impacts occur. A key variable is the degree to which livestock are managed intensively or extensively. There are context-specific positive and negative relationships to climate change depending on these management divergences. The goal is to seek which might be the best options for lowering livestock's negative impacts on the climate and promoting positive impacts.

Raising livestock and consuming their products is increasingly being scrutinized for its role in greenhouse gas emissions and, hence, climate change. Since the landmark publication of "Livestock's Long Shadow" nearly 20 years ago (Steinfeld et al., 2006) by the Food and Agriculture Organization of the United Nations (FAO), the attention of researchers, policymakers, the media and the public has been drawn to questions about the environmental consequences of rearing domesticated animals. Data, research and opinions are proliferating, and yet scientists, practitioners and advocates seem to reach differing conclusions both about the problem and its solutions.

In part, this is not surprising. FAO data for land use show that one-fourth (almost 3.2 billion ha) of the world's land area is covered by permanent meadows and pastures[1] (FAO, 2022) and that ca. 80% of all agricultural land is used for livestock as either grazing land or fodder production (FAO, 2009). Amongst the people involved in rearing some of the estimated 4.6 billion livestock (excluding poultry and pigs) (FAOStat, 2026) on all continents are several hundred million pastoral people with a variety of production systems, climates, livestock species and environments. There are evidently difficulties in discussing monolithic impacts of pastoralism on climate change. Still, academic debates and policy making often draw on uniform approaches that rely on an approximation of each livestock species' impact based on the standardized data used by the Intergovernmental Panel on Climate Change (IPCC). This can lead to misrepresentations of the complex realities of such systems.

A recent exchange between the United Nations Framework Convention on Climate Change (UNFCCC) and the Norwegian statistics authority has revealed that the reported enteric methane emissions from sheep in Norway have been overestimated by 30% in every yearly report, going back to 1990 (Aase, 2025). Similarly, a global meta-analysis of methane emissions from bovids indicates that the emissions from all yaks on the Asian Plateau may be as much as 39% lower than the standard IPCC model (Tier 2[2]) would estimate (Shi et al., 2025). This is not to say that the IPCC models and standard coefficients are wrong, or always overestimate. Despite their flexibility[3], such estimates still need to rely on difficult decisions surrounding simplifications and approximations of each livestock system.

Hayek and Miller (2021) point out that the details needed for developing reliable methane emission indicators are incredibly fine-grained and would need information on for instance how much an animal moves during a day, the seasonal cycle of weather conditions, the temperature of the animal operation facility and even whether or not a crust is allowed to develop on top of the liquid manure tanks. Because of this, measuring emissions in the atmosphere above the livestock system seems to hold potential for better estimates, and at least one study (ibid) shows that for highly intensive systems, methane emissions may actually be as much as 90% higher than IPCC calculations would suggest. Importantly, this discrepancy also indicates that we need to be cautious of the hypothesis that intensifying livestock systems would in fact lead to a reduction of greenhouse gases emissions, especially in developing countries (ibid) and that even with ambitious and costly technological improvements, the effect may be as little as less than a quarter of the emissions in the business-as-usual scenario (Höglund-Isaksson et al., 2020, cited in Hayek and Miller, 2021). And this is before we even start discussing any other social and environmental costs and benefits connected to such uncertain transformations.

Another important concern is around the data bias; as noted by Scoones (2023), most of the data used in the greenhouse emission assessments is gleaned from intensive livestock systems from the global North, while the narratives about GHG emissions from livestock continue to influence policies towards the extensive systems of pastoralists of the global South.

There are high stakes in understanding emissions, and more generally the relationship between livestock production and climate change, since positions taken by governments, international donor organizations and NGOs on these questions can influence support for the livestock sectors, e.g., through the Breakthrough Agenda (Mukherji et al., 2024). Consumers are also increasingly interested in where their food comes from and its impact on the environment, and they make choices about which foods to buy or avoid. Official dietary guidelines, although very different across continents, are in some cases promoting a major reduction in livestock products—especially meat—for "planetary health" (EAT, 2025), and at the same time draw criticism, more recently manifested as legislative initiatives banning the use of meat-related product names such as "hamburgers" and "sausages" for plant-based alternatives (BBC, 2025).The textile industries are also responding with alternatives to livestock products, marketed as less climate damaging. Consumer and policy choices thus reflect the interest in the topic and are likely to have consequences for livestock owners and sustainable rangeland management the world over. The choices are nevertheless based on a limited understanding of the complex relation between pastoralist systems and climate change, one that seldom accounts for local specificieties and indirect effects of pastoralism on climate, through mechanisms such as carbon sequestration (Ali et al., 2016; Assouma et al., 2019), biodiversity preservation (Briske et al., 2026) and albedo maintenance (Beer et al., 2020; Kristensen et al., 2024).

What this Special Issue shows

This Special Issue aims to probe the debate by exploring the roles livestock play in climate change, but especially differentiated according to two distinct types of livestock production system–intensive and extensive. While there are numerous forms of livestock production, varying by environment, animal species, social relations, management methods and world regions, these can be generically grouped into these two forms. The first form is intensive, characterised by greater reliance upon capital investment, technologies such as housing and fencing, and supplementary feed, which allows a denser population of animals per area and a faster animal growth resulting from high inputs such as concentrated feed and antibiotics. The second form is extensive (termed pastoralism), in which animals are predominantly grazed on open pastures, often with mobile herding and communal land use, and characterised by lower external inputs, a higher ratio of

1 In Europe 1/3 of agricultural land, in Latin America, Africa and Asia 3/4 (FAO, 2022).

2 A tier represents a level of methodological complexity for estimating greenhouse gas emissions. Tier 1 is the basic method and relies on global default values, Tier 2 is intermediate and relies on localized emission factors at national or regional level, while Tier 3 is the most complexand detailed, relying on modelling and facility-level measurement. Tiers 2 and 3 are sometimes referred to as higher tier methods and are generally considered to be more accurate (IPCC, 2019).

3 The estimates rely to a large extent on the parameter Y_m which measures how much of the feed energy is converted to methane and is estimated to vary greatly with several feed and animal factors, for instance between 1% and 6.5% for grazing cattle and mature sheep (IPCC, 2006, 10.30).

labour and a lower livestock population per land area, compared to intensive management.

The types of inputs and outputs of these two broadly dissimilar systems are well-studied by now. There are estimates of the impacts of each system on climate change. Evidence is accumulating that intensive livestock systems can have greater negative impacts than extensive systems for climate change, while extensive systems can play a substantial role in safeguarding climate regulating (and other) ecosystem services. To assume that all livestock production systems have comparable harmful environmental effects on the climate may overlook the beneficial effects of extensive systems like pastoralism.

However, the evidence also indicates opportunities to improve production efficiencies in the pastoral livestock sector. Corrêa et al., this Issue find that a degree of intensification of extensive livestock production can generate greater food output per unit of energy consumed and GHG emitted, but some of these efficiencies may be lost when livestock systems transform to being fully intensive. This reflects both a loss of some of the environmental benefits of extensive grazing systems, and a tipping point beyond which intensification leads to energy-hungry, mechanised and presumably lower labour-intense production.

The Special Issue seeks to disentangle the relations between livestock and climate change by examining the evidence. True to the ethos of *Pastoralism-research, policy and practice,* we have encouraged contributions from academics and practitioners, with the assumption that good ideas and insights often emerge at the interface between the generalizable and the particular, lived experiences.

The contributions have both confirmed existing knowledge and surprised us, the editors. On the one hand, this collection shows in detail and with empirical evidence what has emerged as a counter-narrative to the wholesale demonization of livestock keeping: *"it's not the cow, is the how!"*. In other words, if we look at the impact of livestock keeping in any other way than the most reductionist counting of GHG molecules, there are huge differences between systems, livestock species and age groups, etc. The following synopses of 7 country case studies from Brazil, India, Kenya, Mongolia (2), Tanzania and Turkey, as well as 4 general reviews, demonstrate this variability.

Mwilawa et al., this Issue compare traditional pastoral systems (grazing) with feedlot systems in Tanzania, showing how supplementary feeding of concentrate improves cattle performance, thus raising the feed conversion ratio and lowering the emission intensity of methane, meaning less methane is produced per unit of product due to weight gain. The study also noted breed Special Issue, with Boran cattle producing more enteric methane than Tanzanian Short Horn Zebu, likely due to differences in dry matter intake associated with their body size. Despite being younger, Boran cattle's higher frame size correlated with greater feed intake, and therefore higher emissions. However, the article also recognises that such comparisons do not take into account other environmental benefits of more extensive livestock systems, including how pastoral systems can also significantly contribute to the provision of ecosystem services, which can increase with good management.

The article by Franca et al., this Issue goes further and points out the limitations in approaches that look at the impact of livestock systems on climate change in isolation from all the other interactions within pastoralist systems. Based on a large 6-year comparative investigation of pastoral systems across Africa, Asia and Europe, they conclude that even the more detailed Life Cycle Assessment (LCA) approach falls short of accounting for the real, complex interactions between livestock systems and the environment. To begin with, emissions need to be accounted for in a broader ecosystem context; secondly, the impact must also account for the carbon sequestration that these systems facilitate and their impacts on biodiversity. Importantly, they point out, pastoral systems and their impact on the environment (including climate change) can only be understood if we take into account other elements that characterize these systems: land occupancy, patterns of resource use, but, equally important, also their contribution to social and nutritional aspects.

The paper on impacts of cattle farming practices on energy balances and greenhouse gas emissions in different livestock systems of Amazonia, Brazil (Corrêa et al., this Issue), examines greenhouse gas emissions and energy use in relation to the sustainable development of livestock systems. These livestock systems can be characterized as livestock grazing ranches of varying sizes. The region supports a diversity of livestock systems, including dairy and beef fattening units with different degrees of intensification and social and economic inclusion.

In terms of energy efficiency among the Amazonian cattle farms, moderately intensified farms have similar energy consumption per hectare to extensive farms but achieve 55% higher meat production. Intensive farms achieve dramatically higher yields per hectare (9 times higher than in extensive systems), but energy consumption per hectare is 14 times higher, primarily due to increased use of fertilization and supplemental feed. Extensive and moderately intensified farms have similar GHG emissions per hectare, while intensive farms emit 7 times more GHG per hectare than extensive farms, with methane accounting for the bulk of emissions. However, intensive farms have 55% lower emissions per ton of meat than extensive farms (Corrêa et al., this Issue).

The paper underscores that eco-efficiency can be increased through moderate intensification, but the efficiency gains may be reversed through further intensification. This finding may be relevant in other contexts and to understanding the need for distinct development goals, policies and trajectories between intensive and extensive livestock systems.Recommended practices – many already used by pastoralists - that can capture eco-efficiencies include rotational grazing, improved management of stocking rates, maintaining soil fertility, restoration of pastures, and forage management.

The case study in Kenya by Gurmu et al., this Issue highlights the challenges of measuring methane emissions from pastoral systems. Using animal activity data across different seasons (reflecting usual system climate variability), mean Tier 2 annual emission factors were calculated for different cattle age categories. The results revealed significant differences across the locations based on breeds, herd composition, live weight, weight gains, milk yield and digestible energy, all of which influenced methane emissions. The findings stress how using Tier 1 assumptions on pasture-based cattle emissions that do not account for such variability risks miscalculating pastoral systems' emissions.

Similarly, the contribution by Lkhamaachin et al., this Issue also shows the need for more precision in analysing emissions across the very extensive pastoralist systems of Mongolia. In an effort to produce relevant country-specific Tier 2[4] calculations of methane emissions from sheep, they compare emissions differentiated by the sex and age of sheep and by season across three agro-ecological zones (desert-steppe, steppe, and forest-steppe). Unlike standard estimates based on the IPCC universal indices mentioned above, this research relies on measurements of sheep's seasonal weight change, pasture quality and energy expenditure with migration, an essential activity for pastoralist systems which is often not calculated in standard analyses (Lkhamaachin et al., this Issue).

Some of their findings are predictable (females have consistently higher emissions than males, and older have higher emissions than the young), but there are also interesting surprises. Young adult sheep (1–2 years old) emitted up to 20% less than adult sheep and lower than the standard IPCC value, while for mature sheep (older than 3 years) and lambs (younger than 1 year) these values exceeded the IPCC standard. Moreover, Mongolian sheep seem to use more of the energy intake to transform into methane energy, presumably due to the combined effects of harsh climatic conditions, extensive mobility, and the relatively low digestibility of the steppe forage. One of the take-home messages from this contribution is that the application of standard default values for GHG emissions may be misleading due to the influence of forage quality, seasonal energy dynamics and physiological status of the animals. For the Mongolian system, the authors propose, this acknowledgement would mean that instead of standard solutions like reducing numbers of livestock or intensification, one should implement management decisions targeted particularly to ewes during pregnancy and lactation (Lkhamaachin et al., this Issue).

The theme of how best to assess the impact and what management options are optimally suited is also picked up by the contribution from Franca et al., this Issue; they insist on the need to challenge the sometimes simplistic and misleading policy messages without falling into the temptation of advocacy. Instead, they propose a very insightful exploration of how Life Cycle Assessment (LCA) methodology of GHG emission can be extended to include patterns of spatial heterogeneity and temporal variability in emissions, as well as environmental impacts (e.g., carbon sequestration, biodiversity) and social (e.g., nutritional security, health) impacts. Such approaches would expand the LCA to better methodologies such as Environmental LCA, Life Cycle Costs or Social Life Cycle Assessment.

Such flexible and system-wide approaches would be better suited also when analysing the complexities illustrated by the article "Contributions of goats to climate change: how and where" (Kerven, this Issue). Although pastoralist systems depend on a variety of livestock species, goats typically received particularly 'bad press' in recent decades for their perceived environmental impact. This is why the review presented by this contribution is particularly timely and useful. It is timely in part because it underlines the importance goats have in many environmentally challenging and socially marginalized pastoralist systems across continents.

A compounding factor in the contribution of goats to climate change is, of course, the contribution of some breeds to the global market for cashmere fibre, associated with luxury garments. As the article clearly shows, though, one of the more important features of the goat-based pastoral systems is that they play an important role in building up livelihoods in very difficult socio-environmental contexts. Importantly, this overview shows that because goats have a high feed conversion efficiency, they emit less entheric methane than all other domestic ruminants, while these pastoralist systems raising goats are also just as varied. In consequence, any discussion of the role of goats in climate change needs to be based on specific evidence and with a broad field of vision that includes a variety of environmental and social impacts they may play (Kerven, this Issue).

Such a broad approach is taken by the article "Goat transhumance in Mediterranean Turkey: characterization and key factors driving its transformation" (Ocak Yetişgin and Canan, this Issue), which describes how transhumant goat production is influenced by policy frameworks, market integration, ecological shifts, and socio-political dynamics. The paper analyses the Sarıkeçililer community in southern Turkey, who annually migrate 400–450 km between coastal highlands and upland pastures, encompassing both Mediterranean and continental mountain climates. The long-distance transhumance is embedded in the community's culture and tradition, which continues to prioritize household-level subsistence and informal local exchange networks. This creates a partial detachment from structured markets, rendering pastoralism more vulnerable to marginalization. On the other hand, market engagement has influenced flock composition and grazing patterns, as many farmers have adopted higher-yielding breeds that are more dependent on intensive feeding and management.

Climate change is exerting a significant impact on pastoralists in Turkey, through reduction in the quality, quantity and timing of forage and through direct physiological impacts of increased temperatures (Ocak Yetişgin and Canan, this Issue). Climate disruptions have restricted access to pasture and compromised herd health, while increasing labour demands and management uncertainty. Looking ahead, the paper concludes that pastoralism needs to be recognised as a cornerstone of sustainable agriculture, not as a relic of the past. Transhumance can continue to operate as a model of environmental stewardship in the twenty-first century by embedding low-carbon practices, circular resource use, and adaptive governance into pastoral systems. This will require transhumant systems to be integrated into regional land-use planning for both social equity and environmental sustainability, and for pastoralists to be granted better access to veterinary, financial, and market services. The future of transhumance in Turkey is uncertain without deliberate institutional support.

Ngongolo and Gayo, this Issue review the evidence over the last two decades of climate change effects on small holder livestock-keepers in sub-Saharan Africa, including pastoralists, whose livestock production is relatively more vulnerable to climate changes of more erratic or extreme precipitation and temperatures which alter forage availability and livestock disease transmission. In considering efforts to mitigate the negative effects

4 The article uses a combination of global default values (Tier 1) and locally modelled and measured data (Tier 2) on live weight, energy expenditure and forage energy content.

of climate change on small holders' livestock production, the authors point out that studies often overlook the triple-bottom line of social, economic, and environmental aspects in mitigation efforts. While strategies combining carbon sequestration and reduction of GHG emissions offer optimal mitigation, attention should shift towards holistic, multi-faceted approaches which take into account the broader purposes of livestock systems, especially to small holders such as many pastoralists–such as nutrition, social capital, savings and investment. The paper concludes that promotion of agroforestry, rotational grazing (mobility) and soil conservation techniques can not only mitigate impacts of climate change on livestock production, but also reduce the impacts of livestock on greenhouse gases associated with climate change.

The study from the Indian Himalayan region of Jammu and Kashmir by Banka et al., this Issue argues that the traditional rotational grazing by the Chopan community in Trahan pasture remains well within ecological limits, helps to maintain soil fertility and contributes to regional food security, especially in the context of a decline in agricultural land and growing protein deficit. However, despite these benefits to rangelands, the community continue to face structural marginalization, which includes exclusion from land rights and policy frameworks.

Davies et al., this Issue examine the potential role of pastoral lands for opportunities and risks of green transition projects, such as renewable energy and carbon sequestration. The authors map the global photovoltaic and wind energy potential which shows the high potential that lies within the rangelands used by pastoralists. This finding explains the growing demand for pastoralists' land from carbon offsetting and renewable energy actors. The demand for pastoral land is forecast to grow due both to the rising demand for renewable energy and the widespread perception that pastoralist lands are underused and unclaimed. Such a persistent and erroneous rangeland narrative has caused land use change and land alienation on many occasions.

Davies et al., this Issue however provide examples of green transition projects in rangelands that demonstrate both harmful and beneficial outcomes for pastoralists. They argue that equitable green transition projects have been implemented in rangelands in a few countries (e.g., Kenya, Mongolia), based on securing local communities' consent and compensating them in various ways for the use of their land (in the case of renewable energy) or involving them meaningfully in rangeland rehabilitation (in the case of carbon offsets). These examples raise the possibility that green transition projects could make a significant contribution to pastoralist livelihoods, for example by helping secure pastoralist land rights and strengthen their livelihoods. However, to promote a just green transition, they argue, stronger safeguards are urgently needed, combined with raising awareness among investors of pastoralists' rights, and development of more significant benefits for pastoralists.

The paper by Imoli, this Issue, an ethnographic study conducted in Selenge province of northern Mongolia, provides several distinct and vital contributions to the SI. Imoli critiques the 'detached' and 'abstract' concept of climate change used by institutions, which fails to capture the local manifestations and the existential gravity of the crisis experienced by the pastoralists. Imoli argues that the climate crisis is not just an ecological phenomenon but is deeply entangled with the socio-political transformations of the post-socialist transition, including the retreat of the state, livestock privatization and the emergence of severe economic precarity.

Imoli points out the irony inherent in the current rangeland management models dealing with climate solutions, where the pastoralists participate in biodiversity compensation projects funded by mining companies – the same industries competing for their land and contributing to degradation. This process emphasizes how a pastoral system, which was previously integrated with the management of land, labour and livestock through both formal state and informal customary practice, after the collapse of socialism in the 1990s, got uprooted from its social and ecological foundations. This led to an institutional void that left the pastoralists to navigate a volatile free market and changing climate with bare minimum institutional support. The study reveals how climate interventions often fail because they are disconnected from the pastoral institutions and social networks that effectively work alongside the formal state to maintain the rangeland ecosystem integrity (Imoli, this Issue).

Several of the authors of this Special Issue recommend policy reform. In particular, they advocate for policies developed through community participation and respect for culturally embedded knowledge systems, with context-specific economic and climate support mechanisms which recognize pastoralism as a viable model for environmental resilience and adaptability. In the absence of such support, centuries-old pastoral systems will continue to decline, resulting in irreversible losses to both cultural heritage and ecological integrity (Ocak Yetişgin and Canan; Banka et al.). As highlighted by Imoli, this Issue the global efforts to tackle climate change and conservation issues (which are equally embedded in pastoral systems) must move beyond the technocratic model to account for the complex social networks and felt sense of political abandonment that define the realities of contemporary pastoral lives.

What is left unanswered, and the way forward

Our initial intention with the SI was to, at a minimum, open some knowledge areas for debate. We sought to expand the concentration of research beyond the usual confines of adaptation to climate change by shifting the question to what is the active role of pastoralism in climate change— both positive or negative. Our 'working hypothesis' has been that a nuanced context-specific understanding of pastoralist systems may open up new ways to reduce or mitigate the negative impacts where possible. Pastoralism and pastoralists could play a future role in climate change mitigation. This is a relatively less developed field of research.

Pastoralism and its impact on the environment have always been a contested field of study. This goes back to ideas about Bedouin pastoralists' environmental damage in the 14th century (Duffy, 2019). Today, this debate is significantly geared towards GHG emissions, but as this collection aptly illustrates, the debate often relies too much on simplistic assumptions and estimates, and not enough on empirical data. The work of contextualizing, recalibrating and testing general ideas needs to continue. The goal, we propose, should not be to find common metrics, but rather to understand complexities and particularities specific to individual pastoral systems. As this collection suggests, pastoralist systems and their impact on climate change can vary substantially. If policy frameworks are to ensure environmental sustainability, they need to be based on reliable accounts of emissions and on understanding the complex interactions that pastoral livestock systems have with their environments. The papers in the SI indicate that efforts are underway to understand these relationships better and that some equitable solutions for sustainable pastoralist development may be within reach.

The SI emphasizesthe need to differentiate between development pathways for extensive and intensive livestock systems rather than treating these as points along a development continuum (Mwilawa et al. this Issue). Referring to the development of extensive systems as a process of 'intensification' can be misleading, and the development objectives of extensive systems need more clarity. This includes clarifying the full range of outputs from extensive systems, such as the contribution to biodiversity conservation and climate change mitigation, and how these values may be traded off against increased livestock yields. As also concluded in the study by Banka et al., this Issue "applying these metrics to extensive pastoral systems, which are context-specific and low-input, often leads to a mischaracterization of their environmental impact".

The article by Corrêa et al., this Issue on Brazilian livestock systems shows that low efficiencies in extensive systems are attributed to the use of dual-purpose breeds that have low milk yields, although the paper is unclear on the eco-efficiency of combining meat and dairy production on the same land area. Improvements in livestock production efficiency that are compatible with extensive production systems can provide economic benefits to producers as well as climate benefits. Further research into the combined values and efficiencies of producing multiple products would be of greater value to pastoralist systems in other parts of the world. This type of research would benefit from considering the biodiversity impacts of different farming systems, including the value of grassland biodiversity and the risks resulting from grassland intensification through monocultures and soil amendments. The impact of grazing practices on biodiversity and ecosystem functions may have both intrinsic and instrumental values that deserve closer examination in future studies.

The solution proposed by Franca et al., this Issue is also worth reiterating: rather than looking at critiques of standard emission measurements as revamped 'advocacy work', there is much to be gained by looking at alternative, improved methods for measuring the impacts of livestock systems on climate. Therefore, future studies can gain both precision and relevance if their calculations incorporate more fine-grained measurements that rely on local seasonal data and that include additional metrics, such as Environmental LCA, Life Cycle Costs or Social Life Cycle Assessment. As illustrated by several contributions to this SI, this work has already begun. Combatting the climate crisis is not just about the data metrics and reducing livestock numbers, but unpacking the management systems across geographic scales, and also about protecting the mobility and land rights of those who maintain the rangelands. However, the next steps would be to recognize that pastoralists and scientists inhabit different but equally vivid worlds, and policies must bridge these world views to be fair and effective.

Notwithstanding common misconceptions, pastoralist systems are neither isolated from the larger society nor uniform, and are both affected by and contributing to climate change and its mitigation in various ways. Portrayed as a potential solution to combatting climate change - the green transition is not a parallel project to sustainable development, but is a catchphrase that is intended to encompass development practices as a whole. Rather than debate whether or not pastoralism can benefit from the green transition, pastoralists may be better served by recognising that a green transition is underway and that a just, equitable, transition could contribute to many pastoralist development goals. To do so, however, the transition must be pursued based on a full understanding of the value of rangelands and their ecosystem services, and of how investments (such as in renewable energy projects) can contribute to securing pastoralist land and enabling their land management. Recognising the complexity of pastoral land use on the ground can help foster complementarity between energy generation and livestock production on rangelands.

The International Year for Rangelands and Pastoralism (IYRP) in 2026 can be an opportune turning point in achieving more detailed attention, renewed research interest and policy dialogue on the role of pastoralism in climate change. This global initiative, which unites more than 420 organizations, aims to dispel myths about pastoralism, strengthen global policy frameworks, and ensure that rangelands and pastoralists are fully integral to sustainable development (Niamir-Fuller, 2026). This means recognising the complexity and diversity of pastoralist systems' contribution to climate change, as illustrated in this collection. Nuanced understanding is indispensable to advancing just policy pathways for rangelands and distinctive livestock production systems.

Author contributions

AM, CK and JD designed the manuscript, all authors contributed to writing, summarizing individual contributions and editing drafts. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Aase, B. B. (2025). Norway has reported too high emissions from sheep: 30 per cent cut [in Norwegian]. *Nationen*, 2025.

Ali, S., Kuhn, M. J., and Fikre, T. Z. (2016). The role of pastoralism in regulating ecosystem services. *Revue Sci. Tech. de l'OIE* 35 (2), 435–444. doi:10.20506/rst.35.2.2534

Assouma, M. H., Lecomte, P., Corniaux, C., Hiernaux, P., Ickowicz, A., and Vayssières, J. (2019). Pastoral landscapes in the Sahel: a carbon balance with unexpected potential for climate change mitigation. *Perspect. Engl. Ed.* 52, 1–4. doi:10.19182/agritrop/00083

BBC (2025). *No More Veggie Burgers? EU Parliament Votes to Ban Meat Names for Plant-based Foods*. EU parliament votes ban meat names plant-based foods

Beer, C., Zimov, N., Olofsson, J., Porada, P., and Zimov, S. (2020). Protection of permafrost soils from thawing by increasing herbivore density. *Sci. Rep.* 10, 4170. doi:10.1038/s41598-020-60938-y

Briske, D. D., Cromsigt, P. G. M., Davies, J., Fernández-Giménez, M. E., Luizza, M. W., Manzano, P., et al. (2026). Pastoralism can mitigate biodiversity loss on global rangelands. *BioScience* 76 (1), 78–89. doi:10.1093/biosci/biaf158

Duffy, A. (2019). *Nomad's Land: Pastoralism and French Environmental Policy in the Nineteenth-Century Mediterranean World*. Lincoln: University of Nebraska Press.

EAT (2025). *The EAT-lancet commission on healthy, sustainable, and just food systems*. The EAT-lancet commission on healthy, sustainable, and just food systems

FAO (2009). *The state of food and agriculture. Livestock in the balance*. Rome. The state of food and agriculture, 1–180.

FAO (2022). "Land use statistics and indicators," in *Global, Regional and Country Trends – 2000–2020*. Rome. doi:10.4060/cc0963en

FAOStat (2026). *FAOSTAT Data Releases*. Rome: Food and Agriculture Organization of the United Nations.

Höglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P., and Schöpp, W. (2020). Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe—results from the GAINS model. *Environ. Res. Commun.* 2 (2), 025004. doi:10.1088/2515-7620/ab7457

Hayek, M. N., and Miller, S. M. (2021). Underestimates of methane from intensively raised animals could undermine goals of sustainable development. *Environ. Res. Lett.* 16, 063006. doi:10.1088/1748-9326/ac02ef

IPCC (2006). IPCC guidelines for national greenhouse gas inventories. *Chapter 10 Emiss. Livest. Manure Manag.* 12–87. Available online at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf (Accessed January 4, 2026).

IPCC (2019). *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Available online at: https://www.ipcc.ch/site/assets/uploads/2019/12/19R_V0_01_Overview.pdf (Accessed January 4, 2026).

Kristensen, J. Å., Barbero-Palacios, L., Barrio, I. C., Jacobsen, I. B. D., Kerby, J. T., López-Blanco, E., et al. (2024). Tree planting is no climate solution at northern high latitudes. *Nat. Geosci.* 17, 1087–1092. doi:10.1038/s41561-024-01573-4

Mukherji, A., Marchall, S., Arango, J., Costa Jr, C., Flintan, F., Hebebrand, C., et al. (2024). *Breakthrough agenda report: agriculture*. Montpellier: Cgiar. Available online at: https://hdl.handle.net/10568/152247 (Accessed January 4, 2026).

Niamir-Fuller, M. (2026). Welcome to the international year of rangelands and pastoralists – 2026. Available online at: https://iyrp.info/sites/default/files/2026-03/Felix-Dodds-Guest-blog-by-Maryam-Niamir.docx (Accessed January 4, 2026).

Scoones, I. (2023). Livestock, methane, and climate change: the politics of global assessments. *Wiley Interdiscip. Rev. Clim. Change* 14 (1), e790. doi:10.1002/wcc.790

Shi, F., Ma, Z., Mi, J., Yang, X., Jing, X., Yang, X., et al. (2025). Methane emissions from indigenous nitrogen-efficient bovidae are overestimated. *Commun. Earth and Environ.* 6, 786. doi:10.1038/s43247-025-02755-7

Steinfeld, H., Gerber, P., and Wassenaar, T. (2006). *Livestock's Long Shadow: Environmental Issues and Options*. Rome: FAO.

Pastoralism
Research, Policy and Practice

TYPE Review
PUBLISHED 09 December 2024
DOI 10.3389/past.2024.13988

OPEN ACCESS

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RECEIVED 26 October 2024
ACCEPTED 25 November 2024
PUBLISHED 09 December 2024

CITATION
Kerven C (2024) Contribution of goats to climate change: how and where? *Pastor. Res. Policy Pract.* 14:13988.
doi: 10.3389/past.2024.13988

Contribution of goats to climate change: how and where?

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This review examines the contribution of domestic goats (*Capra hircus*) to climate change, particularly through greenhouse gas (GHG) emissions. The review seeks to outline the global numerical importance and physical characteristics of domestic goats; Compare goats with other main livestock species in terms of their climate impacts; Assess the types of environments and farmers most likely to raise goats; Investigate the climate change impacts of raising goats, focusing on variables such as feed sources, management systems (intensive vs. extensive), and methodologies used to measure these impacts. The conclusion is that the negative reputation of goats needs to be re-evaluated, given their importance to poorer farm families and the potential overstatement or misunderstanding of their climate impact. Goats are the third most common ungulate livestock globally, with an estimated population of 1.1 billion. They are particularly suited to harsh environments due to their physiological advantages, such as efficient utilization of fibrous woody material and resilience to extreme climates. Goats are crucial for poorer farmers, especially in lower and middle-income countries in Africa and Asia. They provide milk, meat, and other products, are readily sold and have low labour requirements, making them ideal for families with limited resources. Goats emit less methane per unit body weight compared to other ruminants like cattle and sheep. However, the extent of their greenhouse gas (GHG) emissions varies significantly based on their diet, management system (extensive vs. intensive), and environmental conditions. Extensive systems, where goats forage on natural pastures, may result in low GHG emissions per unit of land area due to carbon sequestration and minimal reliance on high-energy feed. Intensive systems, which use more cultivated energy feed, produce lower methane emissions per unit of product but incur carbon costs arising from feed production. In sum, this review suggests that the negative reputation of goats regarding climate change may be overstated or misunderstood. More research is needed to accurately measure the GHG impacts of goats, considering factors like feed quality, management practices, and carbon sequestration.

KEYWORDS
methane, low income countries, pastoralism, ruminants, green house gases

Introduction

Raising livestock and consuming their products has negative effects for climate change through greenhouse gas (GHG) emissions (Thornton, 2010; Gerber et al., 2013; FAO, 2024). It is safe to say this statement is generally accepted in the scientific community. Policymakers, popular media and activists likewise contend that livestock are having particularly damaging impacts on the environment, especially climate change. Aside from these generalizations, however, little agreement exists on questions of how livestock contribute to climate change, where the problems are most acute, which livestock species are most responsible and under what types of management systems. Here we propose to look at some of these issues.

This review aims to examine the contribution to climate change of one globally significant livestock species – the domestic goat, *Capra hircus*. We begin by outlining the global numerical importance of domestic goats, and identifying the physical characterises which make goats especially suitable for certain environments. Goats are ungulate ruminants - hooved animals whose diets consist of wild or cultivated plants. There are important physiological differences with the other main ruminant livestock species kept. Goats are most likely to be raised in certain types of countries. Some kinds of farmers – mainly poorer families - tend to prefer raising goats in view of the growing global consumption and commercial interest in goat products. Having summarised the global scale of goats in farming, the review examines the climate change GHG impacts of raising goats. Available research data indicates here are several critical variables, beginning with the extent to which roughage constitutes the main source in goats' feed supplies; this is the most consistent variable in explaining livestock GHG emissions when comparing goats with the other main ruminant species. The second critical variable is the extent to which intensive versus extensive goat management affects GHG emissions. The review finally considers the methodologies used to measure the climate change impacts of livestock, including goats. Research is uneven or inconclusive on some of these topics. Nevertheless, there is clear evidence on some of the issues, while other questions remain to be further researched. The review concludes that the negative reputation of goats in some quarters needs to be re-evaluated, as goats make an important contribution to poorer farm families in some of the world's most challenging places, while the climate change impact of goats is either overstated or misunderstood in many instances.

One of the very first animal species to be domesticated by humans some 10,000 years ago (Amills et al., 2017; Hermes et al., 2020), goats of many breeds and usefulness to people are now raised all over the world (Lu, 2023). The number of goats in the world is estimated at 1.1 billion and they are the third most common ungulate livestock after cattle (1.6 billion) and sheep (1.3 billion) (FAOStats, 2024). See Figure 1.

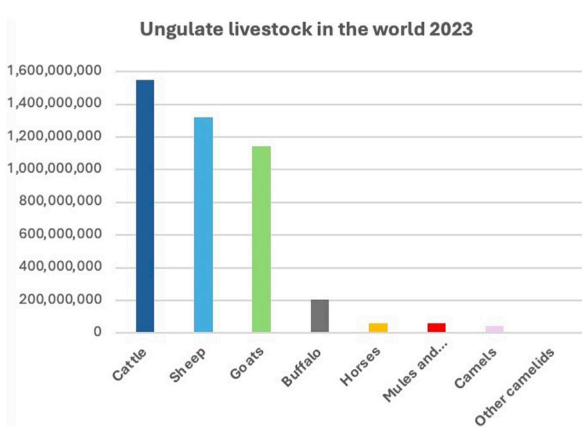

FIGURE 1
Ungulate livestock in the world 2023. Source: FAOstats 2024.

Characteristics of goats compared to other ruminant livestock

Different species of livestock have varied characteristics in relation to their diets. Consequently their usefulness to people and their impacts on the environment and climate is variable. Among livestock, the ruminant group – mainly cattle, sheep and goats - have a unique digestive system, having evolved a specialised stomach which extracts nutrients from plant foods by fermentation, before digestion – hence the process of rumination. Ruminant livestock contribute significantly to the human food chain as they can utilise plant substances such cellulose and other fibrous material in grass and fibrous crop residues which are non-digestible by humans; this material is then converted into meat and milk for human consumption (Silanikove, 2000; Soren et al., 2015). There is a net protein gain for people when calculating the input-output protein balance of ruminant feed intake and ruminant production of food for humans (Mottet et al., 2017). "Typically, ruminant grazing systems consume 0.2 kg human-edible feed protein per kilogram of protein product (0.6 kg kg^{-1} across all ruminant systems)" (Rivero et al., 2021: 2). Cultivation of food crops results in large quantities of crop residues which cannot be eaten by people but can be processed effectively through ruminant guts and subsequently transformed into human food – meat and milk - with a high protein content.

Compared to the world's other main ruminant livestock of cattle and sheep, goats have physiological advantages which determine what they eat, how they eat, where we find them, the nature of their productivity and hence how they are useful, and lastly, the likelihood of potentially damaging impacts on climate.

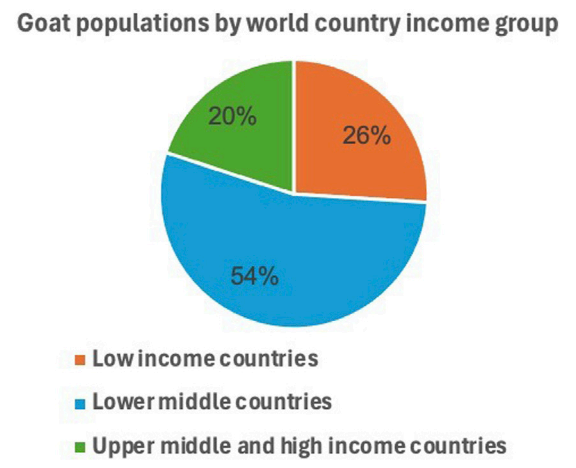

FIGURE 2
Goat populations by world country income group. Source: World Bank 2022, based on gross national income (GNI) *per capita* data in U.S. dollars And FAOStats 2024.

Researchers note that the physiological advantages of goats, for example the anatomy of their upper lips, means they are catholic but selective feeders on mixed herbaceous and woody vegetation. They are efficient in selecting plants and plant parts higher in protein and energy compared to those selected by cows and sheep, but still able to subsist on high fibre diets. Goats also conserve moisture in their gut, minimize water loss, and still produce kids and a relatively good output of milk, meat and manure even when inhabiting deserts (Silanikove, 2000; Pragna et al., 2018). Because of their higher adaptivity and resilience to tough environments, goats are much more likely to be found in certain climatically harsher regions. Goats can thrive in such challenging environments because "Relative to their ruminant counterparts, with a capacity of endocrine control, goats employ greater metabolic adaptations to water deprivation, scarcity of feed, heat stress, cold stress, high altitude, and plant anti-nutritional factors" (Lu, 2023; 107056).

Domestic goats are increasing recognised as having positive environmental impacts on biodiversity when extensively managed on open pastures; see for example Rosa García et al., 2012; Metera et al., 2010), as well having a useful role in brush control to lessen wildfire risks, as demonstrated in Ethiopia and Spain, for instance (Abate et al., 2024; Álverez-Martinez et al., 2016). Goats can help control invasive plant species, prevent the overgrowth of shrubs, maintain open landscapes, and contribute to the diversity of plant species in swards. When allowed to range, their browsing behaviour can create a mosaic landscape structure, which benefits various plant and animal species. Nevertheless, negative biodiversity impacts under certain management conditions are also recognised-see a summary in Lipson et al. (2019). The debate and evidence on whether and how goats are more or less damaging to the land environment is not, however, within the scope of this review focused on climate change impacts of goats.

Global distribution of goats

Some parts of the world have many more goats than others. The lower and middle income countries, principally in Africa and Asia, have around 80% of all goats in the world (Figure 2). Goats predominate in the tropics and sub-tropics, in terms of the number of animals, total production and number of beneficiaries - producers and consumers (Oosting et al., 2014).

The geographical distribution pattern of goats arises from their physiology and anatomy, which makes goats attractive to poorer people in lower income countries. These biological advantages mean that goats are not only prevalent in low-income countries, but furthermore in parts of these countries with more limited animal feed sources. Much of the global goat population is concentrated in the arid and semi-arid agroecological zones of Africa and Asia, subject to heat or extreme winter cold, droughts, and annual or seasonal forage limitations (Koluman Darcan, 2023). See Figure 3. Therefore, "breeds of goats which are indigenous to semi-arid and arid areas are able to utilize low quality high-fibre food more efficiently than other types of indigenous ruminants, or exotic breeds of goats" (Silanikove, 2000: 184). This permits them to exploit both naturally marginal and human degraded environments. Additionally, their climatic adaptability and disease resistance allows them to flourish in diverse conditions while their agility enables them to navigate rugged steep terrains inaccessible to cattle and sheep. Goats also have a higher reproductive rate than other ruminant livestock, with a propensity for twinning, early sexual maturity and high fertility (Lu, 2023). All these factors underlie and reinforce the value of goats to poorer farmers and pastoralists.

Why goats are particularly useful for poorer people in harsh regions

The imbalance in the global distribution of goats is notable, as it underscores the causal link between the physiological advantages of goats and peasant or pastoral agriculture practised in difficult climatic regions.

An early influential catalogue of how goats benefitted people was the global perspective by Peacock and Sherman (2010). They pointed out that goats provide a valuable source of milk to families, even under challenging environmental conditions. Goats are a source of meat for the family, and can be sold, traded or bartered for other foods and goods, such as high calorie grains or household needs. Farmers can sell goat meat, milk, and by-products such as hides and fibre. In some societies, goats have

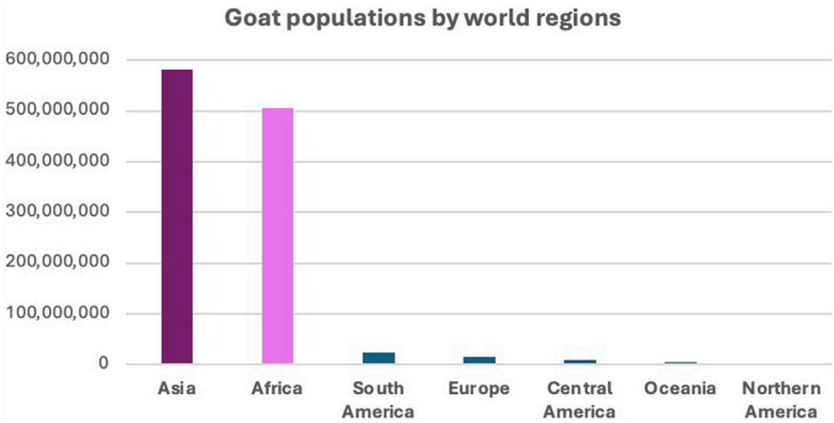

FIGURE 3
Goat populations by world regions. Source: FAOStats 2024.

symbolic significance and are used in cultural events such as marriage and religious ceremonies. Most of these attributes also pertain to other mammalian livestock species – cattle, sheep, camels, buffalos, reindeer, yaks etc. - but what is particularly useful about goats is their capacity to survive, produce and reproduce under the most variable and arduous extreme environments – hot, dry, cold or high. From the deserts of the Sahara, to the high altitude plateau of Tibet, goats are successfully raised by families who depend on their products.

From the aspect of human input efficiency, goats are often the species of choice for rural families with labour constraints (Peacock, 2005). Goats have a lower human labour requirement for herding due to their more diverse dietary selection, since they deploy an ability to forage on a wide range of vegetation and have an efficient digestion. This means that women and the elderly can more easily manage goats, while small children can be entrusted to oversee goats in pastures often nearer to home (Sinn et al., 1999).

Since goats are hardily adapted to survive and prosper in more difficult environments, they are widely preferred by poorer farmers in these places (Peacock, 2005; Pragna et al., 2018). In countries with a greater risk of climate disasters (droughts, floods, freezing snow) or politico-economic upheavals (unstable governments and currencies), resource-poor farmers will choose to keep goats rather than other ruminant livestock, as a cheaper option, faster turnover and quick sales in case of emergencies. For example, in the drylands of East and Southern Africa, goats have lower mortality rates than cattle in the regular droughts that afflict the rangelands (Nkedianye et al., 2011; Vetter et al., 2020). Likewise, after the traumatic socio-economic transformation in Central Asia, when the collapse of the Soviet Union was accompanied by mass rural unemployment and huge loss of livestock from state collective farms (Kerven, 2003), village families began to rebuild their livelihoods by accumulating goats, citing a proverb "If you are poor, you must keep goats" (Kerven et al., 2009).

Given the high population of goats kept by farmers in developing countries, since at least the mid 20th century there have been scientific and development efforts to alleviate poverty by increasing productivity of goats, due to their prevalence and preference among the very poorest farmers and pastoralists (Peters, 1987; Morand-Fehr and Lebbie, 2004). Research and extension on livestock improvement has become more prominent in the tropics of sub-Saharan Africa and southeast Asia (Oosting et al., 2014). Principally these efforts have been aimed at and achieved through raising meat and milk output for home consumption and cash sales by farmers and pastoralists in the world's drylands. The success of these efforts is good news for human nutrition and incomes, but is causing much concern over the impacts on climate change.

Growing consumption and commercialisation of goat products

Goats are not only raised for subsistence and sales by poorer farmers or in climatically harsh regions. Goat products are also increasingly being marketed, sometimes globally, leading to greater public and commercial scrutiny of their environmental impact. The three main products in terms of volume are milk, meat and fibre, while goatskins are also commercially important.

Goat milk is valued among both poorer and richer consumers. "There are far more people consuming goat milk than cow milk in the world", 20 years ago according to Haenlein (2004). For resource-poor farmers and pastoralists in drylands, goats have an advantage in being able to continue lactation even as water availability and forage dwindles (Silanikove, 2000), yielding a small but essential protein supply. Goat milk is also digestible by babies and small children in the absence of mothers' milk, or to people allergic to cows' milk. In high-income countries there is rising demand for gourmet dairy goat products of cheese and yoghurt (Mazinani and Rude, 2020). Globally, there is an ever-increasing number of dairy goats and goat milk production over the last two decades, particularly in Africa and Asia where dairy goat crossbreeds have been developed by researchers and adopted by farmers (Peacock and Sherman, 2010; Lu, 2023).

Considering the increasing world demand for meat as incomes rise (Thornton, 2010), consumers may prefer goat meat compared to other commonly consumed meats of beef, lamb, pork and chicken. Goat meat has less fat, less saturated fat and lower calories but equivalent protein and more iron, compared to other animal meats, based on FAO data cited in Mazinani and Rude (2020). As with increasing world production of goat milk, there is a steady rise in consumption of goat meat (Lu, 2023).

In contrast to the humid or dry hot tropics, in extreme cold continental and temperate climatic regions of Asia, goat fibre (cashmere) is an important source of additional income for millions of often poorer farmers and herders (Kerven et al., 2009). Cashmere goats are raised in deserts, steppes or high altitudes having bitter cold winters of Asia and are not found in Africa, with only an insignificant amount in Europe, the Americas and Australia. The cashmere undercoat protects the goats against extreme cold, and can be harvested and profitably sold by people. The biggest populations of commercially-harvested cashmere goats are in China, Mongolia, Afghanistan, Iran, India and Central Asian countries. In 2018 there were an estimated 700 million cashmere goats in the world (Schneider Group, 2019). Information on the number of cashmere goats in different countries is not officially recorded. As world demand for this valuable product is not abating, consumers and environmentalists are worried about the sustainability of raising goats to sell cashmere, a luxury product (Lindedin, 2024).

With the increase demand for goat products and accompanying supply from producers, more questions are raised about the climate change impacts of bigger goat populations.

Goats' contribution to climate change: What can be measured?

The growing global commercialisation of goat products leads directly to the central question of this review: how does keeping goats contribute to climate change?

The impact of livestock greenhouse gas (GHG) emissions on climate (including methane CH_4) first came to international attention in 2006, with the publication of *Livestock's Long Shadow*, a report by scientists at the UN Food and Agriculture Organization (FAO). The report's conclusions were immediately controversial and remain so, as lobbyists from the meat and dairy industries pressure their governments to object. As a result, scientists responded to challenges of their data and have since refined their methodologies (The Guardian, 2023; Morris and Jacquet, 2024). Furious attacks on the "methane fallacy" from sources like The Western Producer (2019) in Moose Jaw, Saskatchewan, nevertheless continue to rumble through the presses.

Scientists and advocates continue to reach differing conclusions on livestock's role in this global process (Lee et al., 2015; Garnett, 2017; Pitesky et al., 2009; Wolf, 2020). Meanwhile, consumers – at least those surveyed in the USA and Europe - are voting with their wallets, choosing which livestock products to buy or avoid (Sanchez-Sabate and Sabaté, 2019; Stampa et al., 2020). The food and textile industries are responding with alternatives to animal-derived products (McKinsey and Company, 2023; Deloitte, 2023), marketed as less climate damaging. Fashion companies are commissioning detailed life cycle assessments on the impacts of livestock on the environment, hoping to reassure potential buyers of the environmental and climate change neutrality of their animal fibre merchandise (Forbes, 2022; Ecochain, 2024).

The biology and chemistry of livestock GHG emissions is complex, and is still being closely studied. There are some fundamental interactions which need to be understood before rushing into black-and-white conclusions. The main livestock agents that cause GHG emissions are ruminants, including cattle, sheep, goats, buffalos and yaks (Opio et al., 2013; FAO, 2016). This is through the process of rumen enteric fermentation:

> . . .The end products of enteric fermentation are volatile fatty acids which are the primary source of energy in ruminants for both maintenance and production. This process proceeds with the liberation of [four] fermentation gases CO_2, H_2, N_2O, and CH_4 [methane] (Soren et al., 2015:187)

Among these four gases emitted by ruminant livestock, methane (CH_4) particularly contributes to global warming by trapping much more heat in the earth's atmosphere than carbon dioxide (CO_2), although for a shorter time (UNEP, 2024). Because of this, public and scientific attention is sharply focused on methane's impacts on climate change caused by ruminant livestock, including goats.

Broadly, geographic location and climate are known to be the most crucial factors significantly affecting CH_4 production by livestock, according to a widely-cited review (Cottle et al., 2011). That review notes that this is likely due to ambient temperature differences and associated disparities in available feed resources. However, within each different location and climatic zone, there are also many variables which further influence enteric CH_4 production in goats. These variables include type and quality of feed, the physical and chemical characteristics of the feed, feeding level and schedule, the efficiency of feed conversion to products of meat, milk and fibre from goats, the use of feed additives and concentrated feeds to support production efficiency, and the activity, health and genetic make-up of the animal (Soren et al., 2015; Pragna et al., 2018). In other words, even holding environment constant – geography and climate – there are still many other factors that impinge on the output of methane from goats.

In seeking to understand the effects of ruminant livestock on GHG, some of the variables have been precisely measured, some are hard to measure, and other variables are speculative at this stage and need further study. In summary, the key variables are: firstly, the ruminant species, as it is already known that each species emits differently. The next important variable is the extent to which livestock feed depend on roughage versus higher quality feeds. Much reliable data is already available on this question. A third major variable is the distinction between the GHG climate impacts of livestock raised under extensive management versus those raised in more intensive systems. Much less is known about the GHG differences attributable to management. This summary suggests there are complicating factors of species, feed sources and management in sorting out the role of goats in contributing to climate change. Each of these main variables is now considered in more detail.

Ruminant species - goats and others

Research in recent years has clearly shown that emission intensities of the GHG (CO_2, CH_4, and N_20) vary greatly among different livestock species and their products – meat and milk being the principal products considered (FAO, 2016). While FAO closely monitors and updates information on emissions from different livestock species, (including chickens and pigs), unfortunately FAO analyses often group goats together with sheep collectively as small ruminants (Opio et al., 2013). There is a larger sheep population than goats in the world, and sheep produce slightly less CO_2 equivalent (methane) per animal than goats (FAO, 2017). Among the ruminant livestock species it is known that "goats emit less enteric methane (CH_4) than all other domestic ruminant animals per unit body weight" (citing FAO 2017), because "goats have a high feed conversion efficiency, they emit less enteric methane per unit of feed consumed" (Koluman Darcan, 2023:107094). Globally, the world goat population of about 1.01 billion goats (FAOStats, 2024) produced approximately 4.61 million tonnes of enteric methane representing 4.9% of total EME [enteric methane emission] from livestock (FAO, 2016).

Feed sources: The role of roughages

Methane emissions vary according to roughage and concentrates in livestock diets. How much methane is emitted by goats largely depends on what they can eat, where and in what season. A bio-physical relationship has documented since the early 2000s between the content and quality of ruminant forage and feed diets to the consequent methane emissions (Benchaar et al., 2001). The ratio of roughage (principally from pastures) to concentrates in ruminant livestock diets is a fulcrum round which their food intakes vary, and thus the potential GHG emissions.

Roughages in ruminant diets consist of bulky plant materials with a relatively high amount of fibre (digestible cellulose and indigestible lignin) and a lower energy and protein value. Available native roughages include woody shrubs and dried grasses, with plant families and species varying widely between the world's biomes. The ratios of protein and fibre in plants providing roughage will alter considerably by season, plant maturity and local precipitation in different sites grazed and browsed by goats. Cultivated arable plants also produce by-products of roughages fed to ruminants, e.g. maize cobs, rice hulls, grain stalks, cotton, soya and sesame seed cake. Roughages are either grazed in pastures or harvested by humans and fed to the animals (so-called cut-and-carry). "Research shows that different grasses and forages at different stages of development cause ruminants to produce different amounts of CH_4. Forage species of grazing pasture also have a role in influencing enteric CH_4 production in ruminants" (Minson, 1990:350). The inflexion point of differences in methane emissions may occur on whether goats are raised solely on pastures versus more intensively with additional concentrates.

Although involving highly complex sets of relationships, a fundamental result is that "feeding system(s) employed for livestock rearing certainly has an effect on the enteric CH_4 production. Thus, feeding of a high concentrate to low roughage diet produces less enteric CH_4 vis-à-vis low concentrate to high roughage diet" (Soren et al., 2015:187). Since goats are raised and fed in radically dissimilar places and ways around the world according to different production systems, the amount of methane produced by goats will be partially dependent on the feed value of roughages obtained from pastures. The proportion of roughages in the diet changes under extensive or intensive management.

Roughages in diets under extensive management systems

The FAO investigated the question of how GHG emissions varies between different global livestock production systems, using the following classification of extensive systems as "grassland-based livestock production systems in which more than 10 percent of the dry matter fed to animals is farm-produced and in which annual average stocking rates are less than ten livestock units per hectare of agricultural land" (FAO, 1996). Most extensive pastoral systems raise their livestock primarily on available pastures, often communal, as well as crop residues – often *in situ* (Sayre et al., 2013).

Some researchers assume that in arid and semi-arid regions where pastoralists' extensive systems are based on grazing pastures over most or an entire annual cycle, all available feed resources are poor in quality, for example in sub-Saharan Africa (Opio et al., 2013; Graham et al., 2022). In this case, the assumption is that ruminant livestock in these arid and semi-arid regions would therefore have a lower productivity with higher enteric emission per unit output, in comparison to animals given a high quality diet under intensive or semi-intensive management systems in the same or different regions. This assumption can be questioned. If seasonal mobility is practiced, livestock – including goats - are able to reach and consume plants with higher quality feed values at the appropriate season, the strong correlation between GHG climate impact and reliance only on low quality roughage forage sources is less secure.

In many extensive management systems, livestock, including goats, are deliberately herded to or spontaneously seek out the freshest succulent pastures to graze early in the growing season (Coughenour, 1991; Boone et al., 2008; Behnke et al., 2011). While the aim of such seasonal movements is to gain access to plants before they mature and become fibrous roughages, this seasonal movement strategy inadvertently has the benefit of reducing methane emissions. This mobile foraging strategy allows the animals to take advantage of a higher ratio of protein to carbohydrate and fibre forage source, practiced for example in the Sahelian zones of West Africa (Penning de Vries and Djitèye, 1982). The Kazakh long-distance seasonal grazing movements exemplify these functional human-animal relationships: "Livestock migration partially levels out the imbalance between the quality of different forage resources . . . the total biomass output of the dry areas [sandy deserts] is inversely correlated to their nutritional value in the same way as the high level of output from wetter mountain pastures is associated with a lower protein feed value" (Alimaev, 2003:44).

In a very different climate than Central Asia, closely observed studies in Spanish mountain rangelands on seasonal feeding behaviour of feral goats over an annual cycle found that "Browsing use and preference of plant species by feral goats were significantly different across season [and], in general, seasonal fluctuations of diet were consistent with the maximum nutritive value of consumed plants" (Aldezabal and Garin, 2000:133). In another continent and climate, a semi-arid region of South Africa, when comparing the feeding behaviour of free-ranging versus herded goats in a semi-arid communal rangeland area, the goats able to choose their foraging sites were more selective and showed a higher preference for ephemeral herbs and grasses in the wet season; herded goats also preferred legume shrubs with a higher quality feed value (Samuels et al., 2016). Similar findings are recorded for goats under extensive management in other regions, for example, Mongolian Altai (Tsevegemed et al., 2019), Tanzania (Selemani et al., 2013) and Greece (Manousidis et al., 2016). The consumption ratio of roughages to more concentrated protein sources is decreased by such grazing and browsing behaviour by goats. The relatively lower rate of roughage in diets of migratory goats under extensive management practices is an important argument that methane emission per unit of output or animal head may be lower under extensive pastoral livestock management. However, as this relationship is not yet measured it remains speculative.

Adding cultivated feed and concentrates: Intensive management systems

The general conclusion in the research literature is that ruminant livestock raised under intensive concentrate-added systems produce the lowest GHG emissions, because of the ratio of high to low quality feed supplies – roughages to concentrates (Cottle et al., 2011). As already discussed here, the relationship is established that when ruminant livestock are fed low-quality feed (e.g., mainly roughages), they emit higher CH_4 per unit of meat and milk output (Vargas et al., 2022).

Concentrates are comparatively richer than roughages in energy and protein. Concentrates are typically generated by cultivation of cereals, legumes and oil seeds, as well as crop residues and human food processing byproducts such as molasses from sugar, all which frequently depend on inputs such as fossil fuel and agricultural chemicals. Harvesting of roughages can also depend on similar inputs through mechanical methods. In some livestock management practices concentrates are given as supplements, either regularly or in seasons of low pasture availability such as winters or dry seasons.

Some scientists have pointed out that externalities of more intensive management systems may not be properly calculated, such as the embedded emissions associated with producing concentrate diets (Cottle et al., 2011: 503). "For example, feed supplements may improve livestock production and reduce MI [methane intensity relative to production, e.g., kgCH_4 per kg liveweight gain or kg meat or milk] but the impacts of growing and processing these supplements must also be taken into account. Similar considerations apply to feedlot production" (Cottle et al., 2011:492). Concentrates are sometimes transported thousands of km from their source to where livestock are fed. Including the GHG production costs of supplementary feed changes the calculation of GHG emissions for intensive livestock systems (García-Dory et al., 2021).

Comparing GHG impacts of extensive versus intensive management

Certain commentators are asking why the distinction between climate impacts of extensive and intensive livestock management is rarely made (García-Dory et al., 2021; Scoones, 2023). The FAO data models are sometimes challenged by other scientists for being generic and therefore not applicable to all environments, for example:

> "Application of the current prediction equations developed by Food and Agricultural Organization and Intergovernmental Panel on Climate Change overestimated EME [enteric methane emission] from goats, and had low accuracy and precision" and "there is no model for predicting EME in goats developed from a large database emanated from different countries (Patra and Lalhriatpuii, 2016:89).

Two of the key differences at the core of this distinction between extensive and intensive systems centres on feed quality and methane emissions. Firstly, the ratio of roughage feed to concentrates in the diets of selective feeders like goats under extensive mobile systems allows greater access to high quality pasture forage. Secondly, intensive systems appear better in terms of methane emissions due to better quality cultivated feeds, until externalities are factored in.

Recognising that livestock are reared and fed within very different environments and alternative management systems of intensive, extensive and semi-intensive, one study assessed the comparative CH_4 production from these three different livestock feeding systems (Soren et al., 2015). The first major contrast is that developing countries have far greater proportions of livestock raised on locally produced roughages from communal lands as the principal source of feed, while only using minimal supplementation with concentrates. In these extensive management systems, "the quality of the pasture is responsible for the nutrients assimilated by the animal" (ibid: 187). Another notable contrast between management systems was that since goats are the most selective feeders among ruminant livestock, under extensive management conditions, goats were able to exhibit their inherent tendencies to consume a wide variety of plants, compared to sheep with which goats are often herded together in the pastures. In particular, in the dry season goats more than sheep chose to browse more, and have an affinity for protein-rich plants. For goats "the browse often serves as an excellent source of protein in addition to the dry grass" (ibid: 191). The implications of these goat eating habits for methane emissions under extensive management systems have not yet been ascertained. Evidently, it is hard to make accurate calculations of the contribution made by goats to methane emissions. Much depends on where the goats are, what they eat in which season, and how they are managed.

Difficult to establish carbon balances from livestock along the supply chain

There are other GHG effects of livestock apart from methane, however. Comparing emission measures of $C0_2$ versus CH_4 allows a more encompassing measurement of the GHG impacts of producing feed for intensive livestock keeping. An exclusive emphasis on methane – now largely the media focus - makes intensive livestock (and goat) management look better than extensive management, but factoring in $C0_2$ closes the gap.

After the startling messages in FAO's publication of "Livestock's Long Shadow" in 2006, one reaction was that FAO scientists proceeded to look more intently at the associated GHG emissions from different energy sources along the livestock supply chain from production to eventual retail point – i.e., distribution to consumers. Analytical focus turned to life cycle assessments (LCA), which are still being widely conducted on livestock outputs. An early comprehensive global assessment was FAO's publication "*Greenhouse gas emissions from ruminant supply chains*" (Opio et al., 2013).

Certainly the FAO, 2021 global assessment was a huge task, which acknowledged many assumptions, data absences and uncertainties. For assessing the impacts of livestock on GHG emissions, the report only considered human-edible livestock products of meat and milk – in other words, human food – The 2013 FAO calculations did not include GHG emissions associated with livestock's other uses as draught power, fibres, hides, skins and social capital, all of which can be significant components of low-income farm income in cash and in-kind.

Soil carbon sequestration was also not assessed in the 2013 FAO global study, due to a lack of standard criteria and data in all regions. Overlooked in most LCA studies is that ruminant livestock, including goats, contribute to "soil nutrient recycling via excreta . . . enhancing and maintaining soil health (i.e., soil organic C stocks, diverse populations of soil microbes, greater C sequestration" (Chen et al., 2019). Most Life Cycle Assessment (LCA) research has not yet thoroughly investigated the counter-balancing effects of emissions and sequestration from vegetation and soil. The mitigating implications may have a large influence for determining carbon balance, particularly for low-input grazing systems, as Cottle et al. (2011) previously remarked. The focus of LCA research is usually the estimation of CH_4 emission intensity relative to human food production – methane intensity (MI). This is estimated as $kgCH_4$ per kg liveweight gain (LWG) or kg beef or milk product. Accordingly, more weight is attached to CH_4 emissions relative to feed intake and product output (ibid). This methodology is now embedded in international standards often applied by commercial companies to assess the sustainability of their products. We are reminded that methane has an upper limit to the extent it can be stored in soil, reaching equilibrium unless the livestock production system is changed (Wang et al., 2023), but methane is still a powerful source of GHG. On the other hand, $C0_2$ persists for centuries and millennia.

Working out the carbon balance implications of producing high quality feed for concentrate under more intensive ruminant livestock systems is a core question about carbon cost and thus impacts on climate change. Assessing carbon balance requires setting harmful carbon emissions of livestock against carbon benefits to the soil from livestock, as noted above by Chen et al. (2019). Trends around the world are for intensification of livestock production. Pioneer studies which included soil carbon sequestration in assessing ruminant livestock on pastures in USA, for instance Pelletier et al. (2010), reported lower total GHG for pasture-fed beef cows compared with lot-fed beef. A similar early result, also in USA, was found for pasture-fed dairy cows, as when carbon sequestration by grassland was considered, pasture systems reduced net GHG emissions (Belflower et al., 2012). This highlights the possibility of other GHG sinks to counter the higher enteric MI [$kgCH_4$ per kg liveweight gain] anticipated from pasture grazing management systems. At present, there are apparently no similar studies of carbon sequestration created by goats fed on pasture compared to feed lots.

Nevertheless, concern over climate change consequences of raising ruminant livestock is leading to closer consideration of the carbon balances – or offsets - between ruminant emissions and soil carbon sequestration. So far, field studies are limited to developed countries such as Spain (e.g., Escribano et al., 2020) and Italy (Arca et al., 2021), and the USA results as noted above. Estimations of the carbon balance are lacking or deficient for extensive livestock systems in developing and low income countries (Scoones, 2023). Overlooking the carbon sequestration land use outcomes of raising ruminant livestock is a “blind spot,” according to some analysts of the GHG inventory methods (Bellassen et al., 2022).

Evaluating the carbon balances implicated in intensive versus extensive systems depends on how the question is asked. There at least two possible denominators. The conventional LCA approach is to apply the product unit per animal as denominator– meat and milk in weight or protein, per emission of carbon – even when adjusted by carbon sequestration per animal head. Using this denominator leads inexorably to the conclusion that more intensive systems are less climate threatening. Intensively raised animals are individually capable of producing more human food – meat and milk - due to their higher quality diets, breeds and body sizes as well as greater inputs of veterinary drugs, scientific breeding, hormones and other interventions. Therefore, in an intensive system, on average each animal can yield relatively more human food while producing less emissions per animal.

If, on the other hand, carbon emissions are denominated by area of land used per animal – i.e., stocking rate – then as one study shows, “The extensification process shows clear environmental advantage when emission intensity is referred to the area-based functional unit” (Arca et al., 2021). In poorer regions of the world with extreme dry and/or cold winter climates, livestock, including goats, tend to be raised extensively i.e., with a low ratio of animal population per land area. Lacking the inputs of intensive management and spread much more thinly on the ground, their carbon footprint per land area may therefore be lighter. Such a perspective could alter our views about the pros and costs of different livestock management systems around the world. Since goats help to sustain people in some of the most unforgiving landscapes, they deserve to have their role in contributing to climate change re-evaluated. Logically, the next set of questions must be to examine total world quantities of goats and land area involved in these different production systems and climatic regions.

Discussion

Understanding the physiology, eating habits and geographical distribution of goats leads to rethinking how goats fit into the overall concern about livestock’s effects on the climate. Since the people who mainly raise goats are among the most economically vulnerable and often live in environments most likely to be affected by global climate shifts, it is time to start re-evaluating the impact of goats on the climate. Not all the questions have clear answers, and there are still many outstanding research conundrums to pursue.

There are indicators that using lesser external inputs under extensive management compared to intensive management systems may foster less GHG emissions. When appraising these questions, one viewpoint has advocated for a more holistic approach, “avoiding the narrow focus on emissions per animal or unit of product” and instead factoring in environmental benefits for biodiversity, ecosystem services, landscape and cultural values (Scoones, 2023:4). These valuable benefits of goats are recognised, but beyond the scope of this review on the contribution of goats to GHG, and not on the broader environmental and societal impacts.

This review has delved into some scientific progress on measuring new variables and measuring more carefully. Some metrics are settled, including that goats emit less methane per head, can find and-compared to other domesticated ruminants - can eat a wider selection of edible nutritious plants. Ruminant livestock – including goats – raised extensively on pastures may less produce less total GHG than when kept under intensive management with a high proportion of cultivated feed and less carbon sequestration.

The extent to which livestock grazed on pastures results in improved biodiversity and adaptation to climate change is now being widely investigated.

Looking backwards, ruminant livestock have been extremely advantageous to humans for the last ten thousand years – goats being one of the earliest domesticated species which yielded meat and milk, as well as skins, for the people who kept them. As ruminants, goats share the facility of being able to derive nutrition efficiently from plants, but more effectively than the other most popular species of cattle and sheep. The physiology of goats allowed the spread of domestic goats to many different environments over time. Yet now we see that goats are more concentrated in some of the world's extreme climates, remote places and in lower income countries, where farmers and herders can derive a more reliable livelihood from them. When raised on pastures in deserts and mountains, goats can provide food for people where few other livestock species can compete. Looking forwards, the trend is for goats to increase in popularity for their milk, fibres and possibly also for meat. This means that the impact of goats on GHG must be considered.

Due to their adaptability, resilience and eating behaviour, goats deserve to be distinguished from other livestock, rather than being lumped together with the world's sheep or with all other livestock, as in the more popular press articles on climate change. People's great dependence on goats in some regions justifies paying better attention to their usefulness. Ultimately, not all the issues are amenable to precise measurement as some issues are inevitably value-laden. This means that the uncertainties, trade-offs and biases must be acknowledged. There is still work to be done.

Author contributions

CK conceptualised, reviewed and prepared the ms. Much gratitude is due to RB and CTBKL.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

Much is owed to Roy Behnke and Cara Kerven-Loomis for their patience and persistence in commenting on this review. I am grateful to the two reviewers for their helpful suggestions and to colleagues and farmers in Kyrgyzstan, Kazakhstan and Tajikistan who have taught me much about goats.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

References

Abate, T., Abebe, T., and Treydte, A. (2024). Do we need post-tree thinning management? Prescribed fire and goat browsing to control woody encroacher species in an Ethiopian savanna. *Pastor. Res. Policy Pract.* 14, 13039. doi:10.3389/past.2024.13039

Aldezabal, A., and Garin, I. (2000). Browsing preference of feral goats (Capra hircus L.) in a Mediterranean mountain scrubland. *J. Arid Environ.* 44 (1), 133–142. doi:10.1006/jare.1999.0573

Alimaev, I. I. (2003). "Transhumant ecosystems: Fluctuations in seasonal pasture productivity," in *Prospects for pastoralists in Kazakstan and Turkmenistan: from state farms to private flocks*. Editor C. Kerven (London: RoutledgeCurzon), 31–51.

Álvarez-Martínez, J., Gómez-Villar, A., and Lasanta, T. (2016). The use of goats grazing to restore pastures invaded by shrubs and avoid desertification: A preliminary case study in the Spanish Cantabrian mountains. *Land Degrad. & Dev.* 27 (1), 3–13. doi:10.1002/ldr.2230

Amills, M., Capote, J., and Tosser-Klopp, G. (2017). Goat domestication and breeding: A jigsaw of historical, biological and molecular data with missing pieces. *Anim. Genet.* 48 (6), 631–644. doi:10.1111/age.12598

Arca, P., Vagnoni, E., Duce, P., and Franca, A. (2021). How does soil carbon sequestration affect greenhouse gas emissions from a sheep farming system? Results of a life cycle assessment case study. *Italian J. Agron.* 16 (3). doi:10.4081/ija.2021.1789

Behnke, R. H., Fernandez-Gimenez, M. E., Turner, M. D., and Stammler, F. (2011). "Pastoral migration: Mobile systems of livestock husbandry," in *Animal migration–A synthesis*. Editor E. J. Milner-Gulland, 144–252.

Belflower, J. B., Bernard, J. K., Gattie, D. K., Hancock, D. W., Risse, L. M., and Alan Rotz, C. (2012). A case study of the potential environmental impacts of different dairy production systems in Georgia. *Agric. Syst.* 108, 84–93. doi:10.1016/j.agsy.2012.01.005

Bellassen, V., Angers, D., Kowalczewski, T., and Olesen, A. (2022). Soil carbon is the blind spot of European national GHG inventories. *Nat. Clim. Change* 12, 324–331. doi:10.1038/s41558-022-01321-9

Benchaar, C., Pomar, C., and Chiquette, J. (2001). Evaluation of dietary strategies to reduce methane production in ruminants: A modelling approach. *Can. J. Animal Sci.* 81 (4), 563–574. doi:10.4141/a00-119

Boone, R. B., Burnsilver, S. B., Worden, J. S., Galvin, K. A., and Hobbs, N. T. (2008). "Large-scale movements of large herbivore livestock following changes in seasonal forage supply," in *Resource ecology: spatial and temporal dynamics of foraging* (Netherlands: Springer), 187–206.

Chen, S., Arrouays, D., Angers, D. A., Martin, M. P., and Walter, C. (2019). Soil carbon stocks under different land uses and the applicability of the soil carbon saturation concept. *Soil Tillage Res.* 188, 53–58. doi:10.1016/J.STILL.2018.11.001

Cottle, D. J., Nolan, J. V., and Wiedemann, S. G. (2011). Ruminant enteric methane mitigation: A review. *Animal Prod. Sci.* 51 (6), 491–514. doi:10.1071/an10163

Coughenour, M. B. (1991). Invited synthesis paper: spatial components of plant-herbivore interactions in pastoral, ranching, and native ungulate ecosystems. *J. Range Manag.* 44 (6), 530–542. doi:10.2307/4003033

Davies, J. (2024). *Opportunities and challenges of the green transition for pastoralism and indigenous people in Africa. Policy department for external relations, directorate general for external policies of the union*. Publications Office of the European Union. Belgium. Available at: https://coilink.org/20.500.12592/v6wwx4v (Accessed 25 October 2024).

Deloitte (2023). Shifting sands: how consumer behaviour is embracing sustainability. Available at: https://www2.deloitte.com/ch/en/pages/consumer-business/articles/shifting-sands-sustainable-consumer.html.

Ecochain (2024). *Life cycle assessments & the fashion industry – the good, the bad, the potential*. Available at: https://ecochain.com/blog/lca-and-fashion/.

Escribano, M., Elghannam, A., and Mesias, F. J. (2020). Dairy sheep farms in semi-arid rangelands: a carbon footprint dilemma between intensification and land-based grazing. *Land Use Policy* 95, 104600. doi:10.1016/j.landusepol.2020.104600

FAO (1996). "World livestock production systems: Current status, issues and trends," in *FAO animal production and health paper 127*. Editors Seré, C., and Steinfeld, H. (Rome: Food and Agriculture Organization of the United Nations).

FAO (2016). Livestock and climate change. Available at: https://www.fao.org/documents/card/en?details=9d3312eb-8286-4cb1-b942-ba82fa05f812#:~:text=At%20the%20same%20time%2C%20the,CO2%2Deq)%20per%20year.

FAO (2017). *Gleam*. Rome: Food and Agriculture Organization of the United Nations. Available at: https://foodandagricultureorganization.shinyapps.io/GLEAMV3_Public/.

FAO (2021). *Global livestock environmental assessment model (GLEAM)*. Rome: Food and Agriculture Organization of the United Nations. Available at: https://www.fao.org/gleam/en.

FAO (2024). *Livestock and the environment*. Rome: Food and Agriculture Organization of the United Nations. Available at: https://www.fao.org/livestock-environment/.

FAOStats (2024) *Crops and livestock products*. Rome: Food and Agriculture Organization of the United Nations. Available at: https://www.fao.org/faostat/en/#data/QCL.

Forbes (2022). Environmental impact assessments could undermine sustainable fashion. Available at: https://www.forbes.com/sites/brookerobertsislam/2022/05/16/environmental-impact-assessments-could-undermine-sustainable-fashion-experts-explain-why/.

García-Dory, F., Houzer, E., and Scoones, I. (2021). Livestock and climate justice: challenging mainstream policy narratives. *IDS Bull.* 10, 1968–2021.

Garnett, T., (2017). "Livestock and climate change," in: *The meat crisis*. Editors J. D'Silva and J. Webster (Routledge, London), 31–51.

Gerber, P., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., et al. (2013). *Tackling climate change through livestock—a global assessment of emissions and mitigation opportunities*. Rome, Italy: Food and Agriculture Organization. Available at: http://www.fao.org/3/a-i3437e.pdf.

Graham, M. W., Butterbach-Bahl, K., du Toit, C. J. L., Korir, D., Leitner, S., Merbold, L., et al. (2022). Research progress on greenhouse gas emissions from livestock in sub-Saharan Africa falls short of national inventory ambitions. *Front. Soil Sci.* 2, 927452. doi:10.3389/fsoil.2022.927452

Haenlein, G. F. W. (2004). Goat milk in human nutrition. *Small Ruminant Res.* 51 (2), 155–163. doi:10.1016/j.smallrumres.2003.08.010

Hermes, T. R., Frachetti, M. D., Voyakin, D., Yerlomaeva, A. S., Beisenov, A. Z., Doumani Dupuy, P. N., et al. (2020). High mitochondrial diversity of domesticated goats persisted among bronze and iron age pastoralists in the inner asian mountain corridor. *PloS One* 15 (5), e0233333. doi:10.1371/journal.pone.0233333

Kerven, C. (2003). *From state farm to private flock: the prospects for pastoralism in kazakstan and Turkmenistan* (London: RoutledgeCurzon Press).

Kerven, C., McGregor, B., and Toigonbaev, S. (2009). Cashmere-producing goats in central Asia and Afghanistan. *Anim. Genet. Resour. Inf.* 45, 15–27. doi:10.1017/s1014233909990289

Koluman Darcan, N. (2023). Goats and their role in climate change. *Small Ruminant Res.* 228, 107094. doi:10.1016/j.smallrumres.2023.107094

Lee, K. C. L., Newell, J., Wolch, J., and Joassart-Marcelli, P. (2015). Cows, climate and the media. in: *Political ecologies of meat*. Editors J. Emel and H. Neo (Routledge, London).

Lindedin (2024). Animal fibre market report. Available at: https://www.linkedin.com/pulse/animal-fiber-market-size-grow-cagr-500-from-2023-2030-a7g0f/ (Accessed July 4, 2024).

Lipson, J., Reynolds, T., and Anderson, C. L. (2019). Environmental implications of livestock series: Goats. *Gates Open Res.* 3 (343), 343.

Lu, C. D. (2023). The role of goats in the world: society, science, and sustainability. *Small Ruminant Res.* 227, 107056. doi:10.1016/j.smallrumres.2023.107056

Manousidis, T., Kyriazopoulos, A. P., Parissi, Z. M., Abraham, E. M., Korakis, G., and Abas, Z. (2016). Grazing behavior, forage selection and diet composition of goats in a Mediterranean woody rangeland. *Small Ruminant Res.* 145, 142–153. doi:10.1016/j.smallrumres.2016.11.007

Mazinani, M., and Rude, B. (2020). Population, world production and quality of sheep and goat products. *Am. J. Animal Veterinary Sci.* 15 (4), 291–299. doi:10.3844/ajavsp.2020.291.299

McKinsey and Company (2023). Consumers care about sustainability - and back it up with their wallets. Available at: https://www.mckinsey.com/industries/consumer-packaged-goods/our-insights/consumers-care-about-sustainability-and-back-it-up-with-their-wallets.

Metera, E., Sakowski, T., Słoniewski, K., and Romanowicz, B. (2010). Grazing as a tool to maintain biodiversity of grassland-a review. *Animal Sci. Pap. Rep.* 28☹4, 315–334.

Minson, D. J. (1990). *Forage in ruminant nutrition*. San Diego: Academic Press.

Morand-Fehr, P., and Lebbie, S. H. B. (2004). Proposals for improving the research efficiency in goats. *Small Ruminant Res.* 51 (2), 145–153. doi:10.1016/j.smallrumres.2003.08.012

Morris, V., and Jacquet, J. (2024). The animal agriculture industry, US universities, and the obstruction of climate understanding and policy and the obstruction of climate understanding and policy. *Clim. Change* 177 (34), 41. doi:10.1007/s10584-024-03690-w

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., and Gerber, P. (2017). Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Glob. Food Secur.* 14, 1–8. doi:10.1016/J.GFS.2017.01.001

Nkedianye, D., de Leeuw, J., Ogutu, J. O., Said, M. Y., Saidimu, T. L., Kifugo, S. C., et al. (2011). Mobility and livestock mortality in communally used pastoral areas: The impact of the 2005-2006 drought on livestock mortality in maasailand. *Pastor. Res. Policy Pract.* 1, 17. doi:10.1186/2041-7136-1-17

Oosting, S. J., Udo, H. M. J., and Viets, T. C. (2014). Development of livestock production in the tropics: Farm and farmers' perspectives. *Animal* 8 (8), 1238–1248. doi:10.1017/s1751731114000548

Opio, C., Gerber, P., Mottet, A., Falcucci, A., Tempio, G., MacLeod, M., et al. (2013). *Greenhouse gas emissions from ruminant supply chains–A global life cycle assessment*. Rome: Food and Agriculture Organization of the United Nations FAO.

Patra, A. K., and Lalhriatpuii, M. (2016). Development of statistical models for prediction of enteric methane emission from goats using nutrient composition and intake variables. *Agric. Ecosyst. & Environ.* 215, 89–99. doi:10.1016/j.agee.2015.09.018

Peacock, C. (2005). Goats-A pathway out of poverty. *Small Ruminant Res.* 60, 179–186. doi:10.1016/j.smallrumres.2005.06.011

Peacock, C., and Sherman, D. M. (2010). Sustainable goat production—some global perspectives. *Small Ruminant Res.* 89 (2-3), 70–80. doi:10.1016/j.smallrumres.2009.12.029

Pelletier, N., Pirog, R., and Rasmussen, R. (2010). Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States. *Agric. Syst.* 103 (6), 380–389. doi:10.1016/j.agsy.2010.03.009

Penning de Vries, F. W. T., and Djitèye, M. A. (1982). *La productivité des pâturages sahéliens*. Netherlands: Centre for Agricultural Publishing and Documentation Wageningen.

Peters, K. (1987). *Evaluation of goat populations in tropical and subtropical environments*. Addis Ababa: International Livestock research Institute.

Pitesky, M. E., Stackhouse, K. R., and Mitloehner, F. M. (2009). Clearing the air: livestock's contribution to climate change. *Adv. Agron.* 103, 1–40.

Pragna, P., Chauhan, S. S., Sejian, V., Leury, B. J., and Dunshea, F. R. (2018). Climate change and goat production: enteric methane emission and its mitigation. *Animals* 8 (12), 235. doi:10.3390/ani8120235

Rivero, M. J., Lopez-Villalobos, N., Evans, A., Berndt, A., Cartmill, A., Neal, A. L., et al. (2021). Key traits for ruminant livestock across diverse production systems in the context of climate change: Perspectives from a global platform of research farms. *Reproduction, Fertil. Dev.* 33 (2), 1–19. doi:10.1071/rd20205

Rosa García, R., Celaya, R., García, U., and Osoro, K. (2012). Goat grazing, its interactions with other herbivores and biodiversity conservation issues. *Small Ruminant Res.* 107 (2-3), 49–64. doi:10.1016/j.smallrumres.2012.03.021

Samuels, I., Cupido, C., Swarts, M. B., Palmer, A. R., and Paulse, J. W. (2016). Feeding ecology of four livestock species under different management in a semi-arid pastoral system in South Africa. *Afr. J. Range & Forage Sci.* 33 (1), 1–9. doi:10.2989/10220119.2015.1029972

Sanchez-Sabate, R., and Sabaté, J. (2019). Consumer attitudes towards environmental concerns of meat consumption: a systematic review. *Int. J. Environ. Res. Public Health* 16 (7), 1220. doi:10.3390/ijerph16071220

Sayre, N. F., McAllister, R. R., Bestelmeyer, B. T., Moritz, M., and Turner, M. D. (2013). Earth stewardship of rangelands: Coping with ecological, economic, and political marginality. *Front. Ecol. Environ.* 11 (7), 348–354. doi:10.1890/120333

Schneider Group (2019). Annual cashmere market report. Available at: https://www.gschneider.com/annual-cashmere-market-report/#:~:text=China%27s%20cashmere%20production%20accounts%20for,700%20million%20in%20the%20world.

Scoones, I. (2023). Livestock, methane, and climate change: the politics of global assessments. *Wiley Interdiscip. Rev. Clim. change* 14 (1), e790. doi:10.1002/wcc.790

Selemani, I. S., Eik, L. O., Holand, Ø., Ådnøy, T., Mtengeti, E., and Mushi, D. (2013). Variation in quantity and quality of native forages and grazing behavior of cattle and goats in Tanzania. *Livest. Sci.* 157 (1), 173–183. doi:10.1016/j.livsci.2013.08.002

Silanikove, N. (2000). The physiological basis of adaptation in goats to harsh environments. *Small Ruminant Res.* 35 (3), 181–193. doi:10.1016/s0921-4488(99)00096-6

Sinn, R., Ketzis, J., and Chen, T. (1999). The role of woman in the sheep and goat sector. *Small Ruminant Res.* 34, 259–269. doi:10.1016/s0921-4488(99)00078-4

Soren, N. M., Sejian, V., and Malik, P. K. (2015). "Enteric methane emission under different feeding systems," in *Climate change impact on livestock: adaptation and mitigation*. Editors V. Sejian, J. Gaughan, L. Baumgard, and C. Prasad (New Delhi: Springer). doi:10.1007/978-81-322-2265-1_12

Stampa, E., Schipmann-Schwarze, C., and Hamm, U. (2020). Consumer perceptions, preferences, and behavior regarding pasture-raised livestock products: a review. *Food Qual. Prefer.* 82, 103872. doi:10.1016/j.foodqual.2020.103872

The Guardian (2023). ' the anti-livestock people are a pest': How UN food body played down role of farming in climate change. Available at: https://www.theguardian.com/environment/2023/oct/20/the-anti-livestock-people-are-a-pest-how-un-fao-played-down-role-of-farming-in-climate-change.

The Western Producer (2019). Debunked methane study continues to draw attention. *Moose Jaw, Sask.* Available at: https://www.producer.com/livestock/debunked-methane-study-continues-to-draw-attention/.

Thornton, P. K. (2010). Livestock production: Recent trends, future prospects. *Philosophical Trans. R. Soc. B Biol. Sci.* 365 (1554), 2853–2867. doi:10.1098/rstb.2010.0134

Tsevegemed, M., Norovsambuu, T., Jordan, G., and Schlecht, E. (2019). Feed intake of small ruminants on spring and summer pastures in the Mongolian Altai Mountains. *Sustainability.* 11 (20), 5759. doi:10.3390/su11205759

UNEP (2024). Facts about methane. *U. N. Environ. Programme*. Available at: https://www.unep.org/explore-topics/energy/facts-about-methane (Accessed July 9, 2024).

Vargas, J., Ungerfeld, E., Muñoz, C., and DiLorenzo, N. (2022). Feeding strategies to mitigate enteric methane emission from ruminants in grassland systems. *Animals* 12, 1132. doi:10.3390/ani12091132

Vetter, S., Goodall, V. L., and Alcock, R. (2020). Effect of drought on communal livestock farmers in KwaZulu-Natal, South Africa. *Afr. J. Range & Forage Sci.* 37 (1), 93–106. doi:10.2989/10220119.2020.1738552

Wang, Y., de Boer, I. J. M., Persson, U. M., Ripoll-Bosch, R., Cederberg, C., Gerber, P. J., et al. (2023). Risk to rely on soil carbon sequestration to offset global ruminant emissions. *Nat. Commun.* 14, 7625. doi:10.1038/s41467-023-43452-3

Wolf, J. (2020). Quantifying the role of livestock in climate change. in: *Climate change and agriculture*. Editor D. Deryng Cambridge: Burleigh Dodds Science Publishing. 99–136.

World Bank (2022). The world by income and region. Available at: https://datatopics.worldbank.org/world-development-indicators/the-world-by-income-and-region.html.

Pastoralism
Research, Policy and Practice

TYPE Review
PUBLISHED 21 May 2025
DOI 10.3389/past.2025.14225

OPEN ACCESS

EDITED BY
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RECEIVED 18 December 2024
ACCEPTED 09 May 2025
PUBLISHED 21 May 2025

CITATION
Ngongolo K and Gayo L (2025) Climate change impacts and mitigation strategies in Sub-Saharan Africa's livestock production sector. A brief review.
Pastoralism 15:14225.
doi: 10.3389/past.2025.14225

Climate change impacts and mitigation strategies in Sub-Saharan Africa's livestock production sector. A brief review

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Climate change poses significant challenges to Sub-Saharan Africa's livestock production sector, threatening the livelihoods of millions and exacerbating food insecurity and poverty. This review paper comprehensively examines the impacts of climate change on livestock farming systems in the region, including changes in temperature, precipitation patterns, and the spread of diseases and pests. Additionally, it explores mitigation strategies to enhance the resilience and sustainability of Sub-Saharan Africa's livestock production sector, considering adaptation measures, sustainable livestock management practices, and policy interventions. By synthesizing existing research and identifying gaps in knowledge, this paper provides valuable insights for policymakers, researchers, and practitioners seeking to address the complex challenges posed by climate change in Sub-Saharan Africa's livestock production sector. Effective mitigation strategies are crucial for safeguarding livelihoods, promoting food security, and ensuring the long-term sustainability of livestock farming in the region.

KEYWORDS

sustainable agriculture, vulnerability, resilience, smallholder farmers, adaptation

Introduction

Sub-Saharan Africa's livestock production sector stands as a cornerstone of its agricultural economy, providing livelihoods for millions and serving as a vital source of food security and economic stability. For instance, A study from south Africa revealed the benefits from livestock to include; Food Clothing Work Monetary Social Manure Other benefits (Ngongolo et al., 2021; Stroebel, 2004). However, this sector faces escalating challenges due to the impacts of climate change. The region is particularly vulnerable to the adverse effects of climate change, with increasing temperatures, erratic rainfall patterns, and extreme weather events posing significant threats to livestock farming systems. For instance, a study by Thornton et al (2009) revealed that, climate change has impacts on the feed's availability, quality and quantity to livestock water and alters the transmission and epidemiology livestock diseases and their disease vectors. As global temperatures continue to rise, it is imperative to understand the specific impacts of climate change on Sub-Saharan Africa's livestock production sector and to develop effective mitigation strategies to ensure its resilience and sustainability. Smallholders face constraints like farm size, market access, and knowledge gaps. Integrated assessments are needed for effective adaptation strategies. African mixed crop–livestock systems confront climate vulnerabilities, requiring vital adaptation for livelihoods. Smallholders face constraints, impeding resilience despite available solutions. Integrated assessments essential for effective strategies (Descheemaeker et al., 2016).

Sub-Saharan Africa's livestock production sector encompasses a diverse range of livestock species, including cattle, sheep, goats, poultry, and pigs, which are raised under various production systems ranging from extensive pastoralism to intensive commercial farming (Pandey and Upadhyay, 2022; Kaasschieter, et al., 1992). These livestock systems play a critical role in the livelihoods of rural communities, providing income, nutrition, and social capital (Sekaran, et al., 2021). However, they are highly susceptible to the adverse impacts of climate change, which manifest in multiple ways, including reduced forage availability, increased heat stress, heightened disease prevalence, and water scarcity.

In the Southern African Development Community (SADC), 30.6% face severe food insecurity, 8% are malnourished, and 50% live below $1/day (Mapiye et al., 2020). Agriculture, particularly cattle, plays a vital role. However, in Sub-Saharan Africa's livestock production sector is highly vulnerable to the adverse effects of climate change, including shifts in temperature and precipitation patterns, increased incidence of droughts and floods, and the spread of diseases and pests. These impacts jeopardize the health, productivity, and livelihoods of millions of smallholder farmers who depend on livestock for food, income, and assets (Baumgard et al., 2012). Urgent action is needed to address these challenges and safeguard the future of livestock farming in the region. In this case the paper focused on answering the following questions "How do climate change-induced stresses, such as altered precipitation patterns and temperature fluctuations, impact the productivity and resilience of Sub-Saharan Africa's diverse livestock species, considering both indigenous and introduced breeds? What are the most effective and contextually appropriate mitigation strategies for reducing the vulnerability of Sub-Saharan Africa's livestock production sector to climate change, taking into account socio-economic factors, cultural practices, and regional variations? How can sustainable land management practices, including agroforestry, rotational grazing, and soil conservation techniques, be integrated into livestock production systems in Sub-Saharan Africa to enhance resilience to climate change while promoting long-term environmental sustainability and food security?"

Justification

This review paper is justified by the urgent need to understand and subsequently address such complex interactions between climate change and livestock production in sub-Saharan Africa. Climate change impacts such as droughts and heavy rainfall have already affected the livestock sector and will cause further problems in the future. For example, research in Kenya suggests that an additional 1.8 million cattle could be lost by 2030 due to more frequent droughts. The estimated value of these lost animals, together with the production that will not take place, is around USD 630 million (Ericksen et al., 2013). The 2014 IPCC report provided little information on the expected impacts of climate change on livestock and livestock systems, for which much more detailed and comprehensive data is urgently needed (Thornton, et al., 2015). By analysing the impacts of climate change on this sector, as well as mitigation strategies, it aims to provide insights that will be useful to policymakers, researchers and practitioners. This review can provide valuable insights for evidence-based decision making and inform the design of targeted interventions aimed at enhancing the resilience and ensuring the sustainability of the livestock sector in sub-Saharan Africa in the face of the challenges posed by climate change.

Materials and methods

Literature review

A comprehensive review of peer-reviewed scientific literature was conducted using online databases such as PubMed, Web of Science, Scopus, and Google Scholar. Search terms included combinations of keywords related to climate change, livestock production, Sub-Saharan Africa, impacts, and mitigation strategies. Relevant studies, review articles, reports, and policy documents published between 2000 and 2023 were identified and analyzed.

Data collection

Data pertaining to climate change impacts on Sub-Saharan Africa's livestock production sector were extracted from selected studies, focusing on key variables such as temperature trends, precipitation patterns, livestock health, productivity, and socio-economic impacts. Data were organized and synthesized to identify trends, patterns, and gaps in knowledge.

Key findings from the review of the information

Impacts of climate change on the productivity and resilience of Sub-Saharan Africa's diverse livestock species

Climate change-induced stresses, including altered precipitation patterns and temperature fluctuations,

TABLE 1 Impacts of climate change in livestock production in Sub-Saharan Africa.

Sn	Impacts	Description	References
1	Altered Forage Availability	Changes in temperature and precipitation patterns affect vegetation growth, leading to fluctuations in forage availability and quality for livestock	Giridhar and Samireddypalle (2015)
2	Heat Stress	Rising temperatures result in heat stress among livestock, reducing feed intake, growth rates, and reproductive efficiency	Savsani et al. (2015)
3	Water Scarcity	Shifts in precipitation patterns can cause water scarcity, affecting drinking water availability for livestock and leading to dehydration and health issues	Naqvi et al. (2015)
4	Disease Spread	Climate change alters the distribution and prevalence of diseases and parasites affecting livestock, increasing the risk of disease outbreaks and requiring additional disease management measures	Bett et al. (2017)
5	Reduced Reproductive Performance	Heat stress and environmental changes negatively impact reproductive performance in livestock, leading to decreased fertility rates and lower productivity	Savsani et al. (2015)
6	Food Insecurity	Climate-related disruptions to agriculture can lead to food insecurity for both livestock and humans, impacting the availability and affordability of feed and fodder	Godde et al. (2021)
7	Economic Impacts	Climate-related challenges in livestock production can result in economic losses for farmers, affecting their livelihoods and contributing to broader economic instability in rural communities	Bogale and Erena (2022)

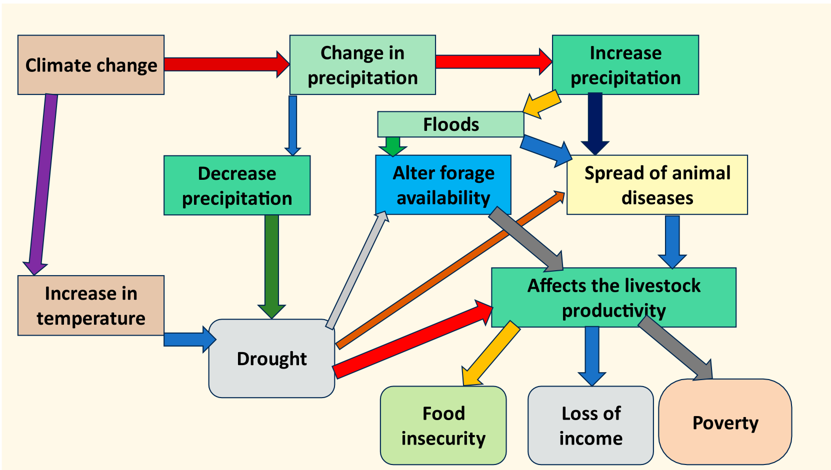

FIGURE 1
The diagrammatic summary of the impact of climate change on the livestock production.

profoundly affect the productivity and resilience of Sub-Saharan Africa's diverse livestock species, encompassing both indigenous and introduced breeds (Saikanth et al., 2023). Understanding these impacts is crucial for devising effective adaptation and mitigation strategies in the region (Table 1; Figure 1). Climate change impacts livestock production through altered forage availability, heat stress, water scarcity, disease spread, reduced reproductive performance, food insecurity, migration, mortality, distribution changes, and economic losses (Baumgard et al., 2012). A study in Ethiopia revealed that, Drought imposes significant economic hardships, causing lost productivity, population reductions, and damage to livestock, crops, soil, and vegetation (Bogale and Erena, 2022). In the Somali region, drought-related animal death rates increased by 60%–80% between 1990–2000 and 2001–2002/03, leading to water depletion, crop failure, and food price hikes (Amerino et al., 2024). In overall the impacts of climate change in livestock production leads to food insecurity, loss of income and poverty (Figure 1).

Mitigation strategies for reducing the vulnerability of Sub-Saharan Africa's livestock production sector to climate change

Mitigation strategies for Sub-Saharan Africa's livestock production sector against climate change involve considering socio-economic factors, cultural practices, and regional variations (Descheemaeker et al., 2016). Addressing issues such as access to resources, integrating traditional knowledge, and tailoring strategies to diverse contexts can enhance resilience and sustainability amidst climate challenges. Socio-economic factors, encompassing farmers' economic status and resource accessibility, significantly influence vulnerability to climate impacts. Strategies should facilitate access to credit for climate-resilient infrastructure, insurance schemes for climate-related losses, and capacity-building programs to enhance adaptive skills among livestock producers. Climate change is transforming agricultural and food systems, threatening livelihoods, particularly among the world's poor. Transformative adaptation is crucial to mitigate risks and vulnerabilities, necessitating adequate, accessible, and appropriate financing. While Multilateral Development Banks play a critical role, expanding public sector climate finance and incentivizing private investments are essential for effective adaptation, thereby improving capacity-building programs and climate resilience infrastructure (Lipper et al., 2021).

Cultural practices also significantly contribute to livestock systems' resilience. Strategies should integrate indigenous knowledge, promote local breeds adapted to climate conditions, and support traditional herding and grazing practices. Community-based management approaches for shared grazing lands can further enhance resilience. Indigenous knowledge of rangeland management in East and the Horn of Africa supports drought-resilient livelihoods. Advocating participatory research that integrates herders' knowledge into policy-making is crucial (Oba, 2009). Herders' selected indicators inform decision-making, shaping resource governance and coping strategies across space and time. Integrated frameworks enhance sustainable management.

Sub-Saharan Africa's diverse climates and ecosystems necessitate customized mitigation approaches (Descheemaeker et al., 2016). Adaptation strategies must acknowledge regional vulnerabilities, available resources, and cultural norms. Stakeholders' active engagement is crucial to overcoming barriers to success, which are diverse and often revolve around biophysical, knowledge, and financial constraints, as indicated by Shackleton (2015). However, deeper exploration is needed to understand the compounded impacts and interactions of these barriers, including the less recognized political, social, and psychological factors (Shackleton, 2015). These are often overlooked unless specifically targeted by research efforts. Water management may be prioritized in arid regions, while disease control and pasture management are critical in humid areas. Future climate projections for Southern Africa indicate decreased rainfall, rising temperatures, and heightened variability, particularly affecting the drier western regions (Nhemachena et al., 2020). This poses significant challenges for agriculture, with projected productivity reductions of 15%–50%, exacerbating food insecurity (Nhemachena et al., 2020). Addressing this requires sustainable water and energy management, alongside accessible adaptation measures, to ensure sustainable development and livelihoods (Nhemachena et al., 2020).

A holistic approach, addressing socio-economic, cultural, and regional factors, ensures targeted, sustainable, and impactful mitigation efforts against climate change's adverse effects on livestock production. For instance, the concern arises from the projection that 80% of global meat production growth will occur in LMICs (low- and middle-income countries). Studies often overlook the triple-bottom line of social, economic, and environmental aspects in mitigation efforts. While strategies combining emissions reduction and carbon sequestration offer optimal mitigation, the focus should shift towards holistic, multi-metric approaches considering the broader purpose of livestock systems (Harrison et al., 2024). Consequential life cycle assessments and socio-economic planetary boundaries can guide sustainability metrics, necessitating collaborative dialogue among stakeholders for globally reconciled metrics to avoid maladaptive outcomes (Harrison et al., 2024).

Importance of sustainable land management practices to enhance resilience to climate change

Integrating sustainable land management practices into livestock production systems in Sub-Saharan Africa can significantly enhance resilience to climate change and promote long-term environmental sustainability and food security (Were et al., 2016). Agroforestry, rotational grazing, and soil conservation techniques are key components of this approach (Figure 2) (Amede et al., 2023).

Agroforestry involves planting trees alongside crops or pastures, which can provide multiple benefits such as improved soil fertility, enhanced biodiversity, and increased carbon sequestration (Mbow et al., 2014). Incorporating agroforestry into livestock production systems can offer shade and shelter for animals, while also diversifying income sources through the production of timber, fruits, and other non-timber forest products (Were et al., 2016). A study, have showed that, Agroforestry holds promise for enhancing food security, climate resilience, and environmental sustainability in Africa's rural areas. It plays a vital role in large-scale mitigation efforts like REDD+ and AFOLU, offering a pathway to resilience for farmers facing climate and land challenges (Mbow et al., 2014).

Rotational grazing involves moving livestock between different grazing areas to prevent overgrazing and allow vegetation to regenerate (Teague and Barnes, 2017). This practice helps maintain soil health, preserve biodiversity, and mitigate erosion. Implementing rotational grazing systems can also improve forage quality and quantity, leading to better livestock nutrition and productivity (Teague and Barnes, 2017). A study that looked at climate smart grazing system, revealed that, traditional rotational stocking (RT) and

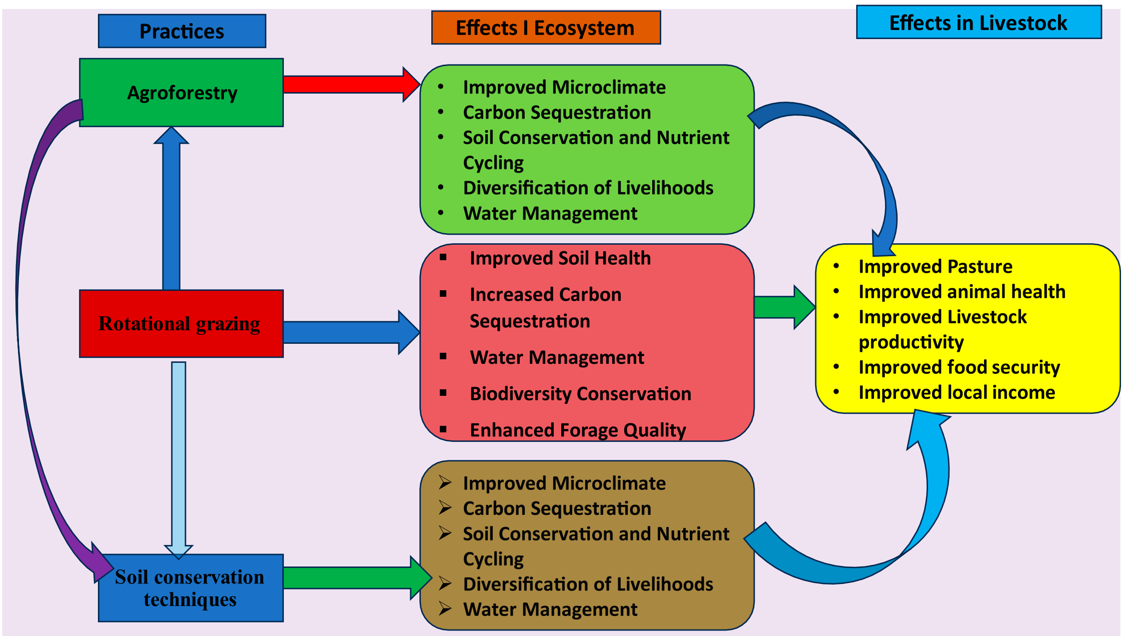

FIGURE 2
Sustainable land management practices to enhance resilience to climate change.

"Rotatinuous" stocking (RN) both contributed on the productivity of pasture and animal in different level, such suggest that, their practices are essential in livestock management system specifically when looking climate resiliency system (Savian et al., 2021).

Soil conservation techniques, including terracing, contour plowing, and cover cropping, aim to prevent soil erosion and enhance soil moisture retention (Figure 2). By reducing soil degradation and improving soil structure, these practices contribute to increased agricultural productivity and resilience to climate change impacts such as droughts and floods (Wolka et al., 2018).

To effectively integrate these sustainable land management practices into livestock production systems in Sub-Saharan Africa, it is essential to provide training and extension services to farmers, access to appropriate technologies and inputs, and incentives for adoption. Additionally, supportive policies and institutional frameworks that promote sustainable land management and provide incentives for conservation efforts are crucial for scaling up these practices across the region. By promoting the adoption of agroforestry, rotational grazing, and soil conservation techniques, Sub-Saharan Africa can build more resilient and sustainable livestock production systems that contribute to food security, mitigate climate change impacts, and conserve natural resources for future generations (Wolka et al., 2018; Wolka et al., 2018; Savian et al., 2021).

Discussion

Sub-Saharan Africa's livestock production sector confronts daunting challenges from climate change, including altered precipitation patterns, temperature fluctuations, water scarcity, disease proliferation, and diminished reproductive performance. These adversities reverberate across food security, economic stability, and livelihoods. Nevertheless, avenues exist to bolster resilience and sustainability through adept mitigation strategies.

Integrated adaptation strategies tailored to Sub-Saharan Africa's diverse livestock species are imperative. These strategies must encompass socio-economic factors, cultural practices, and regional disparities for maximum efficacy and inclusivity. Sustainable land management practices such as agroforestry, rotational grazing, and soil conservation should be mainstreamed to fortify livestock production systems against climate vagaries. These practices hold promise in conserving natural resources, mitigating environmental degradation, and fostering long-term food security.

Securing adequate, accessible, and appropriate climate finance is paramount to execute mitigation and adaptation initiatives. Public sector climate finance expansion and incentivizing private sector investments are pivotal for fortifying climate-resilient infrastructure and enhancing capacity-building programs. Stakeholder engagement, inclusive of local communities, farmers, policymakers, researchers, and development agencies, is pivotal. Their involvement ensures contextually relevant and sustainable strategies. Moreover, prioritizing research and fostering knowledge sharing platforms are essential for unraveling complex climate-livestock-livelihood interactions and disseminating best practices across Sub-Saharan Africa's diverse regions and stakeholders.

Author contributions

KN conceived the idea, penned the initial draft, and conducted literature searches. LG undertook a comprehensive analysis, restructured the content, and meticulously edited and proofread the document.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

We acknowledge the University of Dodoma for providing the space and resources for writing this manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

References

Amede, T., Konde, A. A., Muhinda, J. J., and Bigirwa, G. (2023). Sustainable farming in practice: building resilient and profitable smallholder agricultural systems in sub-Saharan Africa. *Sustainability* 15 (7), 5731. doi:10.3390/su15075731

Amerino, J., Apedo, C. K., Anang, B. T., and Lin, C. (2024). Factors influencing adoption of cocoa agroforestry in Ghana: analysis based on tree density choice. *Sustain. Environ.* 10 (1). doi:10.1080/27658511.2023.2296162

Baumgard, L. H., Rhoads, R. P., Rhoads, M. L., Gabler, N. K., Ross, J. W., Keating, A. F., et al. (2012). Impact of climate change on livestock production. *Environ. stress amelioration Livest. Prod.*, 413–468. doi:10.1007/978-3-642-29205-7_15

Bett, B., Kiunga, P., Gachohi, J., Sindato, C., Mbotha, D., Robinson, T., et al. (2017). Effects of climate change on the occurrence and distribution of livestock diseases. *Prev. vet. med.* 137, 119–129.

Bogale, G. A., and Erena, Z. B. (2022). Drought vulnerability and impacts of climate change on livestock production and productivity in different agro-Ecological zones of Ethiopia. *J. Appl. Animal Res.* 50 (1), 471–489. doi:10.1080/09712119.2022.2103563

Descheemaeker, K., Oosting, S. J., Homann-Kee Tui, S., Masikati, P., Falconnier, G. N., and Giller, K. E. (2016). Climate change adaptation and mitigation in smallholder crop–livestock systems in sub-saharan Africa: A call for integrated impact assessments. *Reg. Environ. Change* 16, 2331–2343. doi:10.1007/s10113-016-0957-8

Ericksen, P., de Leeuw, J., Thornton, P., Said, M., Herrero, M., Notenbaert, A., et al. (2013). Pastoralism and development in Africa: dynamic change at the margins.

Giridhar, K., and Samireddypalle, A. (2015). "Impact of climate change on forage availability for livestock," in Climate Change Impact on Livestock: Adaptation and Mitigation, 97–112.

Godde, C. M., Boone, R. B., Ash, A., Waha, K., Sloat, L., Thornton, P. K., et al. (2021). Risk of Climate-Related Impacts on Global Rangelands-A Review and Modelling Study.

Harrison, S., Franklin, J., Hernandez, R. R., Ikegami, M., Safford, H. D., and Thorne, J. H. (2024). "Climate change and California's terrestrial biodiversity," in Proceedings of the National Academy of Sciences, 121 (32), e2310074121.

Kaasschieter, G. A., De Jong, R., Schiere, J. B., and Zwart, D. (1992). Towards a sustainable livestock production in developing countries and the importance of animal health strategy therein. *Veterinary Q.* 14 (2), 66–75. doi:10.1080/01652176.1992.9694333

Lipper, L., Cavatassi, R., Symons, R., Gordes, A., and Page, O. (2021). Financing adaptation for resilient livelihoods under food system transformation: The role of multilateral development Banks. *Food Secur.* 13, 1525–1540. doi:10.1007/s12571-021-01210-7

Mapiye, O., Chikwanha, O. C., Makombe, G., Dzama, K., and Mapiye, C. (2020). Livelihood, food and nutrition security in southern Africa: What role do indigenous cattle genetic resources play? *Diversity* 12 (2), 74. doi:10.3390/d12020074

Mbow, C., Van Noordwijk, M., Luedeling, E., Neufeldt, H., Minang, P. A., and Kowero, G. (2014). Agroforestry solutions to address food security and climate change challenges in Africa. *Curr. Opin. Environ. Sustain.* 6, 61–67. doi:10.1016/j.cosust.2013.10.014

Naqvi, S. M. K., Kumar, D., De, K., and Sejian, V. (2015). "Climate change and water availability for livestock: impact on both quality and quantity." in Climate Change Impact on Livestock: Adaptation and Mitigation, 81–95.

Ngongolo, K., Omary, K., and Andrew, C. (2021). Social-economic impact of chicken production on resource-constrained communities in Dodoma, Tanzania. *Poultry Sci.* 100 (3), 1009.

Nhemachena, C., Nhamo, L., Matchaya, G., Nhemachena, C. R., Muchara, B., Karuaihe, S. T., et al. (2020). Climate change impacts on water and agriculture sectors in Southern Africa: threats and opportunities for sustainable development. *Water*, 12 (10), 2673.

Oba, G. (2014). Climate change adaptation in Africa: an historical ecology. Routledge.

Pandey, H. O., and Upadhyay, D. (2022). Global livestock production systems: Classification, status, and future trends. *Emerg. Issues Clim. Smart Livest. Prod.*, 47–70. doi:10.1016/b978-0-12-822265-2.00017-x

Saikanth, D. R. K., Kumar, S., Rani, M., Sharma, A., Srivastava, S., Vyas, D., et al. (2023). A comprehensive review on climate change adaptation strategies and challenges in agriculture. *Int. J. Environ. Clim. Change* 13 (11), 10–19. doi:10.9734/ijecc/2023/v13i113138

Savian, J. V., Schons, R. M. T., de Souza Filho, W., Zubieta, A. S., Kindlein, L., Bindelle, J., et al. (2021). 'Rotatinuous' stocking as a climate-smart grazing management strategy for sheep production. *Sci. Total Environ.* 753, 141790. doi:10.1016/j.scitotenv.2020.141790

Savsani, H. H., Padodara, R. J., Bhadaniya, A. R., Kalariya, V. A., Javia, B. B., Ghodasara, S. N., et al. (2015). Impact of climate on feeding, production and reproduction of animals-a Review. *Agri. Rev.* 36 (1), 26–36.

Sekaran, U., Lai, L., Ussiri, D. A., Kumar, S., and Clay, S. (2021). Role of integrated crop-livestock systems in improving agriculture production and addressing food security–A review. *J. Agric. Food Res.* 5, 100190. doi:10.1016/j.jafr.2021.100190

Shackleton, S., Ziervogel, G., Sallu, S., Gill, T., and Tschakert, P. (2015). Why is socially-just climate change adaptation in sub-Saharan Africa so challenging? A review of barriers identified from empirical cases. Wiley Interdiscip. Rev: *Clim. Change*, 6 (3), 321–344.

Stroebel, A. (2004). Socio-economic complexities of smallholder resource-poor ruminant livestock production systems in Sub-Saharan Africa (Doctoral Dissertation). University of the Free State.

Teague, R., and Barnes, M. (2017). Grazing management that regenerates ecosystem function and grazingland livelihoods. *Afr. J. Range & Forage Sci.* 34 (2), 77–86. doi:10.2989/10220119.2017.1334706

Thornton, P. K., Boone, R. B., and Ramírez Villegas, J. (2015). *Climate change impacts on livestock*. CCAFS Working Paper. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Thornton, P. K., van de Steeg, J., Notenbaert, A., and Herrero, M. (2009). The impacts of climate change on livestock and livestock systems in developing countries: a review of what we know and what we need to know. *Agric. Syst.* 101 (3), 113–127. doi:10.1016/j.agsy.2009.05.002

Were, K., Gelaw, A. M., and Singh, B. R. (2016). "Smart strategies for enhanced agricultural resilience and food security under a changing climate in sub-Saharan Africa," in *Climate change and multi-dimensional sustainability in african agriculture: climate change and sustainability in agriculture*, 431–453.

Wolka, K., Mulder, J., and Biazin, B. (2018). Effects of soil and water conservation techniques on crop yield, runoff and soil loss in sub-saharan Africa: a review. *Agric. water Manag.* 207, 67–79. doi:10.1016/j.agwat.2018.05.016

Pastoralism Research, Policy and Practice

TYPE Original Research
PUBLISHED 02 July 2025
DOI 10.3389/past.2025.14566

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OPEN ACCESS

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RECEIVED 28 February 2025
ACCEPTED 16 June 2025
PUBLISHED 02 July 2025

CITATION
Gurmu EB, Kiprotich LE, Kagai JG, Solomon A, Leitner S, Marquardt S, Merbold L, Ndungu PW and Arndt C (2025) Beyond default estimates: developing system-specific Tier 2 enteric methane emission factors for rangeland cattle in Kenya.
Pastoralism 15:14566.
doi: 10.3389/past.2025.14566

Beyond default estimates: developing system-specific Tier 2 enteric methane emission factors for rangeland cattle in Kenya

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Livestock production in Kenya is a significant source of greenhouse gas emissions, particularly methane (CH_4) from enteric fermentation. The objective of the study was to estimate enteric methane (CH_4) emission factors (EFs, kg CH_4/head/year) for rangeland cattle in Kenya. The study utilized the Intergovernmental Panel on Climate Change (IPCC) Tier 2 method, incorporating animal characteristics, performance data, and diet digestibility. Data were obtained from 1,486 cattle across three locations in Kenya's pastoral areas: Kapiti Research Station and Wildlife Conservancy (815 cattle), Olkirimatian Community Ranch (347 cattle), and Shompole Community Ranch (324 cattle) all located in southern Kenya. Animal activity data were collected for four seasons during 1 year at Kapiti, and one dry and one wet season in Olkirimatian and Shompole. The EFs were estimated for wet and dry seasons, allowing the calculation of mean annual EFs. The EFs were calculated for the different cattle categories: adult females and males (≥3 years), young males and females (1–3 years) and calves (<1 year). The results revealed significant differences in herd composition, live weight (LW), weight gains, milk yield, and digestible energy (DE) of pasture among the locations, all of which influence CH_4 emissions. LW varied among the three locations due to differences in breed between sites and varied substantially compared to Tier 1 assumptions, and DE differed significantly across sites (54.5%–66.4%), despite the Tier 1 approach assuming a fixed DE value for pasture (58%). There was a significant difference ($p < 0.05$) in the herd level EF of all cattle categories: Kapiti (64 ± 0.9 kg CH_4/head/year), followed by Olkirimatian (52 ± 1.2 kg CH_4/head/year) and Shompole (42 ± 1.0 kg CH_4/head/year). A comparison of the estimated herd level Tier 2 EFs with computed herd level Tier 1 values revealed that Kapiti exhibited 18% higher mean Tier 2 EFs, while it was lower by 7% and 28% in Olkirimatian and Shompole, respectively. These findings highlight the need for system-specific national EFs that better capture the diversity of production systems and breed differences. Policymakers and researchers should revise IPCC default values to incorporate breed-specific factors within systems.

KEYWORDS
IPCC, pastoral systems, semi-arid environments, ranching, southern Kenya

Introduction

Livestock production is a major agricultural activity in Kenya, contributing 30 percent of the agricultural GDP and 12 percent to the national GDP (Thornton et al., 2019). However, the sector also significantly contributes to greenhouse gas (GHG) emissions, primarily through methane (CH_4) emissions from enteric fermentation (Ortiz-Gonzalo et al., 2017). Methane is a potent GHG with a global warming potential over 80 and 28 times greater than carbon dioxide on a 20- and 100-year timescale, respectively, making it a significant contributor to global warming and climate change (IPCC, 2021). Some estimates show that enteric emissions accounted for 98% of livestock management-associated GHGs in Kenya's livestock production system (Mwaura et al., 2019).

Kenya's diverse agroecological zones support a wide range of livestock production systems, including mixed-crop livestock system, traditional pastoral systems and emerging ranching systems (Kosgey et al., 2008; Njarui et al., 2016; Ngetich et al., 2023). Traditional pastoral systems are characterized by extensive grazing on natural grasslands, with limited external feed inputs and a focus on animal mobility to exploit seasonal variations in forage availability (Lutta et al., 2021). In contrast, ranching systems can provide a more controlled approach to livestock management, aiming to ensure adequate nutrition and manage grazing pressure (Yurco, 2017; Ndiritu, 2021). However, evidence shows that overgrazing in rangelands is often a consequence of constraints on pastoralist mobility—such as land privatization and restricted movement—rather than an inherent outcome of pastoralism itself. When mobility is maintained, pastoralist systems have been demonstrated to be among the most sustainable for managing rangeland resources (Oba, 2011).

Rural populations in the arid and semi-arid lands (ASALs) are predominantly engaged in traditional pastoralism centered on the raising of cattle and other livestock on rangelands (Karanja Ng'ang'a et al., 2016). Traditional pastoralism is explicitly adapted to cope with the seasonality and spatial variability of forage, relying on herd mobility to access dispersed and fluctuating grazing resources (Oba, 2011). This mobility is a key resilience mechanism, allowing pastoralists to buffer against drought and resource scarcity. Sedentarization of pastoralists is not a response to seasonality but rather results from external pressures such as disruption of mobility routes, land fragmentation, and limited-service provision to mobile communities. Such loss of mobility can reduce the system's capacity to respond to environmental variability, potentially increasing vulnerability to feed shortages and land degradation (WISP, 2008; Yurco, 2017; Ndiritu, 2021).

Studying greenhouse gas emissions in pastoralist systems is particularly relevant because these systems are frequently reported to have higher emission intensities per unit of product compared to other livestock systems, largely due to low-input management and variable feed quality (Gerber et al., 2013). However, there is considerable debate about these estimates, as conventional methods may not fully capture the unique ecological dynamics and carbon offsets provided by pastoral rangelands (GIZ, 2022). Accurate estimation of enteric CH_4 emissions is essential for understanding the environmental footprint of livestock production for national GHG livestock inventory accounting and developing effective strategies to mitigate enteric emissions (Gerber et al., 2013). The Intergovernmental Panel on Climate Change (IPCC) provides guidelines for estimating GHG emissions, categorizing the methodologies into different tiers based on data availability and specificity. Tier 1 methods rely on one default emission factor for each animal category for Africa, while Tier 2 approaches aim to generate more detailed, site-specific estimates by using local livestock production data such as animal weight, diet, breed, and herd composition.

Rangeland and pastoral systems in Kenya are characterized by high variability in forage availability, traditional mobility strategies, and increasing exposure to climate and policy pressures. Understanding CH_4 emissions in this context is crucial for developing mitigation strategies that are both scientifically robust and socially equitable. Most existing research in Kenya have estimated Tier 2 enteric CH_4 emission factors (EFs) for mixed-crop livestock systems and reported that the IPCC Tier 1 method tends to overestimate emissions from livestock systems in the country (Goopy et al., 2018; Ndung'u et al., 2020; Goopy et al., 2021; Ndung'u et al., 2022). Furthermore, the studies have employed region-specific methods based on locally developed Tier 2 methods at the International Livestock Research Institute, referred to as the "CSIRO" model and not the official IPCC Tier 2 guidelines. By focusing on three distinct rangeland sites, with different breed composition and management practices, this study aims to provide emission factors that are more representative of the diversity and challenges faced by Kenya's rangeland system.

The objective of this study was to estimate enteric CH_4 emissions from two rangeland systems in three locations in

Southern Kenya: Kapiti Research Station and Wildlife Conservancy Shompole and Olkirimatian community ranches. By adopting the IPCC Tier 2 method, which incorporates animal energy requirements derived from animal characteristics, performance, diet quality and herd structure, the study aimed to generate accurate and location-specific enteric CH_4 emission factors for rangeland systems. This study also considers the net energy mobilized due to weight loss, which is not accounted in the recent IPCC guidelines.

While this study focuses on ranching systems, it is important to recognize that these systems exist along a continuum between traditional pastoralism and more controlled ranching. In Kenya, many rangeland areas are managed by pastoralist communities, and the management practices observed in Olkirimatian and Shompole reflect adaptations of traditional pastoral strategies, such as seasonal mobility and communal land use. By comparing these with the more structured management at Kapiti Ranch, our study offers insights into how different rangeland management approaches—ranging from pastoralist to ranching—affect methane emissions. This comparison is particularly relevant for informing climate change mitigation strategies in pastoral regions, where livestock production remains a critical livelihood and emissions source. The study hypothesized that enteric emission factors of cattle vary among different rangeland systems in Southern Kenya.

Materials and methods

Selection of study sites

This study was conducted in three specific locations in southern Kenya-Kapiti Research Station and Wildlife Conservancy (1.63397°S, 37.1476°E), Olkirimatian Community Ranch (1.8997˚S, 36.3010˚E), and Shompole Community Ranch (2.0910˚S, 36.1179˚E)-representing rangeland cattle systems in semi-arid environments. Kapiti Research Station and Wildlife Conservancy is owned by the International Research Institute (ILRI). The other two ranches are located in Magadi where pastoralism is the predominant livestock production system.

Kapiti Research Station and Wildlife Conservancy is located in the semi-arid drylands in southern Kenya with an average rainfall of 550 mm per year (Carbonell et al., 2021). It is found at an elevation of 1,650–1,900 m above sea level and covers an area of 13,279 ha in Machakos County. It is an extensive ranching system where livestock stays in the grasslands all day.

The two community ranches in Magadi (Shompole and Olkirimatian) are Maasai communities in a pastoral rangeland in the south of Kenya (Kajiado county) with average elevation of 641 m above sea level. Magadi is an area abundant in mostly untouched natural resources, encompassing forests, grassy plains, the Ewaso Nyiro River, and unique volcanic landscapes, which include the alkaline Lake Magadi and the Nguruman Escarpment. Olkirimatian community ranch occupies an extensive area of 24,000 ha. Shompole community ranch covers 62,700 ha. In both ranches, the land is owned by pastoralists who have designated settlement and farming area (Ontiri and Robinson, 2018). The animals are managed in paddocks. The paddocks are communally owned by group ranch members, who enforce grazing rules and sustainable use of the paddocks. The community uses traditional bylaws and grazing committees to regulate access to paddocks, including restrictions on grazing certain areas to allow pasture regeneration, especially during dry seasons.

The cattle in Kapiti Research Station and Wildlife Conservancy were either typical Boran breeds or a crossbreed of Holstein and Boran. This cross is not typical of ranch systems. Shompole Ranch had exclusively crossbreeds (Boran with zebus and Boran with Sahiwal), while Olkirimatian kept both crossbreeds (Boran with zebus and Boran with Sahiwal) and dual-purpose indigenous cattle.

Animal characteristics and performance data

The study followed the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019) to estimate enteric CH_4 emissions. In additions, equations from IPCC (2000) and NRC (2001) were used for the estimation of net energy mobilized due to weight loss and net energy for activity utilizing the daily distance travelled. The Tier 2 method requires local data on various animal characteristics, such as live weight, live weight gain, age, sex, physiological status, milk production, milk quality, work hours, and breed, as well as feed characteristics, including feeding situation and feed digestibility.

In Kapiti, five measurements were taken at the beginning and end of each of the four seasons. However, in Olkirimatian and Shompole, three measurements were taken, aligning with the start and end of the dry season, as well as the end of the subsequent long rainy season.

After the initial farm visit in early 2021, during which the farmers either verbally agreed (Kapiti) or signed consent (Magadi) to participate in the project for the full duration, the researchers conducted repeated farm visits to collect data on live weight, milk yield records, and milk and pasture samples. A representative sub-sample of the herd, 815 cattle in the Kapiti research Ranch, 347 cattle in the Olkirimatian community ranch, and 324 cattle in the Shompole community ranch, was considered in the project. The animals were classified into the following age groups: adult male and female cattle (>3 years), young male and heifers (1–3 years), and calves (<1 year). The animals' age was determined using dentition, following the method described by Torell et al. (2003) when farmers did not know animals' ages. Calves' age was determined by farmer recall. Animals that were missing during subsequent farm visits were replaced with other animals.

Live weight measurement and average daily weight gain/loss

Live weights were measured using calibrated cattle weighing scale (dimensions: 1.2 m × 2 m × 1.3 m; YH-T3 Tscale Electronics MFG, Model KW; Kunshan, China) during each visit. The scale was calibrated with known weights before each weighing session in each household. For Kapiti Ranch, the live weight measurements were taken at the beginning and end of the four distinct seasons in Kenya: hot dry (January to February), long rain (March to May), cold dry (June to October), and short rain (November to December). Due to the drought conditions spanning from 2020 to 2023, the animals in Olkirimatian and Shompole migrated to Tanzania and other parts of Kenya in search of feed and water, showing mobility is better following feed scarcity. Hence, live weight measurements were only possible for the start and end of the cold dry season and the end of long rain.

Average live weight change (LWC) was computed using the difference in live weight for each animal between seasons and divided by the number of days between measurements. If a live weight was missing, the average LWC of the herd was applied. Given that we have different breeds and hence mature weights in the study locations, the study derived mature body weight (MW) for male and female animals from Kenya Livestock Breeds Catalogue (2019) for Kapiti and Government of Kenya (2020) for Olkirimatian and Shompole.

Milk yield and its composition

Daily milk production was recorded by the livestock keepers by measuring the morning and evening milk of each lactating cow using calibrated cans that were provided to the farmers at the beginning of the project. Records were obtained from livestock keepers who were literate, trained in record keeping, and supplied with the necessary record books. The daily milk yield (DMY) was then transferred to data collection sheets and the average daily milk output (DMO) per day per season was calculated from the daily milk yield and daily calf milk consumption (DCMC) using Equation 1.

$$\mathrm{DMO}\left(\frac{\mathrm{L}}{\mathrm{d}}\right) = \mathrm{DMY}\left(\frac{\mathrm{L}}{\mathrm{d}}\right) + \mathrm{DCMC}\left(\frac{\mathrm{L}}{\mathrm{d}}\right) \quad (1)$$

Where; **DMO** is the daily milk output (L/d); **DMY** is the daily milk yield calculated by summing up the total milk for the number of days the livestock keepers recorded the yield and dividing it by the number of days, L/day, and **DCMC** is the daily calf milk consumption (in L/d) of pre-ruminant calves) required for all lactating females accompanied by a young calf using Equation 2.

The DCMC was estimated by following the method of Radostits and Bell (1970).

TABLE 1 Chemical composition of milk (Mean ± SE) in the study area.

Milk composition	Kapiti	Olkirimatian	Shompole
Dry season	N = 37	N = 30	N = 26
Fat (%)	5.7 ± 0.1	5.8 ± 0.3	5.3 ± 0.2
Protein (%)	3.1 ± 0.0	3.3 ± 0.0	3.3 ± 0.0
SNF (%)	8.6 ± 0.0	9.0 ± 0.1	9.2 ± 0.1
Density (g/L)	27.6 ± 0.2	29.3 ± 0.6	30.2 ± 0.5
Lactose (%)	4.7 ± 0.0	5.0 ± 0.1	5.0 ± 0.1
Wet season	N = 40	N = 30	N = 26
Fat (%)	5.4 ± 3.2	6.3 ± 0.1	6.4 ± 0.3
Protein (%)	3.0 ± 0.0	3.4 ± 0.1	3.1 ± 0.0
SNF (%)	8.3 ± 0.1	9.4 ± 0.2	8.6 ± 0.1
Density (g/L)	26.9 ± 0.2	30.4 ± 0.8	27.1 ± 0.4
Lactose (%)	4.6 ± 0.0	5.2 ± 0.1	4.7 ± 0.1

N, number of observations.

$$\mathrm{DCMC}\left(\frac{\mathrm{L}}{\mathrm{d}}\right) = \mathrm{LW}\ (\mathrm{kg}) \times 0.107\left(\frac{\mathrm{L}}{\mathrm{kg}}\right) + 3.39\left(\frac{\mathrm{L}}{\mathrm{kg}}\right) \times \mathrm{LWC}\left(\frac{\mathrm{kg}}{\mathrm{d}}\right) \quad (2)$$

Where; **DCMC** is the daily calf milk consumption; **LW** is the live weight of the calf; **0.107** is the constant representing the amount of milk, the calves need for maintenance for every 1 kg of LW.; **3.39** is the constant representing the amount in L required by the calves to gain one kg of live weight; **LWC** is the average live weight change per day.

Furthermore, milk quality was estimated from morning milk samples from representative lactating cows. The milk samples were collected on random days in a season and the samples were kept in a cooling box and analysed the same day with a portable milk analyzer (Lactoscan S Standard 1040, Bulgaria) for butter fat content (BF%), protein content (%), lactose content (%), and specific gravity. Results are shown in Table 1.

Feed characterization and quality

The researchers collected information about the seasonal feed types directly from farmers or farm staff. A composite sample of the different plant materials consumed by cattle were collected from the three study locations, and pooled per location, and their fresh weights were recorded. The samples were then oven-dried at 50°C until a constant weight was reached (3–5 days), ground using a hammer mill, and passed through a 1 mm sieve. The ground samples were stored in sealed plastic containers at room temperature until analysis. The recommended procedure of AOAC International (2006) (2005) was followed for analyzing dry matter (DM, Method 930.15), total nitrogen (N, AOAC Method 990.03), acid detergent fiber (ADF), and neutral detergent fiber (NDF) (AOAC Method 973.18). The gross energy content of the feeds was determined using a Bomb calorimeter (Par 6300, Par Instruments, (Korir et al., 2022)) using standard protocol. Finally, the seasonal dry matter digestibility (DMD) was estimated from the equation of Oddy et al. (1983), as follows using Equation 3:

$$\mathrm{DMD}\left(\frac{\mathrm{g}}{100\mathrm{g\,DM}}\right) = 83.58 - 0.824 \times \mathrm{ADF}\left(\frac{\mathrm{g}}{100\mathrm{g\,DM}}\right) + 2.626 \times \mathrm{N}\left(\frac{\mathrm{g}}{100\mathrm{g\,DM}}\right) \quad (3)$$

where; **DMD** is dry matter digestibility, % or g/100 g DM; **ADF** is acid detergent fiber, % or g/100 g DM, and **N** is nitrogen content in the feed, % or g/100 g DM.

Subsequently, the DE % was estimated from the seasonal DMD using Equation 4 derived from CSIRO (2007), as IPCC methodology utilizes digestible energy (DE, % of gross energy) for the calculation of net energy requirements,

$$\mathrm{DE}\,\% = \frac{\mathrm{DMD}\,(\%) \times 0.172 - 1.707}{0.81 \times \mathrm{GE}\left(\frac{\mathrm{MJ}}{\mathrm{kg\,DM}}\right)} \times 100 \quad (4)$$

Where; **DE %** is the digestible energy as a percentage of feed gross energy; **DMD** is seasonal dry matter digestibility, %, as estimated in Equation 1, **0.172** and **1.707** are constants used in a formula to convert **DMD** into megajoules (MJ) of metabolizable energy per kilogram of dry matter (DM); **0.81** is a factor that converts metabolizable energy to digestible energy; GE is gross energy of feed (MJ/kg DM).

Locomotion data

The average daily distance traveled was determined using GPS collars. Collars were attached in the morning before releasing the animals for grazing on randomly selected cattle. Due to the limited number of collars and to obtain data from as many animals as possible per season, collars were changed between animals every 3 days (Goopy et al., 2018; Ndung'u et al., 2020). As the animals were confined at night, only data collected between 6:00 a.m in the morning and 7:00 p.m. were considered. Data were obtained from ten cattle during the dry season and eight cattle during the wet season. Enteric CH_4 emission.

Based on the 2019 Refinement to the IPCC (2006), the daily enteric EF was calculated from gross energy intake (GEI) and Ym (the fraction of gross energy intake released in the form of CH_4). The following Tier 2 equation (Equation 5) from IPCC (2019) was used to compute seasonal EF and annual EF:

$$\mathrm{EF}_{\mathrm{season}}\left(\frac{\mathrm{kg\,CH4}}{\mathrm{season}}\right) = \left[\frac{\left(\mathrm{GEI}\left(\frac{MJ}{day}\right) \times \frac{\mathrm{Ym}\,(\%)}{100}\right)}{55.65\left(\frac{\mathrm{MJ}}{\mathrm{kg\,CH4}}\right)}\right] * days\ in\ season \quad (5)$$

where $\mathbf{EF_{season}}$ represents the enteric CH_4 emission factor (in kg CH_4/head/season) estimated from seasonal animal characteristics and performance data based on the IPCC (2019) Tier 2 Equation 10.21, **GEI** is the gross energy intake (in MJ/d) calculated using IPCC equations, and **Ym** is the CH_4 conversion factor, the IPCC (2019) default value of 7.0% was used due to the absence of site-specific value. The factor 55.65 (MJ/kg CH_4) is the energy content of CH_4. Equation 6 shows how the annual **EF** for enteric CH_4 emission (kg CH_4/head/year) was estimated.

$$Annual\ \mathrm{EF}\left(\mathrm{kg}\frac{\mathrm{CH4}}{\mathrm{year}}\right) = \left(\frac{\mathrm{EF}_{\mathrm{season1}}\left(\frac{\mathrm{kg\,CH4}}{\mathrm{season}}\right) + \mathrm{EF}_{\mathrm{season\,2}}\left(\frac{\mathrm{kg\,CH4}}{\mathrm{season}}\right) + \cdots}{\mathrm{Number\ of\ seasons}}\right) \quad (6)$$

The GEI was calculated using Equation 7 derived from IPCC (2019), with the incorporation of the net energy mobilized (**NE_{mob}**) due to weight loss as per IPCC (2000) and the calculation of net energy for travel (NE_t) instead of net energy for activity (NE_a) using the daily distance traveled as per NRC (2001).

$$\mathrm{GEI\ (MJ/d)} = \left[\frac{\left(\frac{\mathrm{NE_m}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right) + \mathrm{NE_t}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right) + \mathrm{NE_l}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right) + \mathrm{NE_p}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right) + \mathrm{NE_{mob}}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right)}{\mathrm{REM}}\right) + \left(\frac{\mathrm{NE_g}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right)}{\mathrm{REG}}\right)}{\mathrm{DE\ (\%)/100}}\right] \quad (7)$$

where **GEI** is gross energy intake, MJ/d; $\mathbf{NE_m}$ is net energy required by the animal for maintenance MJ/d; $\mathbf{NE_t}$ is net for travel, MJ/d; $\mathbf{NE_l}$ is net energy for lactation, MJ/d; $\mathbf{NE_p}$ is net energy for pregnancy, MJ/d; $\mathbf{NE_{mob}}$ is net energy due to weight loss (mobilized), MJ/d; **REM** is the ratio of net energy available in a diet for maintenance to digestible energy; $\mathbf{NE_g}$ is net energy needed for growth, MJ/day; **REG** is the ratio of net energy available for growth in a diet to digestible energy consumed; **DE** is the energy digestibility of feed in each season expressed as a fraction of gross energy (digestible energy/gross energy). The net energy of work was not included in the equation because animals were not used for work.

The NE_m, NE_l, NE_p NE_g, REM, and REG were calculated as per the respective equations in the IPCC (2019) guidelines as shown in the Supplementary Material.

The NE_t was estimated based on Equation 8 derived from NRC (2001) as,

$$\mathrm{NE_t}\left(\frac{\mathrm{MJ}}{\mathrm{d}}\right) = \left(\mathrm{Dist\ (km)} \times 0.0019\left(\frac{MJ/kg}{km}\right) \times \mathrm{MLW\,(kg)}\right) + \left(0.005\left(\frac{\mathrm{MJ}}{\mathrm{kg}}\right) \times \mathrm{MLW\ (kg)}\right) \quad (8)$$

Where, $\mathbf{NE_t}$ is net energy for travel, MJ/d; **Dist.** (in km) is the average daily distance traveled per season, (data obtained from GPS collar); **0.0019** is the energy (MJ) required per kg LW per kg of walking; MLW is the mean seasonal LW in kg; and **0.005** is the energy (MJ) required per kg LW during grazing.

If live weight loss was observed per season, the net energy mobilized (NE_{mob}) was calculated for lactating and other cattle using Equation 9.

The NE_{mob} for lactating cows was calculated as,

$$NE_{mob}\left(\frac{MJ}{d}\right) = 19.7\left(\frac{MJ/kg}{d}\right) \times LWC\ (kg) \tag{9}$$

where $\mathbf{NE_{mob}}$ is the net energy due to weight loss (mobilized), MJ/day; 19.7 is the amount of energy (in MJ) mobilized per kg of weight loss; and **LWC** is average daily weight loss as calculated in Equation 10. Weight loss is taken, such that the estimated NE_{mob} is a negative number.

Seasonal average LWC (kg/day) was calculated per animal per season using Equation 10,

$$LWC\left(\frac{kg}{D}\right) = \frac{LW_{End\ of\ season}\ (kg) - LW_{Start\ of\ season}\ (kg)}{\text{Number of days between measurements}} \tag{10}$$

Where, **LWC** is the average daily live weight change between measurements, kg/day; and **LW** is the measured live weight of the individual animal, in kg.

For other cattle, the amount of energy mobilized through weight loss (NE_{mob}) was calculated by: (1) inserting the LWC (kg/d) as a positive number into Equation 12 to calculate NE_g, and (2) calculating NE_{mob} as negative 0.8 times this NE_g value (IPCC, 2000).

$$NE_{mob}\left(\frac{MJ}{d}\right) = NE_g\left(\frac{MJ}{d}\right) \times (-0.8) \tag{11}$$

Where $\mathbf{NE_{mob}}$ is the net energy mobilized through weight loss (mobilized), MJ/d. It is a negative number; $\mathbf{NE_g}$ is net energy for growth, MJ/d, calculated by inserting LWC as positive in Equation 11; and −0.8 is the fraction of NEg mobilized through weight loss (IPCC, 2000).

The NE_g was calculated following Equation 12.

$$NE_g\left(\frac{MJ}{d}\right) = 22.02 \times \left(\frac{MLW\ (kg)}{C \times MW\ (kg))}\right)^{0.75} \times LWC^{1.097}\ (kg) \tag{12}$$

Where, $\mathbf{NE_g}$ is the net energy needed for growth, MJ/d; **MLW** is the average LW in the season, kg; **C** is a coefficient with a value of 0.8 for females, 1.0 for castrates, and 1.2 for bulls (NRC, 1996); **MW** is the mature body weight of an adult animal individually, mature females, mature males, and steers) in moderate body condition, kg; LWC is the average daily live weight change in the season, kg/d.

Data analysis

Quantitative data analysis used descriptive statistics and one-way analysis of variance (ANOVA). The one-way ANOVA was employed to examine the variation in mean annual live weights, live weight change, and emission factors (EF) across the three locations. A *post hoc* test (Tukey test) was conducted to compare means. Mean annual values for LW, LWC, and EF were calculated by averaging the data from four seasons in Kapiti and two seasons each in Olkirimatian and Shompole. The analyses were carried out using R software and the Microsoft Excel. In all analyses, *p*-values less than 0.05 were considered statistically significant.

Results

Herd characteristics

The cattle were classified into five categories based on age and sex (Table 2). The composition of the herds varied across the three locations, with Kapiti Ranch having the largest female cattle population.

Animal liveweights for all animal classes were substantially larger at Kapiti compared to Olkirimatian and Shompole (Table 2).

In Kapiti, adult females, growing males and females and calves had a 5%–78% higher LW than the (IPCC 2019) Tier 1 value, while adult males had 18% lower LW. All cattle categories except calves had a 13%–29% and 9.8%–27% lower LW than the IPCC Tier 1 values in Olkirimatian and Shompole, respectively (Table 2).

Kapiti had a higher milk yield than Olkirimatian, with a 129% difference. It had a 62% higher milk yield than the IPCC Tier 1, while Olkirimatian and Shompole had a 29% and 46% lower milk yield, respectively.

Across all animal categories, there were no statistical differences concerning annual mean LWC among the three locations, except for adult males, where Olkirimatian exhibited higher annual mean LWC compared to Kapiti and Shompole (Table 3).

Feed quality

Grazing was the principal feeding system throughout the year in the three rangeland systems and supplementation was not a common practice. The quality of cattle feed, as indicated by various parameters, varied among the three locations. Among the three locations, Shompole generally exhibited the highest DE values (Table 4).

Enteric CH_4 production

The CH_4 EF for different categories of cattle across the three study locations of Kapiti, Olkirimatian, and Shompole showed

TABLE 2 Herd structure, mean live weight, (kg, mean ± SE), and average daily milk yield (l, mean ± SE) for the three study locations in Kenya.

Cattle category	Kapiti		Olkirimatian		Shompole		IPCC (2019) Tier 1
	Mean ± SE	N	Mean ± SE	N	Mean ± SE	N	Mean LW
Adult females	374[a] ± 3	234	251[b] ± 5	87	250[b] ± 4	93	356
Adult males	441[a] ± 9	54	249[c] ± 9	71	385[b] ± 17	21	540
Young females	238[a] ± 3	207	173[b] ± 8	45	195[b] ± 5	75	204
Young males	252[a] ± 4	156	177[b] ± 6	67	184[b] ± 6	54	204
Calves	146[a] ± 3	164	90[b] ± 4	77	96[b] ± 3	81	82
Milk yield	3.9[a] ± 0.1	158	1.7[b] ± 0.1	79	3.5[a] ± 0.0	22	2.4

N = number of observations; Adult females (≥3 years); Adult males (≥3 years); young females (1–3 years); young males (1–3 years); Calves (≤1 year); Means with different superscript letters in the same row indicate significant differences at $p < 0.05$.
NB: IPCC Tier 1 values are derived from the pasture/range systems mentioned in the IPCC (2019) Guidelines Table 10A.2 (New).

TABLE 3 Mean live weight change (g/d, mean ± SE) for the three study locations in Kenya.

Cattle category	Kapiti		Olkirimatian		Shompole		IPCC (2019) Tier 1
	Mean ± SE	N	Mean ± SE	N	Mean ± SE	N	Mean
Adult females	44[a] ± 11	234	70[a] ± 15	87	50[a] ± 12	93	0
Adult males	115[b] ± 24	54	283[a] ± 27	71	125[b] ± 50	21	0
Young females	220[a] ± 9	207	302[a] ± 25	45	218[a] ± 15	75	240
Young males	237[a] ± 14	156	283[a] ± 25	67	244[a] ± 20	54	240
Calves	240[a] ± 13	164	254[a] ± 14	77	288[a] ± 11	81	330

N, number of observations; Adult females (≥3 years); Adult males (≥3 years); young females (1–3 years); young males (1–3 years); Calves (≤1 year); Means with different superscript letters in the same row indicate significant differences at $p < 0.05$.
NB: IPCC Tier 1 values are derived from the pasture/range systems mentioned in the IPCC (2019) Guidelines Table 10A.2 (New).

variations. In general, Kapiti tended to have higher EF compared to Olkirimatian and Shompole for all cattle categories. For instance, the overall EF in Kapiti was 25% and 55% higher than Olkirimatian and Shompole, respectively. This trend was also evident for adult males, heifers, young males, and calves, where Kapiti consistently showed higher EF compared to the other locations.

For Kapiti, the Tier 2 EFs for adult females were 22% higher than the IPCC Tier 1, while for Olkirimatian and Shompole, they were 11% and 27% lower EF than IPCC Tier 1, respectively. Heifers in Kapiti and Olkirimatian had 20% and 7% higher Tier 2 EFs than IPCC Tier 1, while in Shompole, Tier 2 EFs were 11% smaller than Tier 1 EFs.

Discussion

Notable differences were observed in the cattle within the three locations. Specifically, the cattle in Kapiti had greater LW and higher milk production compared to those in Olkirimatian and Shompole. These differences in LW and milk production are attributed to factors such as breed.

The Tier 2 enteric CH_4 EF of cattle in Kapiti consistently ranked the highest across all categories when compared to the other two locations. This observation aligns with the understanding that LW plays a significant role in determining NE_m (Ndung'u et al., 2020). In general, the site with the highest LW tended to have the highest EFs, which generally aligned with the hypothesis.

Differences in EF were not consistent for all study sites: Shompole had a higher mean LW than Olkirimatian across all animal classes, but it displayed lower EFs for all animal classes except adult males. This discrepancy can be attributed to the statistically lower LWC in Shompole than in Olkirimatian, except calves, which resulted in a higher net energy mobilized or lower net energy for weight gain. The higher EF of calves in Olkirimatian despite the lower LWC can be attributed to a higher proportion of pre-ruminant calves (<3 months) in Shompole (55% vs. 25%). Since the rumen of pre-ruminant calves is not fully developed, the emission from these animals was assumed to be negligible (Marquardt et al., 2020). The calves in Shompole had higher EF because higher proportion of pre-ruminant calves with lower EFs were excluded from the calculations.

TABLE 4 Quality of cattle feed in the study locations in Kenya.

Feed quality	Kapiti	Olkirimatian	Shompole
Dry season			
DM, %	92.8 ± 0.2	92.2 ± 0.3	92.5 ± 0.3
NDF, %	68.5 ± 1.0	NA	NA
ADF, %	39.3 ± 0.5	36.1 ± 2.2	32.5 ± 2.0
N, %	0.8 ± 0.1	1.3 ± 0.2	1.8 ± 0.2
GE, MJ/kg DM	16.9 ± 0.3	17.3 ± 0.3	17.0 ± 0.2
DMD, %	53.2 ± 0.5	57.3 ± 2.4	61.6 ± 2.2
DE, %	54.5 ± 0.9	58.8 ± 3.6	64.6 ± 2.9
Wet season			
DM, %	93.7 ± 0.2	93.1 ± 0.3	93.4 ± 0.3
NDF, %	62.1 ± 2.4	NA	NA
ADF, %	37.2 ± 1.4	34.2 ± 2.2	30.8 ± 2.0
N, %	1.0 ± 0.1	1.6 ± 0.2	2.3 ± 0.2
GE, KJ/kg DM	17.3 ± 0.1	17.7 ± 0.3	17.4 ± 0.2
DMD, %	55.7 ± 1.5	60.0 ± 2.4	64.5 ± 2.2
DE, %	56.0 ± 1.8	60.4 ± 3.6	66.4 ± 2.9

DM, dry matter; NDF, Neutral detergent fiber; ADF, Acid detergent fiber; N, nitrogen; GE, gross energy; DMD, Dry matter digestibility and DE, feed digestibility expressed as percent of gross energy. NA, No assessment.

Additionally, 10% higher DE% in Shompole compared to Olkirimatian are likely to contribute to the lower EFs in Shompole. The DE variation showed the analysis result of the composite pasture sample. The variation in DE of the pasture across the three locations is generally consistent with the findings of Lee et al. (2017) who showed the variability in the nutritional quality of forage grasses in different locations.

Normally, it is assumed that enteric CH_4 emissions in adult females, including both lactating and dry cows, increase with rising levels of total milk production of the cows (Goopy et al., 2018). Although the mean daily milk output (DMO) of lactating cows was higher in Shompole compared to Olkirimatian (Table 2), the EF of adult females in Shompole was lower, mainly because of the smaller proportion of lactating animals in Shompole than in Olkirimatian (24% vs. 91%, Table 5). As a result, the annual mean NE_l in Shompole was statistically lower (Supplementary Table S5).

The observed differences in enteric CH_4 EFs among Kapiti, Olkirimatian, and Shompole can be largely attributed to variations in management practices across these locations. Kapiti Research Station operates as an extensive ranching system with controlled grazing, improved pasture management, and the use of crossbred cattle (Boran × Holstein), which tend to have higher productivity and LW. This more regulated system allows for better nutritional management and consistent animal performance, contributing to higher emission factors per animal but potentially lower emission intensity per unit of product. In contrast, Olkirimatian and Shompole represent community-managed pastoral systems characterized by herd mobility, communal grazing, and a predominance of indigenous or crossbred zebu cattle. Lower LW, reduced LW gain, and variable feed quality in these settings resulted in lower annual CH_4 emissions per animal compared to the ranching system at Kapiti.

Additionally, the differences in herd structure, such as a higher proportion of young and non-lactating animals in the pastoral systems, further influenced the emission profiles. Communal management and reliance on natural pastures in pastoral systems typically lead to lower productivity, which, while reducing absolute emissions per animal, may increase emission intensity per unit of product (e.g., milk or meat). These findings highlight the importance of tailoring mitigation strategies and national inventories to account for the diversity of management practices and production environments in Kenya's rangelands.

It was not possible to estimate the statistical differences between the estimated Tier 2 EFs and the IPCC Tier 1 values, because there is only one Tier 1 value. However, numerical differences were observed between Tier 2 and Tier 1 EFs, although the difference was not consistent in the three

TABLE 5 Tier 2 Emission factors (mean ± SE, kg CH_4/head/year) for different categories of cattle in the three study locations].

Cattle category	Kapiti		Olkirimatian		Shompole		IPCC (2019) Tier 1
	Mean ± SE	N	Mean ± SE	N	Mean ± SE	N	Mean
Adult females	90.4[a] ± 1.4	234	66.3[b] ± 1.5	87	54.5[c] ± 1.2	93	74
Lactating	101.0[a] ± 1.4	158	66.5[b] ± 1.5	79	63.0[b] ± 3.1	22	
Non-lactating	68.5[a] ± 1.4	76	53.4[b] ± 5.3	8	51.1[b] ± 1.1	71	
Adult males	82.9[a] ± 1.6	54	70.8[b] ± 2.7	71	75.4[ab] ± 3.0	21	79
Young females	54.9[a] ± 0.8	207	48.5[ab] ± 2.2	45	41.1[b] ± 1.1	75	46
Young males	56.3[a] ± 0.9	156	43.0[b] ± 1.5	67	36.4[b] ± 1.5	54	46
Calves	39.5[a] ± 0.6	164	25.5[b] ± 1.0	77	22.0[b] ± 0.5	81	31
Overall	64.5[a] ± 0.9	815	51.7[b] ± 1.2	347	41.8[c] ± 1.0	324	

N, number; Adult females (≥3 years); Adult males (≥3 years); young females (1–3 years); young males (1–3 years); Calves (≤1 year); Means with different superscript letters in the same row indicate significant differences at $p < 0.05$.

locations. The difference can be attributed to several parameters. One parameter is the variations in mean LW, which was 18% lower in adult males and 5%–78% higher for other categories of cattle in Kapiti. In Olkirimatian, Tier 2 mean LW was 10% higher in calves and 13%–54% lower for other categories of cattle. In Shompole, it was 17% higher in calves and 4%–29% lower for other categories of cattle (Table 2). Moreover, methodological differences in the calculation of Tier 2 EFs in the present study and Tier 1 estimate contributed to the difference. For instance, IPCC Tier 1 did not consider the NE_{mob} due to weight loss. In contrast, this study estimated the NE_{mob} in the case of weight loss for all categories, following equations adopted from IPCC (2000). Furthermore, according to IPCC (2019) Tier 1, adult animals are typically assumed to have no net weight gain over an entire year, assuming that reduced intakes and emissions associated with weight loss are balanced by increased intakes and emissions during periods of weight gain. However, in the present study, adult animals were observed to show average annual gains although some were observed to lose weight. Hence net energy for growth was calculated for adult animals.

The main difference between Tier 1 and Tier 2 lies in the assumptions made for activity data. The results indicate that using a single default value for the whole of Africa does not adequately capture the diverse regional conditions. Moreover, even within similar systems and regions, variations exist that could be better explained by accounting for breed differences. Therefore, revising IPCC default values to include system-specific estimates for different regions and cattle breeds could help countries without Tier 2 emission factors enhance the accuracy.

The Tier 1 approach applies a fixed DE value for pasture, but our findings show significant variation in observed DE across sites. Understanding whether these differences are linked to agroecological zones, difference in soil composition and if they can be predicted is crucial. Pasture management improvements can enhance pasture digestibility and composition when pasture production and quality is poor. This would lead to higher weight gains, lower feed intake per unit of growth, and ultimately, reduced EFs. Supplementation could be explored during periods of low forage availability to avoid body weight losses, as our findings indicated that some animals experienced body weight loss, highlighting the potential of targeted supplementation strategies in mitigating seasonal nutritional gaps. By improving energy intake during critical periods, supplementation could help stabilize weight gain and reduce the variability in EFs.

A key limitation of this study is the unequal number of measurement periods across the three locations: five at Kapiti and only three at Olkirimatian and Shompole. This discrepancy resulted primarily from the high mobility of pastoral herds in Olkirimatian and Shompole, especially during drought conditions, which made repeated sampling logistically challenging. Consequently, the data from these two sites may not fully capture the extent of seasonal variability in animal performance and CH_4 emissions that could occur under different climatic conditions. Despite this limitation, the three study sites were purposefully selected to represent the diversity of rangeland cattle systems in southern Kenya-Kapiti as an extensive ranching system and Olkirimatian and Shompole as community-managed pastoral systems. While the findings provide valuable system-specific EFs, caution should be exercised in generalizing these results to all rangeland systems in Kenya or similar environments. Future research with more frequent and evenly distributed measurements across all sites and seasons would further strengthen the representativeness and applicability of the EFs generated in this study.

Conclusion

This study provides critical insights into the variability within comparable rangeland systems and its implications for national emission factors (EFs). Our findings demonstrate that using a single default EF for large regions, such as Africa, does not accurately reflect local conditions. Even within geographically similar areas, we observed significant differences in herd composition, live weight (LW), weight gains, milk yield, and digestible energy (DE) of pasture, all of which influence CH_4 emissions.

A key finding is the substantial variation in LW compared to Tier 1 assumptions, as well as significant differences in observed DE across sites, despite the Tier 1 approach assuming a fixed DE. Additionally, we observed body weight loss in some cattle, particularly during periods of low forage availability, emphasizing the potential role of strategic supplementation to maintain weight gain and stabilize emissions. It is important to recognize that in East Africa, pastoralist land use closely mirrors the ecological functions of grazing wildlife, and greenhouse gas emissions from livestock in pastoral systems can be comparable to those from wild herbivores in similar ecosystems. This challenges conventional approaches that attribute all emissions from livestock to pastoral systems as anthropogenic, without accounting for the natural baseline of emissions that would occur from wildlife. Incorporating this perspective into national inventories could lead to more nuanced and equitable climate policies, particularly in wildlife-rich regions such as Kenya and the broader East African rangelands.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal studies were approved by International Livestock Research Institute. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the owners for the participation of their animals in this study.

Author contributions

EG: Writing – original draft, Methodology, Formal Analysis; LK: Data collection; JK: Data collection, Resource mobilization; AS: Data cleaning; SL: Writing – review and editing, Methodology; SM: Writing – review and editing, Conceptualization, Methodology; LM: Writing – review and editing, Conceptualization, Methodology, Fund acquisition; PN: Writing – review and editing, Methodology; CA: Writing – review and editing, Conceptualization, Methodology, Fund acquisition. All authors contributed to the article and approved the submitted version.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The ESSA project (Earth observation and environmental sensing for climate-smart sustainable agropastoralism ecosystem transformation in East Africa) was funded by the European Union through the EU-DeSIRA programme. It also received financial support from the CGIAR Research Initiatives Livestock and Climate and Mitigate+: Low-Emission Food Systems, which are supported by contributors to the CGIAR Trust Fund. Additionally, the work was funded by the International Fund for Agricultural Development (IFAD) through the research projects “Greening Livestock: Incentive-Based Interventions for Reducing the Climate Impact of Livestock in East Africa” (Grant No. 2000000994) and “Programme of Climate Smart Livestock” (PCSL, Programme No. 2017.0119.2). It was also funded by the New Zealand Government to support the objectives of the Livestock Research Group of the Global Research Alliance on Agricultural Greenhouse Gases. Additional support for this research was provided through CGIAR Science Program on Sustainable Animal and Aquatic Foods, Climate Action, and Multifunctional Landscapes and supported by contributors to the CGIAR Trust Fund. CGIAR is a global research partnership for a food-secure future dedicated to transforming food, land, and water systems in a climate crisis.

Acknowledgments

The authors would like to thank the colleagues of the Mazingira Centre and Kapiti Research Station & Wildlife Conservancy, particularly Nelson Kipchirchir, Elly Kibira, and Nehemiah Kimengich, for their support during field and lab work. We would also like to thank Jane Poole for the guidance on data analysis.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. While preparing the manuscript AI was utilized to check and improve the language.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/past.2025.14566/full#supplementary-material

References

AOAC International (2006). *Official methods of analysis*. Arlington, VA, USA: AOAC International.

Carbonell, V., Merbold, L., Díaz-Pinés, E., Dowling, T. P., and Butterbach-Bahl, K. (2021). Nitrogen cycling in pastoral livestock systems in sub-saharan Africa: Knowns and unknowns. *Ecol. Appl.* 31 (6), e02368. doi:10.1002/eap.2368

CSIRO (2007). *Nutrient requirements of domesticated ruminants*. Collingwood, VIC, Australia: CSIRO Publishing.

Gerber, P., Hristov, A., Henderson, B., Makkar, H., Oh, J., Lee, C., et al. (2013). Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: A review. *animal* 7 (s2), 220–234. doi:10.1017/s1751731113000876

GIZ (2022). "Pastoralism and resilience of Food production in the face of climate change," in *Technical background paper*. Editors Saverio, K., Christine, L., Friederike, M., Wiebke, F., and Tobias, F. (Bonn and Eschborn, Germany).

Goopy, J. P., Ndung'u, P. W., Onyango, A., Kirui, P., and Butterbach-Bahl, K. (2021). Calculation of new enteric methane emission factors for small ruminants in western Kenya highlights the heterogeneity of smallholder production systems. *Animal Prod. Sci.* 61 (6), 602–612. doi:10.1071/an19631

Goopy, J. P., Onyango, A. A., Dickhoefer, U., and Butterbach-Bahl, K. (2018). A new approach for improving emission factors for enteric methane emissions of cattle in smallholder systems of East Africa–Results for Nyando, Western Kenya. *Agric. Syst.* 161, 72–80. doi:10.1016/j.agsy.2017.12.004

Government of Kenya (2020). Inventory of GHG emissions from dairy cattle in Kenya 1995-2017. Available online at: http://www.kilimo.go.ke/wp-content/uploads/2020/07/Kenya-Dairy-Cattle-GHG-inventory-Report_06_07_2020.pdf.

IPCC (2000). "Good practice guidance and uncertainty management in national greenhouse gas inventories. Chapter 4: agriculture," in *Methodology report*. Editors Penman, J., Kruger, D., Galbally, I., Hiraishi, T., Nyenzi, B., and Emmanuel, S.

IPCC (2006). "Emissions from Livestock and Manure Management," in *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use.* Editors Dong, H., Mangino, J., McAllister, T. A., Hatfield, J. L., Johnson, D. E., Lassey, K. R., et al. (Geneva, Switzerland: IPCC), Chapter 10.

IPCC (2019). "Emissions from livestock and manure managemen," in *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories, volume 4: agriculture, forestry and other land use*. Editors Buendia, E. C., Tanabe, K., Kranjc, A., Jamsranjav, B., Fukuda, M., and Ngarize, S. (Geneva, Switzerland: IPCC). *Chapter 10.*

IPCC (2021). "Summary for Policymakers," in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Editors Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berge, S., et al. (Geneva, Switzerland: IPCC). Cambridge, United Kingdom: Cambridge University Press. 3–32.

Kenya Livestock Breeds Catalogue (2019). Ministry of agriculture, livestock, fisheries and cooperatives state department of livestock, AU-IBAR

Korir, D., Marquardt, S., Eckard, R., Sanchez, A., Dickhoefer, U., Merbold, L., et al. (2022). Weight gain and enteric methane production of cattle fed on tropical grasses. *Animal Prod. Sci.* 63 (2), 120–132. doi:10.1071/an21327

Kosgey, I., Rowlands, G., van Arendonk, J. A., and Baker, R. (2008). Small ruminant production in smallholder and pastoral/extensive farming systems in Kenya. *Small Ruminant Res.* 77 (1), 11–24. doi:10.1016/j.smallrumres.2008.02.005

Lee, M. A., Davis, A. P., Chagunda, M. G., and Manning, P. (2017). Forage quality declines with rising temperatures, with implications for livestock production and methane emissions. *Biogeosciences* 14 (6), 1403–1417. doi:10.5194/bg-14-1403-2017

Lutta, I. A., Wasonga, V. O., Karanja, R., Saalu, F., and Njiru, J. (2021). "Costs and benefits of sustainable rangeland management practices in Northern Kenya," in *Report for the economics of land degradation initiative in the framework of the "reversing land degradation in Africa through scaling-up evergreen agriculture*. project.

Marquardt, S., Ndung'u, P., Onyango, A. A., and Merbold, L. (2020). "Protocol for a Tier 2 approach to generate region-specific enteric methane emission factors (EF) for cattle kept in smallholder systems," in *ILRI manual.*

Mwaura, F., Ngigi, M., and Obare, G. (2019). Determinants of households' agricultural and energy associated greenhouse Gases emissions among smallholders in western Kenya. *J. Sustain. Dev.* 12 (4), 177. doi:10.5539/jsd.v12n4p177

Ndiritu, S. W. (2021). Drought responses and adaptation strategies to climate change by pastoralists in the semi-arid area, Laikipia County, Kenya. *Mitig. Adapt. strategies Glob. Change* 26 (10), 10–18. doi:10.1007/s11027-021-09949-2

Ndung'u, P. W., Bebe, B., Ondiek, J., Butterbach-Bahl, K., Merbold, L., and Goopy, J. (2020). Corrigendum to: improved region-specific emission factors for enteric methane emissions from cattle in smallholder mixed crop: Livestock systems of nandi county, Kenya. *Animal Prod. Sci.* 60 (13), 1668. doi:10.1071/an17809_co

Ndung'u, P. W., Takahashi, T., Du Toit, C. J. L., Robertson-Dean, M., Butterbach-Bahl, K., McAuliffe, G., et al. (2022). Farm-level emission intensities of smallholder cattle (*Bos indicus*; B. indicus–B. taurus crosses) production systems in highlands and semi-arid regions. *Animal* 16 (1), 100445. doi:10.1016/j.animal.2021.100445

Ng'ang'a, S. K., Bulte, E. H., Giller, K. E., Ndiwa, N. N., Kifugo, S. C., McIntire, J. M., et al. (2016). Livestock wealth and social capital as insurance against climate risk: a case study of samburu county in Kenya. *Agric. Syst.* 146, 44–54. doi:10.1016/j.agsy.2016.04.004

Ngetich, W., K Gitau, G., O Abuom, T., and O Aboge, G. (2023). Description of cattle production systems in different agro-ecological zones of Narok County, Kenya. *East Afr. J. Sci. Technol. Innovation* 4 (4). doi:10.37425/eajsti.v4i4.765

Njarui, D., Gichangi, E., Gatheru, M., Nyambati, E., Ondiko, C., Njunie, M., et al. (2016). A comparative analysis of livestock farming in smallholder mixed crop-livestock systems in Kenya: 1. Livestock inventory and management. *Livest. Res. Rural Dev.* 28 (4). Available online at: http://www.lrrd.org/lrrd28/24/njar28066.html.

NRC (1996). *Nutrient requirements of beef cattle, national research council*. Washington, DC: National Academy Press.

NRC (2001). *Nutrient requirements of dairy cattle, national research council*. Washington, USA: National Academy Press.

Oba, G. (2011). "Mobility and the sustainability of the pastoral production system in Africa: Perspectives of contrasting paradigms," in *Future of pastoral peoples in Africa organized by" pastoralism" in the future agriculture consortium at ILRI in addis ababa, Ethiopia from*, 21–23.

Oddy, V., Robards, G., and Low, S. (1983). "Prediction of in vivo dry matter digestibility from the fibre and nitrogen content of a feed," in *Feed information and animal production*. Editors G. E. Robards and R. G. Packham (Farnham Royal, United Kingdom: Commonwealth Agricultural Bureaux). 395–398.

Ontiri, E. M., and Robinson, L. W. (2018). "Community-based rangeland management in Shompole and Olkiramatian group ranches, Kenya: taking successes in land restoration to scale project," in *ILRI project report* (Nairobi, Kenya: ILRI).

Ortiz-Gonzalo, D., Vaast, P., Oelofse, M., de Neergaard, A., Albrecht, A., and Rosenstock, T. S. (2017). Farm-scale greenhouse gas balances, hotspots and uncertainties in smallholder crop-livestock systems in Central Kenya. *Agric. Ecosyst. and Environ.* 248, 58–70. doi:10.1016/j.agee.2017.06.002

Radostits, O., and Bell, J. (1970). Nutrition of the pre-ruminant dairy calf with special reference to the digestion and absorption of nutrients: a review. *Can. J. Animal Sci.* 50 (3), 405–452. doi:10.4141/cjas70-063

Thornton, P., Enahoro, D., Njiru, N., van Wijk, M., Ashley, L., Cramer, L., et al. (2019). "Program for climate-smart livestock systems," in *Country stocktake: Kenya, ILRI report* (Nairobi, Kenya: ILRI).

Torell, R., Bruce, B., Kvasnicka, B., and Conley, K. (2003). "Methods of determining age of cattle," in *Cattle producer's library: CL712* (Reno, NV: University of Nevada). Available online at: http://www.unce.unr.edu/publications/files/ag/other/cl712.pdf (Accessed August 2, 2023)

WISP (2008). Sustainable Pastoralism – moving forward with appropriate policies.

Yurco, K. (2017). Herders and herdsmen: the remaking of pastoral livelihoods in Laikipia, Kenya. *Pastoralism* 7, 15–11. doi:10.1186/s13570-017-0086-0

Pastoralism
Research, Policy and Practice

TYPE Original Research
PUBLISHED 25 July 2025
DOI 10.3389/past.2025.14461

OPEN ACCESS

EDITED BY
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RECEIVED 07 February 2025
ACCEPTED 16 June 2025
PUBLISHED 25 July 2025

CITATION
Corrêa DCdC, Poccard-Chapuis R, Blanfort V, Bochu J-L and Lescoat P (2025) Impacts of cattle farming practices and associated livestock systems on energy balances and greenhouse gas emissions in the municipality of Paragominas - State of Pará - Amazonia. *Pastoralism* 15:14461. doi: 10.3389/past.2025.14461

Impacts of cattle farming practices and associated livestock systems on energy balances and greenhouse gas emissions in the municipality of Paragominas - State of Pará - Amazonia

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Greenhouse gas (GHG) emissions and energy use are important parameters in the development of sustainable livestock systems. On-farm management practices can maximise energy efficiency and reduce gas emissions, however, these practices have yet to be identified and characterized. This study evaluated the eco-efficiency of cattle farming, considering a combination of the energy balance and GHG emissions from 33 farms in the Brazilian Amazon (Paragominas - Pará), using a diagnostic tool adapted to the region. The farms represented the diverse production systems operating in the area, distinguished by their activity (dairy, breeder, breeder-fattener and fattener), degree of intensification, and agrarian situation (corresponding to the farm's geographical location and social and economic inclusion in the municipality). Energy efficiency on beef cattle farms is on average 16.29 GJ/t live weight (min = 1.74 GJ/t, max = 43.01 GJ/t), and on dairy farms 2.74 GJ/1000 L (min = 0.17, max = 6.48), i.e., respectively 46% and 40% lower than the figures reported by studies conducted in metropolitan France. Improved grazing enhances natural resources by optimising the use of forage biomass, which has a positive impact on energy efficiencies. The purchase of young animals and fertilisation account for a high percentage of energy consumption, with fuel constituting the major part of the direct energy consumed. GHG emissions are on average 17.40 teqCO_2/t live weight (min = 6.13, max = 40.85), similar to those of metropolitan France (14 teqCO_2/t). When emissions from livestock and storage by forests and pastures over 20 years of age are taken into account, farms have a positive carbon balance. The deforestation levels of each farm over the past 20 years have a strong impact on this balance sheet, which can make it negative.

This study highlights the effectiveness of the method in identifying systems and practices that could help farms achieve greater sustainability in terms of energy use and GHG emissions.

KEYWORDS

environmental impact, efficiency, livestock production, livestock emissions, ecological intensification

Introduction

Livestock expansion in the Amazon, and GHG emissions

Between 2000 and 2021, global meat production increased by 53%, reaching 357 million tons in 2021, which included 73 million tons of beef (FAOSTAT, 2023). During this period, Brazil was the second leading producer in the world, boasting a cattle herd of nearly 239 million head, with about 43% of that held in the Legal Amazon (IBGE, 2023). Defined by Law No. 1,806 of 6 January 1953, the Legal Amazon comprises the states of Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima, and Tocantins, and part of Maranhão. Created for regional planning and development purposes, it includes biomes beyond the Amazon rainforest, such as parts of the Cerrado savanna and a small part of Pantanal wetland (Brasil, 1953), according to the map by Tyukavina et al. (2017).

Despite contributing only 9% to the national Gross Domestic Product (GDP), the Legal Amazon was responsible for approximately 52% of Brazil's greenhouse gas (GHG) emissions in 2020 (IPS Amazônia, 2023). In 2023, the Land Use, Land Use Change and Forests (LULUCF) sector was responsible for the largest share of gross GHG emissions in Brazil, corresponding to 46% of the national total. In the same year, 98% of the emissions attributed to the LULUCF sector originated from deforestation, and 65% of this amount was specifically due to deforestation in the Amazon (Seeg, 2024).

The agricultural and livestock sector is the second largest emitter of GHG in Brazil, contributing approximately 28.5% of the nation's total emissions, with 62% of this figure originating from enteric fermentation of the herd (MCTI, 2022). To reconcile animal production with environmental impacts, strong measures, such as support for research, incentives for efficient and regenerative management, and the adoption of innovative practices, must be adopted to facilitate reductions in GHG emissions from livestock (FAO, 2017) and fossil energy use. The relationship between livestock systems and environmental issues related to land use is complex and often analysed in a simplified way, which can compromise the understanding of their impacts on sustainability. Although livestock farms use extensive areas of land, their effect is not inherently negative; rather, it is contingent on factors such as the type of production system, herd and pasture management, underlying biome where grazing takes place, and the governance of grazed land (Manzano et al., 2024). In Brazil, with contrasting biomes such as rainforests with no strong evolutionary history of grazing, and savannas with sustained strong presence of wild megaherbivores until recently, such complexity is crucial to understand sustainability.

In Brazil, the ecological intensification of cattle farming is widely cited as a means to achieve sustainable agriculture and livestock production. By intensifying grazing production systems, it is possible to increase production without increasing land extension while also contributing to ecosystem services (Cardoso et al., 2020; Cardoso et al., 2017; Palermo et al., 2014). On the other hand, the intensification of production systems affects energy consumption on livestock farms, mainly due to increased inputs. To achieve sustainable livestock production, the environmental impacts of livestock systems, including those generated by the consumption of fossil energy, must be reduced. This can be accomplished by developing systems in which the energy outputs from animal production exceeds the energy inputs. Such an approach also has the potential to reduce GHG emissions (Pérez Neira et al., 2014).

According to Latawiec et al. (2014), the intensification of cattle farming in Brazil is described as "moderate," mainly based on the exploitation of grazed resources. In this context, the intensification of systems comprises two sets of strategies: 1) the adoption of grazing practices designed to increase the production and quality of grazing (e.g., rotational grazing, fertilisation management); and 2) the use of feed and supplementation during the fattener phase. Adopting these practices can potentially contribute to greater weight gain, lower GHG emissions and lower energy consumption per kg of animal product. This also may contribute to increased animal stocking rates, decreased slaughter ages and better land use (de

Abbreviations: ACCT, AgriClimate Change Tools; ELBF, Extensive-Large-Breeder-Fattener; ELF, Extensive-Large-Fattener; EMB, Extensive-Medium-Breeder; EMBF, Extensive-Medium-Breeder-Fattener; EMD, Extensive-Medium-Dairy; ES, Extensive farms; ESB, Extensive-Small-Breeder; ESD, Extensive-Small-Dairy; ESF, Extensive-Small-Fattener; ILBF, Intensive-Large-Breeder-Fattener; ILD, Intensive-Large-Dairy; ILF, Intensive-Large Fattener; IS, Intensive farms; ISD, Intensive-Small-Dairy; ISF, Intensive-Small-Fattener; MIS, Farms in moderate intensification; MLB, Moderate Intensification-Large-Breeder; MLB, Moderate Intensification-Small-Breeder; MLBF, Moderate Intensification-Large-Breeder-Fattener; MLF, Moderate Intensification-Small-Fattener; MMD, Moderate Intensification-Medium-Dairy; MMF, Moderate Intensification-Medium-Fattener.

Carvalho et al., 2023; Ruggieri et al., 2020; Rouquette Jr, 2016; Barbero et al., 2015; Gimenes et al., 2011).

In addition to traditional livestock systems, the adoption of integrated systems, such as silvopastoral systems (SPS), stand out as sustainable alternatives due to their potential to reconcile agricultural production and environmental conservation. These systems are capable of increasing livestock production, recovering the landscape and producing environmental/ecosystem services (Manzano et al., 2024; Mauricio et al., 2019). In the Amazon, the adoption of integrated systems, such as integrated crop-livestock systems (ICLS) and integrated crop-livestock-forest systems (ICLFS), has shown positive effects on the productivity, sustainability, and socioeconomic performance of livestock farms (Martorano et al., 2021).

To consider ways to maintain or increase agricultural production while simultaneously managing natural resources more effectively through the adoption of effective agricultural strategies, we decided to use the concept of eco-efficiency. Eco-efficiency can be defined as the efficiency with which a quantity of agricultural products is obtained from a set of natural resources (land, water, nutrients, energy, biological diversity) while minimising the production of negative environmental externalities, such as GHG emissions (Keating et al., 2013; Keating et al., 2010).

Livestock and deforestation: the colonization of land in the amazon

The Brazilian Amazon is a focal point in debates concerning livestock and the environment. It represents one of the largest biodiversity and forest biomasses in the world while also forming one of the largest reserves of land that is potentially convertible for agricultural use (Larrea-Alcázar et al., 2021; Lambin et al., 2013). The region is undergoing major transformations in its livestock system that are characterised by an agrarian transition where solutions are being developed in response to tensions between agricultural and ecological perspectives (Osis et al., 2019; Plassin, 2018).

The colonization of the Amazon rainforest beginning in the 1960s was closely linked to territorial occupation policies promoted by the government. These were based on opening roads and distributing land along pioneer fronts (Ianni, 1978). In addition to the public land settlement programs, a large-scale migration within the Amazon began (Vaz, 2013), causing a "struggle for land," where the opening of pastures was the main tool for land appropriation and valorisation (Schmink and Wood, 1992). This occupation led to the establishment of distinctive agrarian situations characterized by the predominance of extensive livestock management, significant deforestation, and minimal use of inputs and labour. Farm trajectories followed a main trend of deforestation for pasture expansion, causing progressive soil degradation. Since the beginning of the 21st century, mechanized agriculture, linked to soybean production, has been expanding on degraded pasture lands, with two main consequences: (i) livestock intensification thanks to soil fertilization, mechanization, and crop-livestock integration, and (ii) land valorisation, which has led to an increase in new deforestation and pasture expansion (Osis et al., 2019; Poccard-Chapuis et al., 2020; Richards et al., 2014).

The region of Paragominas is typical of this trajectory, with successive "boom and bust" cycles since the 1960s, involving timber extraction, livestock, charcoal and soybean (Piketty et al., 2015). Due to uncontrolled deforestation, the municipality was representative of the blacklist created in 2008 by the federal government. Three years later, thanks to an innovative jurisdictional policy known as "green municipality," Paragominas was removed from the blacklist and become a regional model for sustainable development (Viana et al., 2016).

Concurrent with the zero deforestation policies, an adaptation phase has been put in place, aimed at facilitating a transition to more sustainable systems and enhancing ecosystem services (Pinillos Cifuentes et al., 2020). Intensifying production in areas that were already open, starting with optimising grazing use and investing in practices such as rotational grazing, fertilisation, and agriculture-livestock integration, is expanding (Poccard-Chapuis et al., 2015; Cerri et al., 2016; Aubron et al., 2022). Nevertheless, the role of the forest remains inadequately recognized (Pinillos et al., 2021).

Diverse livestock systems are currently present in the Amazon, ranging from intensive confinement fattening systems to extensive pasture grazing systems. Consequently, there are different dynamics in the GHG and energy emission balance sheets, and thus very different frameworks and solutions for sustainable production. Agricultural practices in each production system impact GHG emissions and energy consumption. Adopting resilient practices is therefore one approach to facilitate the agroecological transition. To adapt these practices to the different livestock farming scenarios, it is first necessary to know these production systems.

Understanding emissions from livestock farming systems and their sources, and obtaining accurate national estimates, are crucial for informing a discussion on the scientific and policy priorities of the region (Moran and Wall, 2011). Similarly, to achieve energy efficient systems, it is necessary to first quantify and analyze the energy consumption and production of the different systems (Pérez Neira et al., 2014). However, there is little data on GHG intensity and energy balances in Brazil, especially in terms of data collected directly from producers, and data from the Amazon region are even rarer (Bogaerts et al., 2017; Clerc et al., 2012).

Among the tools used for the global assessment of the environmental impact related to livestock farming is life-cycle

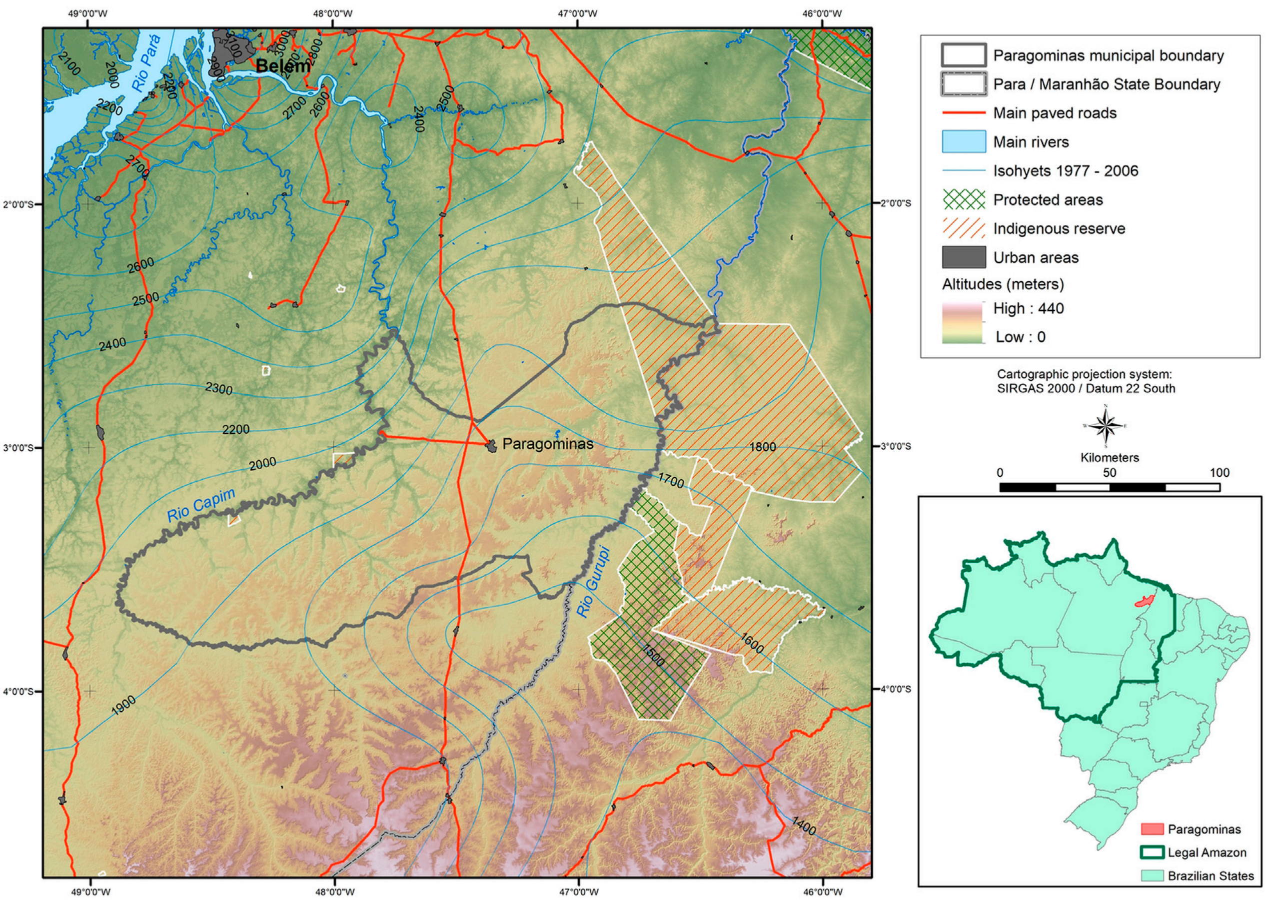

FIGURE 1
Location of the municipality of Paragominas in the Amazonian biome.

analysis - LCA (Scoones, 2023). This article conducted evaluations in accordance with the principles of LCA. It contributes to the production of information by profiling both the production and consumption of energy and GHG production in actual rural properties of the Amazon region, based on field data.

In this paper, we seek to understand how farm practices and the intensification of cattle farming systems impact the eco-efficiency of farms in terms of energy consumption and production and GHG emissions. This study aims to produce information on the GHG emissions and energy balance of 33 livestock farms with different intensification levels in the Amazon biome. The ultimate objective is to identify the most eco-efficient systems, in line with the practices adopted. Our work also aims to help enrich information regarding emissions and consumption associated with livestock activities under real conditions over an agricultural year, with a focus on farms in the Amazon biome where very few such studies have been conducted.

Materials and methods

Study area

The study was conducted in the municipality of Paragominas, located in the state of Pará in the northeastern region of the Brazilian Amazon (Figure 1). The climate in Paragominas is characterized as tropical, humid, and dry with a constant high temperature (26.6°C) and high humidity (on average 80%) (Pinto et al., 2009). Annual precipitation is high (2,000 mm per year between 2000 and 2014 in Paragominas) (Tropical Rainfall Measuring Mission - TRMM). This precipitation is unevenly distributed over the year, with a dry season between July and December during which only 14% of the annual precipitation is received.

The municipality has diverse agrarian situations, which correspond to pioneer fronts, slash-and-burn agriculture, extensive consolidated family farming on the periphery, specialised family farming, extensive livestock farming on the periphery, zero deforestation, and intensification corridor

10.3389/past.2025.14461

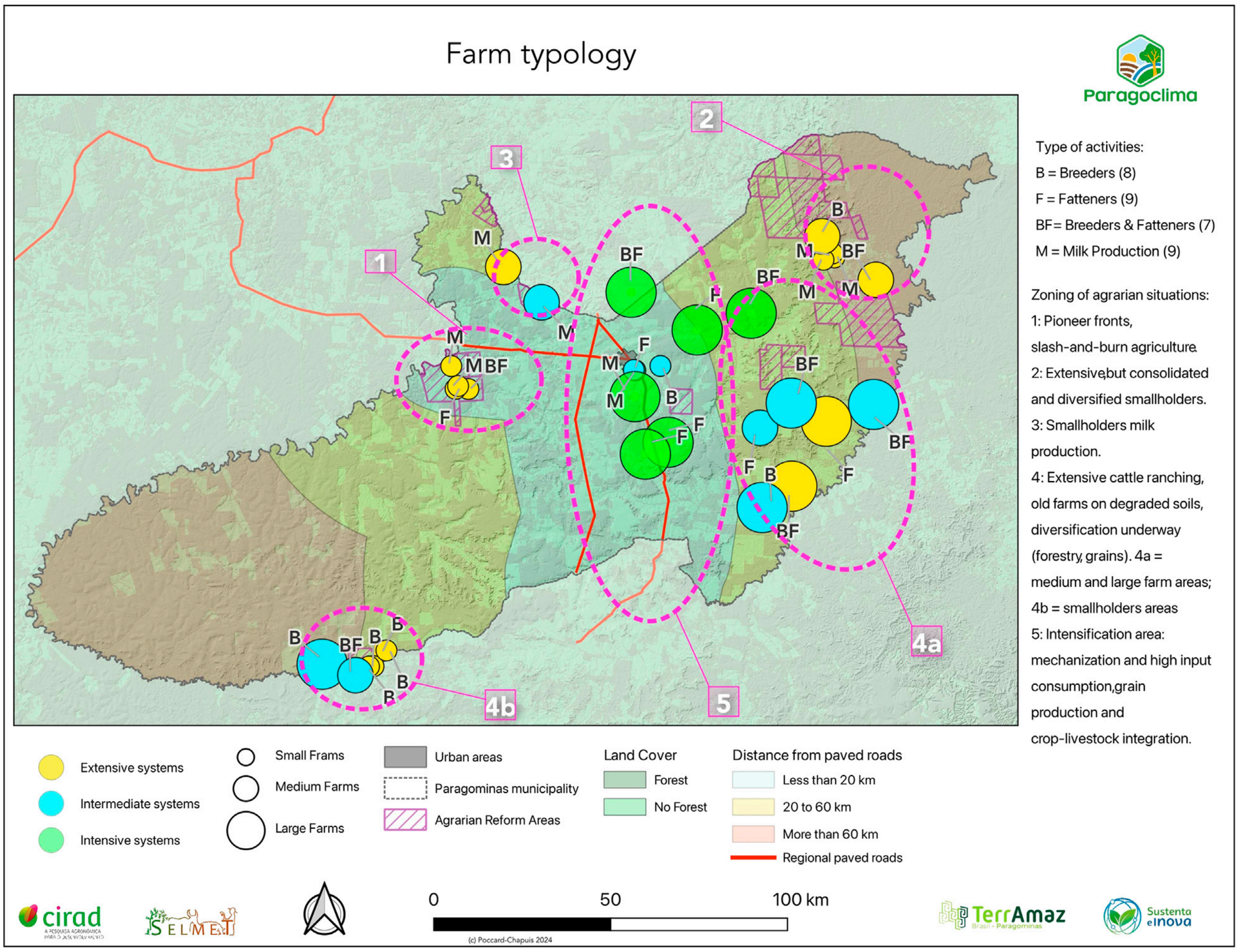

FIGURE 2
Different cattle farming systems studied in Paragominas, categorized according to their degree of intensification, production orientation and agrarian situation.

(Plassin, 2018). It also is developing livestock systems with different production orientations (milk, breeder, breeder-fattener, fattener) and intensification levels characteristic of the region (animal stocking rate, use of fertilisers and pesticides, pasture management, concentrate supplementation, etc.) (Figure 2).

On both large and small farms, the livestock systems in Paragominas can be characterized as livestock grazing ranches, with land properties delimited by fences and under individual private governance. Internally, these farms are divided into various plots of cultivated pastures, allowing the mobility of animals within the property. The ownership and management of herds are individual rather than collective. In some cases, mobility occurs between farms with different productive functions, such as units specialized in breeding, rearing or fattening. In rare cases, pasture management systems assume characteristics similar to pastoralism: low intensity of management over large areas can reflect pastoral practices, but in the context of private land and property.

In areas with extensive management, the use of fire for the renewal of pastures still persists; however, this technique has been progressively abandoned due to negative impacts on the soil, fire risks and reduced economic profitability, which has contributed to the decline of these systems in the region.

Assessment of the energy balance and greenhouse gas emissions at the cattle farm level

AgriClimate change tools - ACCT

AgriClimate Change Tools (ACCT), an on-farm tool based on the Planète (Solagro, 2002) and Dia'terre (Ademe, 2011) methods, which refer to international standards (AgriClimate

TABLE 1 Equations for energy yield and energy efficiency and GHG emissions.

Equation	Indicator	Equation
Equation 1	Energy Yield (GJ/GJ)	$\frac{\text{GJ of farm products}}{\text{GJ consumed for production}}$
Equation 2	Energy Efficiency (GJ/t produced)	$\frac{\text{GJ consumed for production}}{\text{ton of product (beef or milk)}}$
Equation 3	EL Efficiency (t $eqCO_2$/t produced)	$\frac{\text{Gross emissions (teqCO2)}}{\text{ton of product (beef or milk)}}$
Equation 4	ENL Efficiency (t $eqCO_2$/t produced)	$\frac{\text{Gross emissions+Storage de C (teqCO2)}}{\text{ton of product (beef or milk)}}$
Equation 5	ENT Efficiency (t $eqCO_2$/t produced)	$\frac{\text{Gross emissions+Storage de C+emissions from deforestation (teqCO2)}}{\text{ton of product (beef or milk)}}$

C storage = considered C storage of pastures over 20 years old, primary and secondary forests (aerial and underground), and practices that store C. Emissions from deforestation = from the last 20 years.

Change Project, 2013), was chosen from among the many tools used to calculate GHG emissions and energy balances. ACCT was in line with the needs of our study, in particular because of its global approach at the farm level and the distribution of energy and GHG consumption by agricultural activity. The main reason for our choice was that the tool, thanks to its design in Microsoft Excel, was modifiable and therefore adaptable (unlike a closed proprietary application), which was essential in a job like ours, determined by local conditions.

Indeed, the realisation of a balance sheet adapted to Amazonian farms relies in particular on an appropriate representation of the forest sector in the balance sheets (emissions due to deforestation and carbon storage in the aerial biomass). The tool also allowed the use of energy and GHG coefficients specific to the areas studied. Our work has thus led to a gradual improvement of ACCT for the Amazon region in certain areas of the territory.

Energy consumption

ACCT assesses the consumption of non-renewable energy, both direct (fuel, gas, electricity, etc.) and indirect (inputs, purchased feed, materials, buildings), across all farm activities during a crop year using the life-cycle analysis principle. Similarly, agricultural products (meat, milk, crops, etc…) are converted into energy. Material and energy inputs and outputs are inventoried and translated into energy flows by assigning coefficients from the literature that are considered robust. The energy results are expressed in primary energy (Gigajoule, GJ), thus making it possible to define all the energy flows of the holding (Agriadapt, 2013; ADEME, 2011). The tool provides two indicators at the year level: i) energy yield (Equation 1), which is defined as the ratio of GJs of farm products per GJ consumed for production, where high efficiencies are favourable; and energy efficiency (Equation 2), the ratio of GJs consumed for production per ton of product, where high efficiencies are unfavourable (Table 1).

GHG emissions and changes in carbon stocks (C)

The sources of gross GHG emissions considered in ACCT are related to the i) direct (fuel, gas…) and indirect use of energy (input manufacturing), ii) animal production (enteric fermentation and manure), and iii) soil.

ACCT provides an estimate of the annual change in on-farm carbon stocks induced by land use changes, including emissions from deforestation. The tool also takes into account favourable practices for C storage, including forest infrastructure using IPCC Tier 2, and emissions avoided by renewable energy production (Agriadapt, 2013; ADEME, 2011).

The result of the calculations provides the gross emissions per hectare indicator (teqCO_2/ha UAA/year), representing the ratio of gross emissions ($eqCO_2$) to hectares of utilised agricultural area (ha UAA). Efficiency values for GHG emissions (t $eqCO_2$/t produced/year) vary depending on the frame of reference used. Three efficiencies representing three scales of analysis were considered: (i) efficiency of livestock emissions - EL efficiency (Equation 3), (ii) efficiency of net livestock emissions - ENL efficiency (Equation 4), and (iii) efficiency of total net emissions - ENT efficiency (Equation 5) (Table 1).

Using the ACCT results of energy consumption and GHG emissions, it was possible to create farm groups based on their eco-efficiency performance, which in our work is measured by two indicators: energy efficiency and efficiency of livestock emissions.

Each efficiency is divided into low, medium, and high efficiency categories. This division was carried out using a graphical representation of the farms where it was possible to visually define the three categories.

Although the categorisation by sample mean is simple, we consider this method to be the most effective way to divide the categories. The reason is that there are no default efficiency values to make this classification, since performance is variable for each region and type of production, and depends on the intrinsic characteristics of the sampled universe.

To enhance the readability of the results, we refer to the farms by code, which represent respectively the degree of intensification (E - Extensive, M - Moderate Intensification, I - Intensive; categories defined at the beginning of the results), the size (S - small, M - medium, L - large) and the type of production

(D - dairy, B - breeder producer, BF – Breeder- Fattener producer, F - Fattener producer), and a figure which corresponds to the number of the farm.

Adapting to the Amazonian context

ACCT was developed in 2013 by the Solagro Association as part of the "Life+ AgriClimateChange" program for use in Europe, it was then adapted to overseas conditions in tropical zones (Martinique, Guadeloupe and Réunion) (Solagro, 2013).

In 2015, the adaptation focused on the specificities of French Guiana farms in an Amazonian context, including GHGs related to deforestation and soil C storage (Dallaporta et al., 2020; Dallaporta et al., 2016). The tool was then transposed into the context of the Brazilian Amazon (Lenoir, 2022; Moniot, 2021), using the Anerpaan tool (Clerc et al., 2012), which was already adapted to the Brazilian Amazon context.

The main changes concerned parameter values. They are detailed and substantiated in Supplementary Material S1.

Data collection

Sampling strategy

Thirty-three rural properties were selected in Paragominas - Pará - Brazil, for the years 2021 and 2022. The sample represented the diversity of agrarian situations in the municipality according to Plassin (2018), as well as the different production orientations and intensification levels.

Databases mobilised

Farm information was extracted from two databases. For primary and secondary forest cover and pasture and crop area, we used data from the Mapbiomas.org 4.1 collection (Mapbiomas, 2024), which is a platform that includes land use maps and informs land use changes. For deforestation, we used data from the Instituto Nacional de Pesquisas Espaciais - INPE (INPE, 2024), and the PRODES Project, which monitors satellite deforestation in the Legal Amazon; this allows us to compare the information obtained during interviews with that of official databases.

Where producers did not directly provide the necessary data or where the reported values were very divergent, we used standard values based on the literature and the available municipal database. The main elements reworked were the amount of salt, electricity consumption, fuel consumption for pasture reform and maintenance, the amount of seeds used for pasture, the amount of herbicides used on the holding and the areas in forest and pasture that were used from the official database of the Cadastro Ambiental Rural – CAR of farms, rather than declarative data (Supplementary Material S2).

Investigations

Data collection took place in three stages. The first was a semi-directional interview with the producer to learn about livestock systems and identify technical routes, inputs and farm products. In a second step, data from the Mapbiomas and INPE databases were inserted. Finally, in case of inconsistencies between the reported data and the official databases, a return to the producer made it possible to compare the two data sources, with the aim of understanding, modifying or explaining the observed variations.

Data analysis

After ensuring data consistency, we applied simple descriptive statistics. Eco-efficiency groups that take into account energy efficiency and gross GHG emissions were identified. Non-parametric statistics [Kruskal-Wallis, Mann-Whitney U test (or Dunn test)] were used to better identify the variables discriminating these groups.

Results

Farming systems evaluated

The farming systems observed differ in their degree of intensification, production (dairy and meat, dairy, breeder, breeder-fattener, fattener) and agrarian situation (1 - pioneer front, slash-and-burn agriculture; 2 - extensive but consolidated and diversified family farming; 3 - specialised family farming; 4 - extensive farming, old-growth farms on degraded land, diversification in progress; and 5 - intensification corridor).

Systems according to degree of intensification

Extensive farms (ES) are characterized by the exclusive use of grazing. They have monoculture grazing areas, with few plot divisions, do not engage in fertilising or liming, and do manual weed management (mowing or herbicides). In general, they have few inputs and reduced infrastructure and labour, and their production capacity is maintained through the exploitation of the abundant natural resources available.

Moderately intensified farms (MIS) have adopted relatively simple practices to improve the productivity of land and labour, increasing inputs, dividing grasslands into plots, regularly provide fertilisers and liming, and investing in mechanisation and animal supplementation.

Intensive farms (IS) are characterised by large infrastructure, high investment in inputs, mechanisation, and rotational grazing with annual fertilisation and liming, leading to a high animal stocking rate and the adoption of integrated agriculture-livestock systems or even feedlots.

TABLE 2 Characteristics of the extensive (ES), moderate intensification (MIS) and intensive (IS) cattle farming systems studied in Paragominas.

Features		Degree of intensification		
		ES (16)	MIS (9)	IS (8)
Total area (ha)	S	64 (11)	94 (2)	34 (2)
	M	363 (3)	857 (3)	-
	L	12,887 (2)	3,872 (4)	4,174 (6)
Utilised Agricultural Area UAA (ha)	S	55 (11)	93 (2)	34 (2)
	M	206 (3)	253 (3)	-
	L	5,005 (2)	1,668 (4)	1784 (6)
Herd (heads)	S	53 (11)	125 (2)	110 (2)
	M	278 (3)	289(3)	-
	L	3,194 (2)	1,432 (4)	5,912 (6)
Meat production (kg/ha UAA)	B	80 (5)	150 (3)	-
	BF	120 (2)	100 (2)	1,170(2)
	S	240 (3)	430 (2)	1,590 (4)
Meat production (kg/head)	B	59 (5)	111 (3)	-
	BF	117 (2)	129 (2)	175 (2)
	S	222 (3)	300 (2)	321 (4)
Milk production (L/cow/day)		5.7 (5)	6.0 (1)	9.0 (2)
Milk production (L/ha UAA)		492 (5)	327 (1)	2087 (2)
Meat Animal density (AU/ha)		0.8 (10)	0.9 (8)	3.4 (6)
Milk animal density (AU/ha)		1.0 (6)	0.5 (1)	1.5 (2)
Forest area (%)		2.5 (16)	41 (9)	32 (8)
Deforested area[a] (%)		38 (16)	7 (9)	7 (8)
Type of grazing	Alternate or rotational		Rotational	Rotational CLI
Fertilisers and liming	No		Little	Yearly
Weed control	Manual Mowing and herbicides		Manual Herbicides	Mechanised Mowing and herbicides
Supplementation	No		Finishing	Yes

[a]Surface deforested in the last 20 years. ES, extensive system; MIS, moderate intensification system; IS, intensive system; UAA = useful agricultural area; AU, animal unit (450 kg LW), S, small; M, medium; L, large; B, breeder; BF, breeder-fattener; F, fattener; CLI, crop-livestock integration. In brackets number of farms assessed.

Of the 33 farms, only two have crops (maize and sorghum) for animals. Farms are divided into small (S), medium (M) and large (L) areas or herds; and separated by type of production: dairy (D), breeder (B), breeder-fattener (BF) and fattener (F) for animal production (Table 2).

Two farms had been established for less than 2 years, and while they had invested in purchasing animals, they had not yet achieved significant sales. As a result, they were eliminated in the assessment of production and energy and GHG emissions balances and treated separately to illustrate early-stage operations.

On beef cattle farms, the production of meat in kilograms per hectare and kilograms per head varies according to the fattening method used. On dairy farms, the production per cow is similar in ES and MIS, and appears lower for MIS in litres per hectare, but this is based only on a single value. In IS, milk production per cow and per hectare is much higher than in the other two systems, linked to fertilisation of grassland and the provision of complementary feed.

TABLE 3 Energy consumption and greenhouse gas emissions from the extensive beef and dairy (ES), moderate intensification (MIS) and intensive (IS) cattle farming systems in Paragominas.

Energy consumption	Beef farming systems					Dairy farming systems				
	Degree of intensification			SEM	*p*-Value	Degree of intensification			SEM	*p*-Value
	ES *(10)*	MIS *(7)*	IS *(6)*			ES *(5)*	MIS *(1)*	IS *(2)*		
Consumption range (GJ/t prod)	0.83–37.92	2.27–39.60	17.40–43.01			0.17–2.25	4.89	6.42–6.48		
Average consumption (GJ/t prod)	12.15	12.58	27.52	3.02	<0.10	0.82	4.89	6.45	0.98	<0.05
Average consumption (GJ/ha UAA)	2.52	3.3	35.2	3.82	<0.05	0.55	1.60	13.47	2.10	<0.05
Fuel (GJ/t lw)	1.03	0.96	1.26	0.20	NS	0.44	0.96	1.14	0.20	NS
Electricity (GJ/t lw)	0.04	0.20	0.65	0.14	NS	0.00	0.00	1.99	0.33	<0.05
Food (GJ/t lw)	0.00	0.93	1.74	0.31	<0.10	0.00	0.00	1.10	0.28	NS
Fertilisation (GJ/t lw)	0.14	1.11	5.57	0.61	<0.05	0.00	1.29	1.31	0.24	<0.05
Phytosanitary (GJ/t lw)	0.26	0.18	0.28	0.10	NS	0.06	1.46	0.05	0.18	<0.05
Purchase of animals (GJ/t lw)	9.72	8.59	17.59	2.78	NS	0.03	0.65	0.00	0.08	<0.05
Other (GJ/t lw)	0.71	0.61	0.43	0.02	<0.05	0.29	0.54	0.87	0.09	<0.05
GHG emission positions without lucf sector										
GHG emissions (tCO_2/year)	1,536	2070	14,250			251	322	930		
Emission range (tCO_2/t prod)	5.07–40.85	17.97–21.02	6.66–15.24			2.84–7.70	4.90	2.59–2.60		
GHG emissions (tCO_2/t prod)	23.18	15.17	10.32	2.33	<0.10	6.05	4.90	2.60	0.74	NS
GHG emissions (tCO_2/ha UAA)	2.08	2.52	14.94	1.77	<0.05	3.15	1.60	5.42	0.62	NS
% CO_2	1%	4%	9%		<0.05	1%	5%	25%		NS
% CH_4	89%	87%	76%		<0.05	75%	58%	64%		NS
% N_2W	10%	9%	15%		<0.05	24%	37%	11%		NS
GHG emission positions with lucf sector										
Emission range (tCO_2/t prod)	10.47–527.46	7.71–149.70	9.23–77.13			21.33–98.94	10.40	2.59–30.31		
GHG emissions (tCO_2/t prod)	160.95	51.26	35.13	27.23	<0.10	57.21	10.40	16.45	11.36	NS
GHG emissions (tCO_2/ha UAA)	14.09	5.55	39.71	5.17	<0.05	28.64	3.40	32.35	7.16	NS
% CO_2	0%	4%	5%		<0.05	0%	2%	21%		NS
% CH_4	31%	61%	36%		0.102	9%	27%	28%		NS
% N_2W	3%	6%	9%		<0.10	3%	18%	5%		<0.05
%Deforestation	66%	29%	51%		0.107	88%	53%	46%		NS

SEM, standard error of the mean; LUCF, land use change and forest; UAA = useful agricultural area, prod = product. In brackets number of farms assessed.

For dairy, the results only concern nine farms with just one MIS, which does not represent the reality of the municipality. The sample comprises six small farms (approximately 69 ha UAA and 19 dairy cows); two medium-sized farms (approximately 173 ha UAA and 40 dairy cows) and one large farm of 300 ha UAA and 177 dairy cows. These farms also have meat production (male calves and cull cows), the meat production is respectively 49, 122 and 128 kg ha of UAA for the small, medium and large farms.

As regards the degree of intensification, the average meat production of dairy farms is 49.2, 33.0 and 208.5 kg ha of UAA respectively for the extensive, moderate intensification (one farm) and intensive systems.

Systems according to production orientation

The economic activity of beef cattle farming can be breeder, breeder-fattener and fattener. In Paragominas, herds are composed mainly of the Zebus types of the Nelore and sometimes Sindi breed, and less frequently of the bullfighting types Angus, and Aberdeen. Eight, seven and nine breeder producers with ES, MIS and IS intensification levels were studied.

On breeder farms (B), the herd consists primarily of mothers for breeding (which will be sold as culled cows) and calves intended for sale. On breeder-fattener farms (BF), the herd consists of mothers and male calves for fattening. On fattener farms (F), grazer animals are purchased for finishing, mainly males, fattened with grass or in confinement or semi-confinement systems. On dairy production farms (D) that also produce meat, the main income comes from milk, which can be marketed *in natura* or processed into cheese. The herd is much smaller than in the B, BF and F, and consists mainly of cows and heifers crossed between the Zebu (Nelore and Gir) and Taurine (Dutch) breeds.

Systems according to agrarian situation

The five agrarian situations encountered are (Figure 1):

1) Pioneer front, slash-and-burn agriculture (Colônia Oriente) characterised by a recent colonisation (2000), with productive but fragile pastures and an intensification process with slash-and-burn and diversification (e.g., pepper), its land structure comes from an unregulated occupation;
2) Consolidated extensive family farming (assentamento Luiz Inácio e Colônia três lagoas) - recent colonisation (1999) with low-productive pasture and intensification process with slash-and-burn agriculture and diversification (dairy). The family farms are generally under 500 ha in size. Decisions are taken by the heads of holdings; salaried labour is in the minority and is not generally involved in decision-making;
(3) Family agriculture specialised in milk (assentamento Mandacaru) - recent colonisation (1999) with low-productive pasture (overgrazing, fire), subsistence, mechanisation and milk;
4) Extensive livestock farming on the periphery (zero deforestation) - colonisation between 1970–1980 with low-productive pasture (overgrazing, fire) and input-efficient intensification, diversification (forest plantations, grains). The land structure is a type of patronage agriculture (in this situation we also found an area of Assentamento, called Assentamento Águia, which we described as situation 4a). In this type of operation, the owners usually employ a manager and several farm workers. Strategic, tactical and operational decisions vary between the operations manager, manager and workshop managers depending on the size of the operation;
5) Intensification corridor - colonisation from 1960 onwards with productive pasture and intensification with high levels of inputs; the land structure is characterized by patronage agriculture (Figure 1).

Energy balance and greenhouse gas emissions

Energy consumption

Beef cattle farms

The energy consumption in gigajoule (GJ) per ton of live weight produced (t of LW) is not discriminating between degrees of intensification ($p = 0.081$), only an upward trend is observed in the intensive system. Energy consumption per hectare of UAA is similar in the extensive (ES) and moderate intensification (MIS) farm types (Table 3). However, meat production per hectare on MIS farms is 55% higher than ES farms (Table 1), showing that the MIS system produces more with the same amount of energy.

For ES and MIS farms, the main sources of energy consumption are the purchase of animals and fuel. For intensified systems (IS), these include buying animals and fertilisation. Fertilisation ($p < 0.05$) and feeding ($p < 0.10$) increase or tend to increase with intensification (adoption of practices such as grazing management and animal supplementation), while other purchases decrease with intensification ($p < 0.05$).

For IS farms, energy consumption per hectare is 14 and 11 times higher, respectively, than in ES and MIS farms (higher input use for production) (Table 3). Meat production per hectare is 9 and 6 times higher in IS (1.38 t) than in ES (0.15 t) and MIS (0.23 t) farms, respectively. This performance can be attributed to the prevalence of most of the fattening farms within the intensive system (Table 2).

Dairy farms with associated beef

Dairy farms are characterised by relatively small UAA areas averaging 83 ha for ES farms, 201 ha for MIS farms and 179 ha for IS farms, and produce 492, 327 and 2087 L of milk/ha UAA, respectively. The animals are exclusively grass-fed, and there are no self-consumption crops for the herd (Table 2).

Energy consumption (GJ) per 1,000 L of milk (1000 L) and per hectare of UAA (ha UAA) increases significantly ($p < 0.05$) as the system intensifies (Table 4), although the single MIS farm does not follow this trend. Production per cow remains similar between ES and MIS farms, with production two times lower than IS farms. This difference is even more pronounced if milk production per hectare is expressed; IS produces 4 and 6 times more milk than ES and MIS (Table 2). The main sources of ES

TABLE 4 Energy efficiency, energy yield, consumption and energy production in meat and milk farming systems with extensive associated beef (ES), moderate intensification (MIS) and intensive (IS) systems in Paragominas.

Degree of intensification	Farm	Energy (GJ/ ha AAU)		Energy yield (GJ output/GJ input)	Energy efficiency (GJ/ton produced)
		Entrance	Exit		
	Beef				
ES	ESB1	0.1	0.3	2.69	4.98
	ESB2	0.2	1.2	7.70	1.74
	ESB3	0.3	1.4	5.48	2.44
	ESB4	0.1	0.3	4.07	3.29
	ESF1	10.3	6.6	0.64	37.92
MIS	ESF2	7.5	5.1	0.68	35.65
	EMB	0.1	1.5	16.23	0.83
	EMBF	0.4	1.5	3.51	3.95
	ELBF	1.1	2.0	1.85	8.73
	ELF	5.2	4.3	0.83	21.88
	MLB	1.1	2.4	2.17	6.07
	MLF	9.7	5.9	0.61	39.61
	MMF	17.6	13.1	0.75	28.23
	MLB1	0.2	1.0	5.89	2.27
IS	MLB2	0.8	2.7	3.27	4.1
	MLBF1	0.4	1.4	3.66	3.77
	MLBF2	0.3	1.2	3.31	4.04
	ISF	56.2	77.2	1.37	17.4
	ILBF1	7.3	5.9	0.80	20.35
	ILBF2	54.3	41.7	0.77	27.57
	ILF1	28.4	23.7	0.83	27.59
ES	ILF2	52.7	41.1	0.78	29.23
	ILF3	12.1	6.3	0.52	43.01
	Dairy with associated beef				
	ESD1	0.1	2.4	26.41	0.17
	ESD2	0.3	2.7	8.36	0.48
	ESD3	0.8	1.5	1.85	2.24
MIS	ESD4	0.9	3.9	4.30	0.82
	EMD	0.3	4.2	16.77	0.41
	MMD	1.6	1.7	1.06	4.89
IS	ISD	14.3	8.0	0.56	6.42
	ILD	12.6	8.0	0.64	6.48

Abbreviations: ESB: Extensive-Small-Breeder; ESF: Extensive-Small-Fattener; ESD, Extensive-Small-Dairy; EMB: Extensive-Medium-Breeder; EMBF: Extensive-Medium-Breeder-Fattener; EMD: Extensive-Medium-Dairy; ELBF: Extensive-Large-Breeder-Fattener; ELF: Extensive-Large-Fattener; MLB: Moderate Intensification-Small-Breeder; MLF: Moderate Intensification-Small-Fattener; MMF: Moderate Intensification-Medium-Fattener; MMD: Moderate Intensification-Medium-Dairy; MLB: Moderate Intensification-Large-Breeder; MLBF: Moderate Intensification-Large-Breeder-Fattener; ISF: Intensive-Small-Fattener; ISD: Intensive-Small-Dairy; ILBF: Intensive-Large-Breeder-Fattener; ILF: Intensive-Large Fattener; ILD: Intensive-Large-Dairy.

consumption are fuel, other purchases and plant health, related to farm maintenance and grazing (brush cutters and herbicides). On MIS farms, the same items have higher consumption than on ES farms, plus fertilizers.

IS farms have milking machines, milk tanks and supplementation for cows, which raises their energy consumption ($p < 0.05$ compared to ES and MIS), in addition to the fuel and fertilisation dedicated to pasture management.

Greenhouse gas emissions

Beef cattle farms

ES and MIS farms have similar GHG emissions per hectare of UAA, while IS farms emit 7.0 and 5.9 times more ($p < 0.05$) respectively. However, expressed in tons of meat, IS emissions are 55% and 32% lower than ES and MIS, respectively. In the three systems assessed, methane accounts for the bulk of emissions (per ha and excluding deforestation), representing over 75% of GHG emissions (Table 3).

N_2O emissions come mainly from fertilizers, liming, NH_3 production and leaching on agricultural soils. CO_2 emissions increase as the system intensifies due to fuel use and animal transport. Emissions from the land-use change sector vary between 29% and 66% of GHG emissions and are related to deforestation over the past 20 years with significant differences between systems ($p < 0.05$).

Dairy farms with associated beef

Emissions per hectare of UAA and per 1,000 L of milk produced are not significantly different ($p > 0.05$). However, a downward trend is observed in the intensive system (19% and 57%). In dairy farms, excluding deforestation, CH_4 emissions are also the largest contributors, accounting for 58% and 75% of total emissions. The N_2O comes second in the ES and MIS. The intensive system accounts for the largest share of CO_2 emissions (21%). Deforestation accounts for 46%–88% of emissions, far higher than on beef cattle farms. This is because the dairy farms studied were established recently, and have a higher percentage of deforestation (Table 3).

Energy and GHG efficiencies of cattle systems

Energy efficiency

Beef cattle farms

Table 4 presents the energy yield and energy efficiency, energy consumption and production per hectare of agricultural area used (GJ/ha UAA) of the 23 farms.

Energy efficiency is 16.29 GJ/t LW. The farms are ordered by degree of intensification, 12 farms have low efficiency, i.e., they have high livestock production relative to their input consumption. These are farms with extensive and moderately intensifying systems, where production is orientated around breeding and breeding-fattening. Eight farms with varying degrees of intensification but which are mostly based on animal fattening have high efficiency, with little production compared to inputs.

Efficiency groups are identified as follows: high efficiency farms are highlighted in red, medium efficiency in grey, low efficiency in green, and energy yield above 1, thus characterising farms that produce more than they consume.

Beef cattle farms with low energy efficiency have energy yield values above 1.85 GJ/GJ, while farms with average energy efficiency have an energy yield between 0.80 and 1.37 GJ/GJ. Finally, farms with high energy efficiency have energy yields ranging from 0.52 GJ/GJ to 0.83 GJ/GJ. Levels of energy consumption and production vary considerably by type of production, with larger fluxes on fattener intensive farms and smaller fluxes on breeder extensive farms (Table 4).

ES and MIS breeder operators consume on average 0.2 GJ/ha UAA, mainly fuel. On breeder-fattener farms, there are large variations in energy consumption depending on the animals in confinement (ILBF1 and ILBF2 with 7.3 and 30.8 GJ/ha UAA, respectively) leading to the purchase of animals, feed and fertilisers. On the other farms, the average consumption is 0.6 GJ/ha UAA. Consumption on ES and MIS farms is similar among fatteners (16.7 GJ/ha UAA on average), while on SI farms the average is 37.4 GJ/ha UAA through the purchase of animals, feed and fertilisers.

Dairy farms with associated beef

The average energy efficiency is 2.74 GJ/1000 L. Extensive farms tend to have low efficiency while intensive farms (MIS and IS) tend to have high efficiency (Table 3). Farms with an energy efficiency of more than 4.3 GJ/GJ are those in the low efficiency category, unlike MIS and IS farms with an energy yield of less than 1.1 GJ/GJ.

MIS and IS farms, with high energy efficiency, consume an average of 5.7 GJ to produce 1,000 L of milk, while ES farms with low energy efficiency consume 0.5 GJ of energy to produce the same amount of milk.

Efficiency of GHG emissions

Beef cattle farms

More than 75% of livestock emissions are from enteric CH_4 and manure on pasture (Table 3). The GHG emission efficiency values for the three scales of analysis are presented in Tables 5, 6.

Table 5 presents the efficiencies of beef cattle farms and the indicators that influence these efficiencies. Efficiency groups are identified as follows: high efficiency operations are highlighted in red, medium efficiency in grey, low efficiency in green and negative efficiency in dark green. The three efficiency groups are defined based on the average efficiency (EE) at the farm level, which is 17.40 t eqCO_2/t LW. This metric is commonly used in

TABLE 5 Efficiency of emissions from livestock (EL Efficiency), efficiency of net emissions from livestock (ENL Efficiency) and efficiency of total net emissions (ENT Efficiency) from cattle extensive meat (ES), moderate intensification (MIS) and intensive (IS) systems in Paragominas.

Degree of intensification	Farm	EL Efficiency	ENL Efficiency	ENT Efficiency	Production Indicators				Carbon indicators		
		t eqCO_2/ t LW	t eqCO_2/ t LW	t eqCO_2/ t LW	Heads	Kg LW/ ha UAA	Kg/ head	AU/ ha	tCO_2/ ha/ year	tCO_2/ ha/ year	Area
ES	ESB1	39.42	-169.58	82.1	22	24.1	63.6	0.3	6.07	5.04	4a
	ESB2	34.59	-12.87	-0.23	70	88.6	61.3	1.2	1.12	4.22	4a
	ESB3	40.85	-6.26	11.28	50	106.6	51.6	1.4	1.87	5.04	4a
	ESB4	38.84	-52.44	436.21	23	65.5	56.1	1.0	32.49	6.08	4a
	ESF1	8.44	-6.22	116.65	35	272.6	250.0	0.8	33.49	7.48	1
	ESF2	7.30	12.91	140.72	75	210.7	196.7	0.9	26.93	2.01	1
	EMB	21.73	-26.81	258.39	233	112.1	106.6	0.8	31.98	5.45	2
	EMBF	18.98	-86.23	-21.74	252	108.2	107.3	0.7	6.97	11.47	4
	ELBF	16.60	-104.39	-102.97	2000	126.4	127.0	0.8	0.18	15.62	4
	ELF	5.07	-66.41	-61.00	4387	235.8	430.0	0.5	1.27	18.62	4
	Average	23.18	-51.83	85.94	715	135.1	145.0	0.8	14.24	8.10	
MIS	MLB	18.0	-1.58	0.30	176	179.3	112.2	1.2	0.34	3.51	5
	MLF	8.26	8,00	9.60	74	244.7	250.0	0.7	0.39	3.20	5
	MMF	6.13	-23.82	-22.23	70	622.2	350.0	0.7	0.99	24.34	4
	MLB1	18.70	-47.62	183.39	860	75.9	111.1	0.5	17.54	5.06	4a
	MLB2	18.86	-139.28	-134.43	1450	199.5	110.0	2.0	0.97	31.57	4
	MLBF1	21.02	-164.32	-163.15	2008	99.1	104.3	0.8	0.12	18.43	4
	MLBF2	15.24	-143.50	-132.93	1409	86.2	152.9	0.4	0.91	13.70	4
	Average	15.17	-73.16	-37.06	954	215.3	170.1	0.9	3.04	14.26	
IS	ISF	10.07	12.98	12.98	114	3230.0	255.0	9.3	0.00	2.23	5
	ILBF1	13.99	-15.78	47.36	5800	359.6	194.8	1.3	22.70	11.83	5
	ILBF2	15.24	9.34	52.44	3990	1969.3	155.1	6.3	84.88	25.22	4
	ILF1	6.66	6.98	42.32	8,000	1030.9	350.0	1.1	35.33	9.11	5
	ILF2	7.04	2.13	4.33	16,000	1802.4	340.2	2.1	3.96	26.05	5
	ILF3	8.91	-10.74	-4.59	1000	281.0	340.0	0.3	1.73	8.42	5
	Average	10.32	0.82	25.80	5817	1445.5	272.5	3.4	24.77	13.81	

Abbreviations: ESB: Extensive-Small-Breeder; ESF: Extensive-Small-Fattener; EMB: Extensive-Medium-Breeder; EMBF: Extensive-Medium-Breeder-Fattener; ELBF: Extensive-Large-Breeder-Fattener; ELF: Extensive-Large-Fattener; MLB: Moderate Intensification-Small-Breeder; MLF: Moderate Intensification-Small-Fattener; MMF: Moderate Intensification-Medium-Fattener; MLB: Moderate Intensification-Large-Breeder; MLBF: Moderate Intensification-Large-Breeder-Fattener; ISF: Intensive-Small-Fattener; ILBF: Intensive-Large-Breeder-Fattener; ILF: Intensive-Large Fattener; LW: live weight; UAA: useful agricultural area; AU : animal unit (450kg LW). L/d: litre/day.

most studies to provide context for the results in relation to previous research.

In terms of livestock efficiency - EL (the emission/ production ratio and live weight), low or high values are highly dependent on meat production per head. Of the 23 farms, only four have high efficiency, intensive system farms have the lowest efficiencies.

By including the carbon stock of farms, all farms are very efficient in terms of ENL, mainly due to the conservation of forest areas, which is mandatory in the Amazon region under Brazilian

TABLE 6 Efficiency of emissions from livestock (Efficiency EL), efficiency of net emissions from livestock (Efficiency ENL) and efficiency of total net emissions (Efficiency ENT) from dairy farming systems with extensive associated meat (ES), moderately intensified (MIS) and intensive (IS) systems in Paragominas.

					Production Indicators				Carbon indicators		
		EL Efficiency	ENL Efficiency	ENT Efficiency					Emissions deforestation	Storage Total	
Degree of intensification	Farms	t eqCO_2/ 1000L	t eqCO_2/ 1000L	t eqCO_2/ 1000L	Heads	L/ha AAU	L/d/ cow	AU/ha	t CO_2/ha/year	t CO_2/ha/ year	Area
ES	ESD1	7.70	-4.9	36.2	47	543.1	4.9	1.5	22.32	6.95	1
	ESD2	6.54	5.1	45.2	126	658.5	5.6	1.2	26.41	1.40	2
	ESD3	6.76	0.9	92.9	50	365.8	5.0	0.8	33.67	2.20	2
	ESD4	2.84	-1.5	17.0	60	263.9	8.0	0.3	4.88	1.16	1
	EMD	6.44	-17.9	46.0	350	628.4	5.0	2.4	40.23	15.34	4
	Average	6.05	-3.66	47.48	127	491.9	5.7	1.2	25.50	3.02	
MIS	MMD	4.90	-7.22	-1.7	140	326.9	6.0	0.5	1.80	4.33	3
	Average	4.90	-7.22	-1.7	140	326.9	6.0	0.5	1.80	4.33	
IS	ISD	2.59	1.0	1.0	105	2230.9	9.0	1.3	0.00	3.75	5
	ILD	2.60	-6.9	20.8	680	1944.0	9.0	1.7	53.86	18.60	5
	Average	2.60	-2.95	10.9	393	2087.5	9.0	1.5	26.93	4.04	

Abbreviations: ESD: Extensive-Small-Dairy; EMD: Extensive-Medium-Dairy; MMD: Moderate Intensification-Medium-Dairy; ISD: Intensive-Small-Dairy; ILD: Intensive-Large-Dairy; LW: live weight; UAA: useful agricultural area; AU : animal unit (450kg LW). L/d: litre/day.

law. Large farms have the largest C stock, giving the lowest ENL values. By combining forest carbon storage (air and underground) and pasture carbon storage (soil carbon), farms have mostly negative emissions, they are carbon sinks, excluding deforestation.

In terms of ENT efficiency, 39% of farms have high efficiencies, owing to the massive emissions from deforestation over the last 20 years. In order to clarify the results of the different efficiencies presented, Figure 3 presents the values of emissions from livestock, total carbon storage, emissions from deforestation and the emissions balance from beef cattle farms. All farms that have had emissions from deforestation greater than gross emissions from livestock have high ENT efficiency. The exception is the EMBF farm, where the total storage exceeds emissions from the deforested area.

Gross CO_2 emissions per hectare of UAA in the extensive and intensifying system are similar, close to 2.0 t CO_2/ha UAA; in the intensive system, this average rises to 14.9 tCO_2/ha UAA/ year (Table 3).

For ENT efficiency, including deforestation, ES and MIS farms have high emission values, related to their agrarian situation (1, 2 and 4a - Assentamento areas), while large farms with high deforestation emissions belong to areas 4 and 5.

Dairy farms with associated beef

The efficiencies in Table 6 follow the same colour principle as in Table 5. The mean EL efficiency of livestock emissions is 5.05 t eqCO_2/1000 L. On intensive system farms, EL efficiencies are lower in relation to the level of milk production. However, there is an extensive farm (ESD4) with low efficiency due to a high unit production (8 L milk per cow). This farm has the smallest animal feed with 0.3 AU/ha and the lowest production per hectare, which refers to the discourse on land use, the same applies to the MMD farm. For ENL efficiency, we see the same trend for beef cattle farms, with rather negative emissions and only one farm with average efficiency.

Figure 4 presents the values of emissions from livestock, total carbon storage, emissions from deforestation and the emissions balance from dairy farms with associated beef. In terms of ENT efficiency, farms are performing well, even though emissions from livestock exceed total carbon storage, as is the case for the ISD3 and ISD farms. The ESD2 farm has an average ENL efficiency due to its higher gross emission from livestock compared to the total carbon storage of the farm.

By measuring ENT efficiency, most farms now have high efficiency, owing to large emissions from deforestation, with both low-ENT farms not having deforested in the last 20 years.

Energy consumption and GHG emissions from start-up farms

Two start-up farms were studied. The first is a medium size farm in a moderate intensification system (MIS) with breeder-fattener production - MMBF. The second is a small farm in an extensive system (ES) orientated around dairy production - ESD.

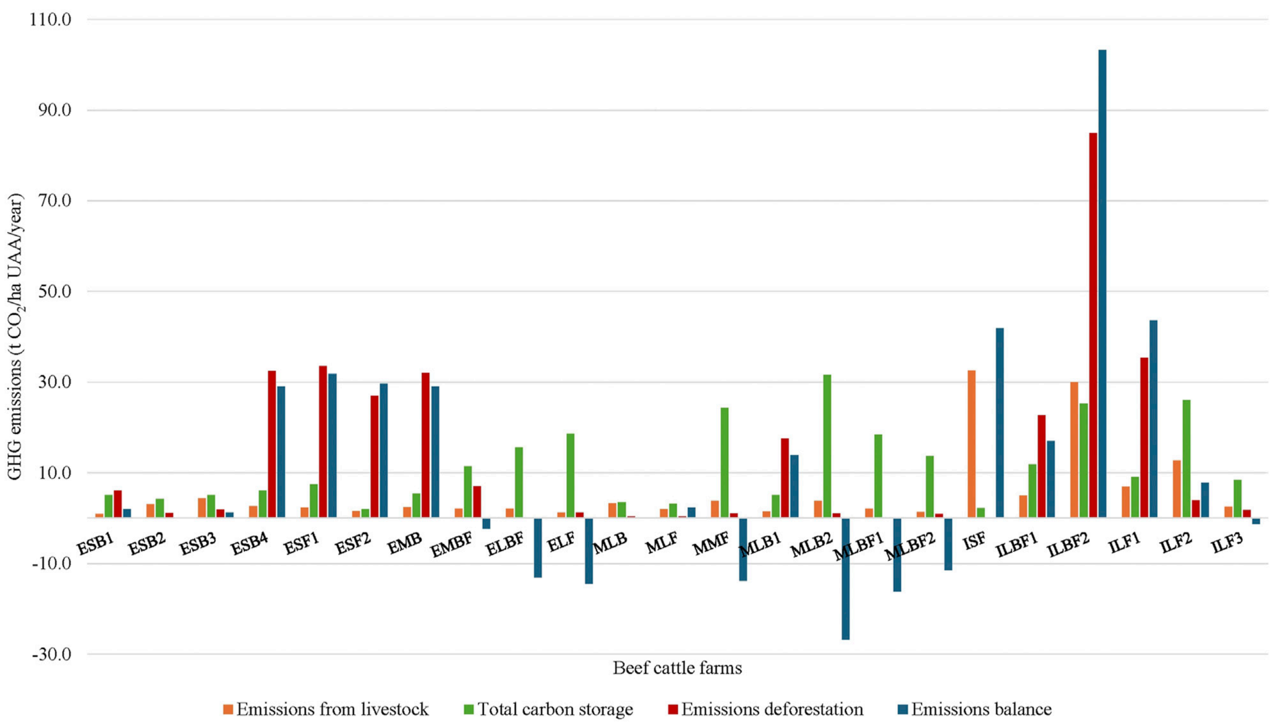

FIGURE 3
Emissions from livestock, total carbon storage, emissions from deforestation and the emissions balance from beef cattle farms.

Energy consumption

The MMBF farm has limited meat production of only 12 kg/ha UAA, which is low compared to the average of 227 kg/ha UAA seen in other moderate systems (Table 2). As a result, the energy consumption per ton produced reaches 84.82 GJ/t LW, which is well above the 12.58 GJ/t LW reported in Table 2 for the same system. Furthermore, the energy consumption per hectare is 1.0 GJ/ha UAA, compared to an average of 3.3 GJ/ha UAA for MIS meat farms. The main source of energy consumption of this farm was the use of plant protection products, agricultural fuel, fertilisers and limestone for the recovery of pastures, which were degraded when the producer arrived; investment in agricultural infrastructure and equipment also accounted for a large share of total consumption.

The ESD farm's initial investment in acquiring animals for herd formation yielded an energy input of 2.6 GJ/ha UAA, compared with an average of 0.55 GJ/ha UAA of the ES dairy farms. Low milk production of only 168 L/ha/year and 4 L/cow/day had an impact on consumption of 15.48 GJ/1000L, 19 times higher than the average for extensive farms (0.82 GJ/1000 L) (Table 3).

Greenhouse gas emissions

GHG emissions from the MMNE farm are 1.52 tCO_2/ha UAA and 127.89 tCO_2/t LW, which is extremely high compared to the average of 15.17 tCO_2/t LW of stable farms (Table 3). As with other farms, methane is the main gas accounting for 87% of emissions, and when land use, land-use change and forestry (LULUCF) emissions are considered, deforestation accounts for 89% of emissions.

Emissions from the ESD farm are 1.7 tCO_2/ha UAA and 6.99 tCO_2/t LW without taking into account the LULUCF sector; if the sector is taken into account, emissions related to deforestation now account for 96% of total emissions.

Eco-efficiency groups combining energy and GHG

Eco-efficiency groups based on the indicators of energy efficiency (GJ/t LW) and GHG emissions efficiency - Efficiency EL (t eq CO_2/t LW) were created, and were classified according to their performance. Two categories per indicator are proposed according to the average: beef cattle farms (16.29 GJ/t LW and 17.39 eqCO_2/t LW), and dairy farms with associated meat (2.74 GJ/1000L and 5.04 t eqCO_2/1000 L).

Four eco-efficiency zones were established: E-GHG+ group: low energy efficiency and high EL efficiency; E + GHG+ group: high energy efficiency and high EL efficiency; E-GHG-group: low energy efficiency and low EL efficiency; and E + GHG-group: high energy efficiency and low EL efficiency (Figures 5A,B).

The farms that belong to the E-GHG+ group are those that perform well in terms of energy. They operate with very few inputs

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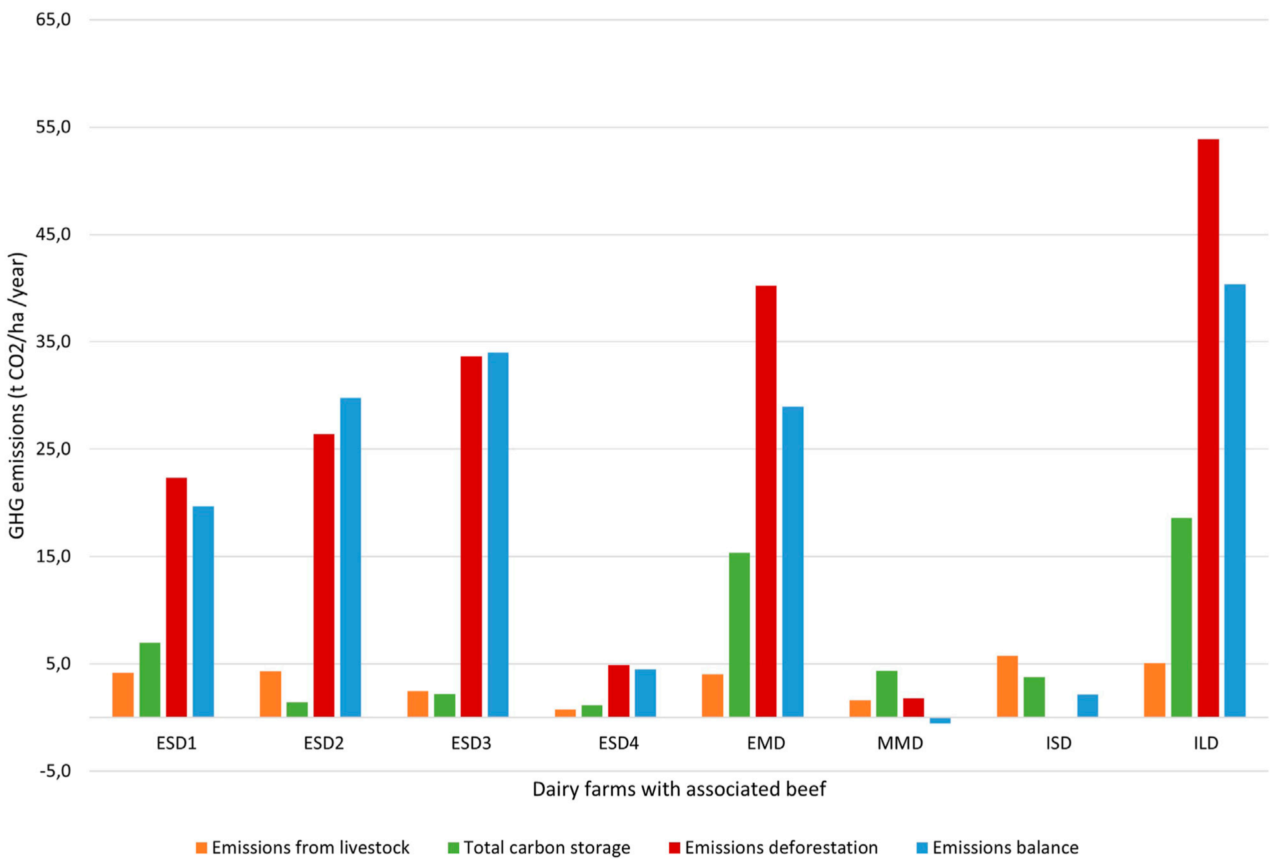

FIGURE 4
Emissions from livestock, total carbon storage, emissions from deforestation and the emissions balance from dairy farms with associated beef.

in an extensive system, producing meat or milk by taking advantage of the soil and climate resources that favour grass production, but which do not allow large production volumes, which increases the efficiency of livestock emissions. The farms more representative of the group are ESB1, ESB2, ESB3, ESB4, ESD1, ESD2 and EMD. None of the farms were representative of the E + GHG+ group.

In the E-GHG-group, which is ideally eco-efficient, there is only one ESD4 dairy farm, which is characterised by low input consumption and highly productive animals. The E + GHG-group includes intensive and moderately intensifying farms with high inputs not accompanied by an increase in production, are represented by the ILF1, ILF2, ILF3, MSF, MMF, ISD and ILD farms. In the meat system, the extensive farms ESF1 and ESF2 are also in this group.

Discussion

Energy balance

Energy consumption per hectare logically increases with the intensification of systems linked to a greater use of inputs. These intensive systems are based on the purchase of young animals and fattening them with purchased feed and/or fertilised pasture, all energy-consuming items. Sá et al. (2013) evaluated the energy balance of meat production in mixed or specialised agricultural systems for 20 years in the Cerrado, and obtained values of 20.38 GJ/ha in fertilised pastures and 62.59 GJ/ha in agriculture-livestock integration systems with direct seeding. Our meat intensive systems consume on average more (35.2 GJ/ha) than the specialised meat systems, while the ES and MIS systems consume much less (2.52 and 3.3 GJ/ha).

Analysing our 31.17 GJ/t LW fattener systems, they show similar energy efficiency as those of Vázquez (2020) in Mexico, who reported a value of 31.40 GJ/t LW in a study of three farms; and much lower than fattener farms in other tropical regions, such as Reunion (62 GJ/t LW) (Vayssières et al., 2011). For dairy farms, the same authors reported efficiency values of 7 GJ/1000 L compared to 2.74 GJ/1000 L in our study.

The IS farms tend to consume more energy per amount of output than MIS and ES farms. On dairy farms, fuel, fertilizers, and feed for cows are the main consumption items, and the low volume of milk production per cow makes for high efficiencies. In the dairy farms in our study, these are dual-ability mixed cows with low productivity, with an average production of 4.22 L/cow/

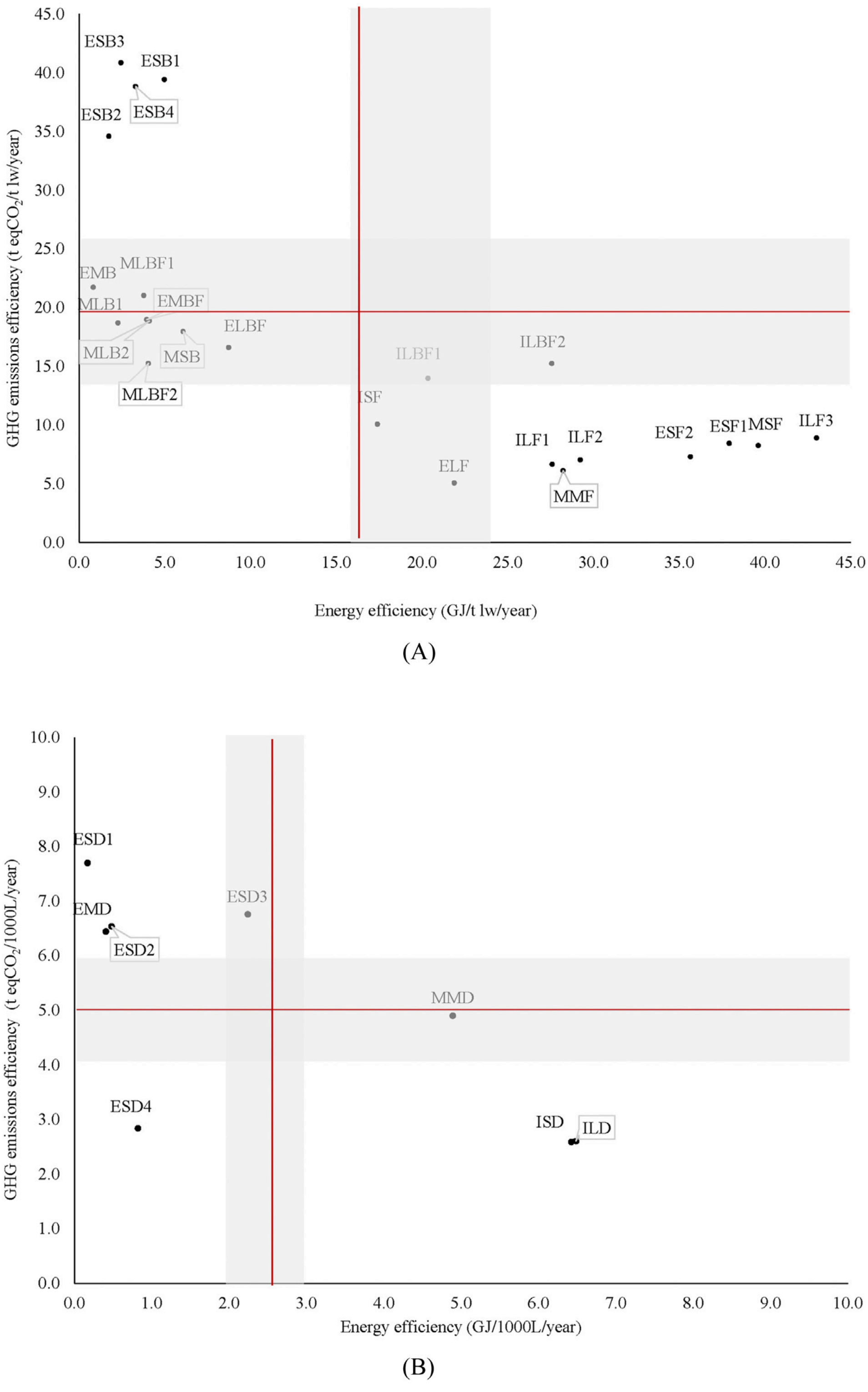

FIGURE 5
(A,B): Eco-efficiency groups based on indicators of energy efficiency (GJ/t LW or 1000 L) and GHG emissions efficiency (teq CO_2/t LW or 1000 L) from beef cattle and dairy farms with extensive (E), moderate intensification (M), and intensive (I) beef production systems in Paragominas. **(A)** Beef cattle farms. **(B)** Dairy farms with associated beef.

day. This is the reality in most properties in the municipality that do not have a well-consolidated milk production line (Rodrigues et al., 2020).

Extensive farms have the lowest efficiencies because they consume very few inputs, and even though they produce little, their outputs still exceed their inputs. These same farms have the highest energy yield values, i.e., they produce more energy than the total used, and can reach values above 16 GJ/GJ for animal meat and milk production systems (Table 4). Bonaudo et al. (2012), in a study carried out on six farms in Paragominas, report that the average energy yield of breeder, fattener and fattener-breeder farms was 3.48, 2.69 and 0.99 GJ/GJ. These yields were not related to the intensity of the system, but rather to the animal and plant production efficiencies. In our study, we found energy yield values of 5.94, 0.78 and 2.32 GJ/GJ for the same types of farming systems respectively, with higher values observed on ES farms.

In the search for more efficient livestock systems, the low energy efficiency observed in extensive systems represents a significant limitation. This low efficiency is associated with a reduced use of inputs, which, in turn, results in low levels of productivity in meat and milk production. Thus on one hand, extensive livestock farming preserves biodiversity but has low productivity. On the other hand, intensive livestock farming increases production at the cost of using chemical inputs that can harm ecosystems. In this context, moderate intensification has the potential to strike a balance between productivity and environmental conservation (Abramovay et al., 2025).

For MIS beef cattle farms, the energy yield and efficiency values are rather good and appear similar to those of the ES farms, but animal production per head is higher and can double, as for the breeder system. According to Manzano et al. (2024), it is essential to identify a balance between reducing dependence on fossil energy and maintaining adequate production levels to enable systems that are sustainable from both an environmental and economic point of view.

The moderate intensification of livestock farming is the main strategy for reconciling increased productivity with a reduction of socio-environmental impacts in Latin America (Poccard-Chapuis et al., 2015). This is a production model that is cost effective for all types of producers and does not require advanced technological skills to implement. In addition, it takes advantage of the region's favourable climatic conditions, such as high solar radiation and adequate rainfall, and is primarily based on renewable resources (Abramovay et al., 2025; Köberle et al., 2023; Pacheco et al., 2017).

On beef cattle farms, MIS appear to perform well in terms of energy: they increase production through investments on the farm without increasing energy efficiency. With an average efficiency of 12.58 GJ/t LW, these types of farms in the Brazilian Amazon are nearly three times more energy efficient compared to other regions such as Metropolitan France and French Guiana (30 and 36 GJ/t LW, respectively) (Bordet et al., 2010). Energy consumption per livestock production unit is higher than in cropping systems, due primarily to feed purchases (Pelletier et al., 2011). In our sampling, efficiencies are lower because these farms manage large areas of highly productive pasture with low input levels and little equipment and infrastructure.

Energy yield values in our study are more closely related to the type of production than to the intensification of the system. Fattener farms are disadvantaged by purchases of animals, while breeder and breeder farms are more energy efficient in ES or MIS. An MIS is more advantageous in that it has the potential to increase production from its investments, unlike an ES, which has low energy efficiency due to its mining and limited livestock farming.

A reasoned and limited use of energy is necessary for economic, ecological and social reasons. By quantifying the energy efficiency of livestock systems, it is possible to design a sustainable livestock system that produces both food and energy, as well as to make more informed policy decisions regarding livestock (Guevara et al., 2014; Perez-Neira et al., 2014; Funes-Monzote et al., 2009; Pervanchon et al., 2002).

This study analysed the energy consumption, use and production of different rural properties in the Amazon region. Its original approach makes it possible to propose productive practices. The moderate intensification system has demonstrated energy efficiency, whereas other studies indicate that the highest level of energy efficiency is achieved by eliminating synthetic fertilizers and herbicides, which also reduces fuel consumption (Bertilsson et al., 2008; Pimentel et al., 2005). However, this approach leads to limited animal production.

GHG emissions

Our results show that the averages of total GHG emissions increase with the intensification of the production system, with significant differences for meat-producing systems, and with the same non-significant trend for dairy farms. The main contributing gas is CH_4 from enteric fermentation of animals and faeces in the soil. Carbon dioxide (CO_2) emissions were the lowest, remaining below 15%, with the exception of the intensive system on dairy farms (25% due to feed purchases and fuel and electricity consumption).

In 2020, Brazil's agriculture and livestock sector contributed 28.5% of the country's total emissions, 62% of which came from enteric methane (MCTI, 2022). CH_4 emissions in livestock are intrinsic to ruminant physiology and soil biochemical processes, and a rise in the number of intensive systems leads to increased emissions per hectare. However, there are alternatives for reducing CH_4 emissions, including improved forage (low fibre content and greater digestibility) (Ruggieri et al., 2020; Barbero et al., 2015) obtained through practices such as rotational grazing (Rouquette Jr, 2016; Gimenes et al., 2011) and feed supplementation that alter ruminal fermentation (de Carvalho et al., 2023; Dias et al., 2023; Simioni et al., 2022; Neto et al., 2017; Fiorentini et al., 2013). These are practices adopted in particular on farms that intensify their production system.

Emissions per hectare are higher in the most intensive systems due to the animal stocking rate per hectare. Values of 2.08, 2.52 and 14.94 tCO_2/ha/year for ES, MIS and IS were observed. Thus, fertilisation increases emissions (Molossi et al., 2020), although fertilizers combined with good grazing management allows more productive grazing (Cunha et al., 2022; Berça et al., 2021; Corrêa et al., 2021; Oliveira et al., 2020; Delevatti et al., 2019), promoting carbon storage in soil (Azevedo et al., 2024; Figueiredo et al., 2017), and GHG mitigation.

Emissions per quantity of beef or milk produced (EL efficiency) tend to decrease in the most intensive farms compared to the extensive system, with a decrease of 57% (Table 3).

For beef cattle farms, the efficiency EL (17.40 t $eqCO_2$/t LW) is slightly higher than that observed in metropolitan France (14.20 $eqCO_2$/t LW) but much lower than that of neighbouring French Guiana (30.00 t $eqCO_2$/t LW). In dairy farms, the EL efficiency was 5.05 t $eqCO_2$/1000 L compared to 1.5 in metropolitan France (Planète, 2010) and 1.8 t $eqCO_2$/1000 L in La Réunion (Vayssières et al., 2011). In our study, EL efficiency was defined on a *per capita* basis, so on farms with breeder systems the efficiencies are not as good as on farms with the fattener systems. In our sample, intensive system farms have the highest efficiencies due to their higher output in kilograms per head and per hectare (Table 5).

Similar EL efficiency values were reported by Bonaudo et al. (2012), who obtained values of 18.9, 16.0 and 14.8 t $eqCO_2$/t LW for the breeder, fattener and breeder-fattener systems, respectively in Paragominas; and by Vayssières et al. (2011) in tropical conditions, with 18.5 and 10.4 t $eqCO_2$/t lw/year in the breeder and fattener systems.

The EL efficiency of dairy farms is much higher than the values reported in the literature, linked to low productivity per head. Improving it would require measures leading to better *per capita* productivity, including animal nutrition and genetics (Simioni et al., 2022; Oliveira et al., 2014; Freitas et al., 2011). With minimal investment, rotation grazing with a stocking rate adapted to the carrying capacity is a practical and viable alternative to a reduction in emissions per ton of product.

The low efficiency of emissions leads to low-carbon livestock production. However, these farms have very variable values for production per hectare and stocking rate, with only three intensive fattener-system farms having good animal production associated with a high animal stocking rate and good production per hectare.

Low-emission farms per product may not be effective in terms of land use. Most beef cattle farms produce between 24.1 and 200 kg/ha per hectare, below the national average for commercial farms of 258 kg/ha (Barbero et al., 2015). Approximately 50% of the farms in this study have an animal stocking rate of less than 0.9 AU/ha, while pastures in wetlands have a loading potential of between 1 and 3 AU/ha, which can rise to 2 to 8 AU/ha depending on fertilisation (Lira et al., 2017).

One of the main causes of deforestation in the Amazon biome is extensive livestock farming (Haddad et al., 2024; Poccard-Chapuis et al., 2020; Garcia et al., 2017). This is a historical dynamic that traces back to the territorial expansion in the Amazon, during which a simple technical model of livestock farming shaped deforested and homogeneous landscapes; and which is characteristic of the colonisation of Paragominas. Taking into account land and forest use change ("LUCF sector"), farms in the extensive system have a higher percentage of emissions from deforestation than those derived from livestock (Table 3). This response is linked to the agrarian situation of the farms. Eleven of the 15 farms in the extensive meat and milk system are located in a *colônia* or an *assentamento* (Tables 5, 6), characterized by a more recent installation, with a larger area deforested in the period considered.

"*Assentamento rural*" are rural settlements in Brazil established through a federal land regulation by the National Institute of Colonisation and Agrarian Reform (INCRA) allowing a policy of colonization or agrarian reform (Navegantes-Alves, 2011). "*Colônias*" are settlements that originate from the colonization process in the Amazon, and that can become *assentamentos*.

The different agrarian situations found in the municipality of Paragominas were studied in this work, and they show a deforestation specific to each system. MIS and IS farms are included in agrarian situation 4 - ES in perimeter "zero deforestation" and 5 - intensification corridor with a period of colonization between 1960 and 1980. The only MIS farm with significant deforestation is located in an *assentamento*, while the other MIS are in areas with significant carbon storage. On IS farms, most large farms have continued to open new areas over the past 20 years (Tables 5, 6).

In addition to the agrarian situation in the region, deforestation in the Amazon is driven by a combination of local production dynamics and external demands. The expansion of livestock and agriculture, particularly the cultivation of soybeans, corn, and sorghum, plays a major role in this process. Land dynamics and land competition between soybean farmers and ranchers intensify this process. While the domestic market is responsible for most of the deforestation, international demand has an even greater environmental impact, concentrating on high-value commodities. In this scenario, a systemic approach that integrates national and international actors is essential, strengthening environmental oversight and governance at multiple scales (Haddad et al., 2024; Moffette and Gibbs, 2021).

Looking at the efficiency of net livestock emissions, all farms have low or negative emissions per animal product. This comes from the characteristics of farms in the Amazon that have large forest areas and exploit pastures that are more than 20 years old and store carbon in the soil.

The moderate intensification system has the best emission indicators, although in terms of EL efficiency the values are average. Solutions for creating more sustainable systems include the ecological intensification of livestock farming through the adoption of practices that are accessible to all producers, such as rotational grazing, maintaining soil fertility, restoration, and forage management. More costly and technical practices, such as the integration of agriculture with livestock and agro-sylvo-pastoral systems, also are relevant options.

Practices for achieving eco-efficiency

The E-GHG+ group characterises traditional systems in the Amazon. They use abundant fodder, do not stock forage or use inputs, and have low production levels. The energy efficiency of this group is correct, but the GHG emissions per product are high. The lack of fertilisers to maintain soil fertility contributes to pasture degradation, leading to lower productivity and reduced sustainability of livestock farming (Dias-Filho, 2014), as well as lower livestock production per hectare (Oliveira et al., 2024).

One of the strategies to maintain low energy efficiency while reducing GHG emissions is moderate system intensification. This approach is particularly relevant for farms with energy efficiency below 7 GJ/t LW and average emission efficiency (below 25 t eqCO_2/t lw), which are close to qualifying for the E-GHG-group.

The ideal eco-efficiency of the E-GHG-group is achieved through low input consumption and highly productive animals linked, for example, to good grazing management. In meat production farms, medium and large MIS and ES farms are close to the E-GHG-group. They have a low input-to-output ratio relative to production, resulting in moderate emissions per hectare.

On beef cattle farms, high energy efficiency is due to the purchase of animals, which leads to a high energy cost. However, when inputs are more suitable for production and energy efficiency decreases, farms move closer to the E-GHG-group (e.g., ISF and ELF). These farms have completely different systems. An ISF farm has average energy efficiency through its high output per hectare with larger outputs related to grazing management and the provision of supplementation to animals. On an ELF farm, purchases of inputs are limited to the purchase of animals raised on a well-managed pasture with no other inputs for fattening. If inputs increase, with the purchase of feed, for example, without increased production, the efficiency of emissions increases, as for ILBF1 and ILBF2.

As an alternative to extensive livestock systems in the Amazon, integrated production systems such as SPS, ICLS and ICLFS also promote efficient land use, environmental recovery, and economic gains, configuring themselves as promising strategies for the sustainable intensification of livestock (Silveira et al., 2022). Systems integrating the forest component were not observed in our sample, however, they are beginning to be adopted in the municipality, impacting system improvement, mainly in relation to the stock of organic carbon in the soil compared to conventional systems (Sales et al., 2018).

Conclusion

The information in this study comes from interviews with farmers from different agrarian situations in the municipality of Paragominas, considered as a pole of agricultural development in the Amazon and presented as a model for sustainable livestock production. Our findings show that farms that adopt intensification techniques have lower GHG emissions per kilogram of product than extensive livestock under grazing, while energy consumption per kilogram and per hectare increases with system intensification, even though these farms are more energy efficient than those in other parts of the world. Differences in GHG emissions are also directly related to the agrarian status of properties in relation to land use change.

This work highlights some important limitations in the use of off-the-shelf calculators to assess livestock GHG emissions and energy balances, such as the use of regional energy and GHG cost coefficients for the transportation of poorly known inputs. The lack of accurate information from producers on entries and exits from the system, combined with information drawn from farmers' memories and registers, and not from measurements on the ground, lead to inaccurate reporting. Finally, the small sample size for dairy cattle limits the potential for causal inference.

However, despite this uncertainty, this study provides key insights for a coherent technical response focused on the production system. In addition to researching the absolute values of GHG emissions and energy consumption, this study used a tool to compare systems and identify practices aimed at optimizing the eco-efficiency of farms.

For future research, it appears necessary to continue the assessments based on methods of quantifying GHG emissions, such as the installation of a flow tower. The deforestation-related emission amortisation time and the envisaged carbon stock of old-growth pastures also has a major impact on the results and can be better understood and assessed in the light of developments in scientific studies in this field.

This study highlights the importance of using tools for calculating GHG and energy emissions that are tailored to regional conditions, which makes it possible to better identify the impacts of agricultural practices and thus adopt appropriate measures. This work also provided an opportunity to reflect on the impact of taking account of changes in land use and carbon stocks on emission balances, which are still not very well integrated in scientific studies. While we have solid data on the impact of agricultural practices on energy consumption and GHG emissions, broader analyses of environmental performance, such as water quality, air quality and biodiversity, are essential to complement information on the effects of different practices.

The results are important to promote the integration of virtuous practices into livestock systems that facilitate ecological intensification and reduce environmental impacts.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

DC led the redaction of the paper and contributed to data analysis; RP-C administered the project, contributed as a co-supervisor and reviewed and edited the manuscript; VB contributed to the conceptual frame of the studies and the paper and interpreted the results; J-LB contributed to data processing and analysis at the farm level; PL served as the main supervisor, reviewed and edited the manuscript. All authors reviewed the results and approved the final version of the manuscript.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The current work was supported by the TerrAmaz project funded by the Agence Française de Développement (Grant number: AFD CZZ264701G).

Acknowledgments

The authors thank Margot Moniot and Mathilde Lenoir for their contribution to data collection and the Brazilian Agricultural Research Corporation (EMBRAPA) for hosting the Paragominas campus. We also thank the local pastoral communities for their welcoming responses to the interviews.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/past.2025.14461/full#supplementary-material

References

Abramovay, R., Matte, A., Sanseverino, E. C., Ritt, A. L., and Galiano, M. W. (2025). Regenerative cattle farming in Latin America and the Caribbean, far beyond the oxymoron. *Rev. Econ. Sociol. Rural* 63. doi:10.1590/1806-9479.2025.289950en

ADEME (2011). *Réalisation d'un bilan des émissions de gaz à effet de serre – Filière agricole et agro-alimentaire: guide sectoriel 2011*. Paris: ADEME, 2011. Available online at: https://librairie.ademe.fr/changement-climatique/3344-realisation-d-un-bilan-des-emissions-de-gaz-a-effet-de-serre-filiere-agricole-et-agro-alimentaire.html (Accessed May 26, 2022).

Agriadapt (2013). Une agriculture respectueuse du climat - Evaluations et améliorations pour l'énergie et les émissions de Gaz à Effet de Serre à l'échelle de l'exploitation agricole dans l'Union européenne: Manuel 2013. Available online at: https://agriadapt.eu/wp-content/uploads/download-manager-files/Manual_French.pdf. (Accessed May 26, 2022).

AgriClimate Change Project (2013). *Une agriculture respectueuse du climat : Evaluations et améliorations pour l'énergie et les émissions de Gaz à Effet de Serre à l'échelle de l'exploitation agricole dans l'Union européenne.* Available online at: https://agriadapt.eu/wp-content/uploads/download-manager-files/Manual_French.pdf. (Accessed March 20, 2022).

Aubron, C., Corniaux, C., and Flori, L. (2022). "Adaptation aux changements locaux et globaux des systèmes d'élevage au pâturage," in *Élevages au pâturage et développement durable des territoires méditerranéens et tropicaux*. Editors A. Ickowicz and C. H. Moulin (Versailles: Editions Quae), 32–80.

Azevedo, J. C. D., Cardoso, A. D. S., Lage Filho, N. M., Faturi, C., Silva, T. C. D., Domingues, F. N., et al. (2024). Effects of agricultural expansion on soil carbon and nitrogen stocks in the Amazon deforestation arc. *Soil Syst.* 8 (1), 25. doi:10.3390/soilsystems8010025

Barbero, R. P., Malheiros, E. B., Araújo, T. L. R., Nave, R. L. G., Mulliniks, J. T., Berchielli, T. T., et al. (2015). Combining Marandu grass grazing height and supplementation level to optimize growth and productivity of yearling bull. *Anim. Feed Sci. Technol.* 209, 110–118. doi:10.1016/j.anifeedsci.2015.09.010

Berça, A. S., Cardoso, A. D. S., Longhini, V. Z., Tedeschi, L. O., Boddey, R. M., Reis, R. A., et al. (2021). Protein and carbohydrate fractions in warm-season pastures: effects of nitrogen management strategies. *Agronomy* 11 (5), 847. doi:10.3390/agronomy11050847

Bertilsson, G., Kirchmann, H., and Bergstrom, L. (2008). "Energy analysis of organic and conventional agricultural systems," in *Organic Crop Production e Ambitions and Limitations*. Editors H. Kirchmann and L. Bergstrom (Netherlands: Springer), 173–188.

Bertipaglia, L. M. A., Freitas, D. D., Fregadolli, F. L., Melo, G. M. P. D., Reis, R. A., and Berchielli, T. T. (2011). Suplementação da dieta de novilhos de três grupos genéticos em pastagem de *Brachiaria brizantha* cv. Marandu. *Acta Sci. Anim. Sci.* 33, 417–425. doi:10.4025/actascianimsci.v33i4.10872

Bogaerts, M., Cirhigiri, L., Robinson, I., Rodkin, M., Hajjar, R., Junior, C. C., et al. (2017). Climate change mitigation through intensified pasture management: estimating greenhouse gas emissions on cattle farms in the Brazilian Amazon. *J. Clean. Prod. 162*, 1539–1550. doi:10.1016/j.jclepro.2017.06.130

Bonaudo, T., Clerc, A. S. A. S., Nahum, B. B., de Castro, R. R. D., and Poccard-Chapuis, R. R. (2012). "Efficacité énergétique et émissions de GES de systèmes d'élevage bovin viande en Amazonie," in *Rencontre de recherches sur les ruminants*, 151–154.

Bordet, A-C., Bochu, J-L., and Touchemoulin, O. (2010). *Références PLANETE 2010, Fiche 10 - Production "Bovins viande"*. Toulouse : SOLAGRO, 9.

Brasil, (1953). Lei n°1.806, de 6 de janeiro de 1953. *Dispõe sobre o Plano de Valorização Econômica da Amazônia, cria a Superintendência da sua execução e dá outras providências*. Available online at: http://www.planalto.gov.br/cciviL_03/Leis/1950-1969/L1806.htm. (Accessed November 15, 2024).

Cardoso, A. D. S., Barbero, R. P., Romanzini, E. P., Teobaldo, R. W., Ongaratto, F., Fernandes, M. H. M. D. R., et al. (2020). Intensification: a key strategy to achieve great animal and environmental beef cattle production sustainability in *Brachiaria* grasslands. *Sustainability* 12 (16), 6656. doi:10.3390/su12166656

Cardoso, A. D. S., Brito, L. D. F., Janusckiewicz, E. R., Morgado, E. D. S., Barbero, R. P., Koscheck, J. F. W., et al. (2017). Impact of grazing intensity and seasons on greenhouse gas emissions in tropical grassland. *Ecosystems* 20, 845–859. doi:10.1007/s10021-016-0065-0

Cerri, C. C., Moreira, C. S., Alves, P. A., Raucci, G. S., de Almeida Castigioni, B., Mello, F. F., et al. (2016). Assessing the carbon footprint of beef cattle in Brazil: A case study with 22 farms in the state of Mato Grosso. *J. Clean. Prod.* 112, 2593–2600. doi:10.1016/j.jclepro.2015.10.072

Clerc, A. C., Bonaudo, T., Nahum, B., Dias de Castro, R., and Poccard-Chapuis, R. (2012). "Efficacité énergétique et émissions de GES de systèmes d'élevage bovin viande en Amazonie," in *XIXème rencontres recherches ruminants (dec. 05-06, 2012)* (Paris, France).

Corrêa, D. C. d. C., Cardoso, A. D. S., Ferreira, M. R., Siniscalchi, D., Gonçalves, P. H. d. A., Lumasini, R. N., et al. (2021). Ammonia volatilization, forage accumulation, and nutritive value of marandu palisade grass pastures in different n sources and doses. *Atmosphere* 12 (9), 1179. doi:10.3390/atmos12091179

Cunha, A. M. Q., Macedo, V. H. M., de Oliveira, J. K. S., Melo, D. D. M., Domingues, F. N., Cândido, E. P., et al. (2022). Nitrogen fertilisation as a strategy for intensifying production and improving the quality of Massai grass grown in a humid tropical climate. *J. Plant Nutr.* 45 (14), 2213–2227. doi:10.1080/01904167.2022.2046078

Dallaporta, B., Bochu, J. L., and Blanfort, V. (2020). Projet adaptation à la Guyane de l'outil public de diagnostic énergétique et carbone des exploitations agricoles ACCT-DOM - Bilans énergétiques et GES des exploitations agricoles de Guyane. *Cirad and Solagro - Unpubl. data.*, 2020.

Dallaporta, D., Bochu, J. L., Vilbf, M., Ouliac, B., Zoogones, L. J., Lecomte, P., et al. (2016). "Taking into account carbon sequestration of pasture in carbon balance of cattle ranching systems established after deforestation in Amazonia," in *Proc. 10th int. Rangeland congress, saskatoon, Canada*, 399–400.

de Carvalho, V. V., Souza, W. L., Perdigão, A., Niehues, M. B., de Matos, I. E., Ribeiro, M. M., et al. (2023). 343 Combination of feed additives to reduce methane emissions and increase performance by feedlot cattle. *J. Animal Sci.* 101 (Suppl. ment_3), 275–276. doi:10.1093/jas/skad281.330

de Figueiredo, E. B., Jayasundara, S., de Oliveira Bordonal, R., Berchielli, T. T., Reis, R. A., Wagner-Riddle, C., et al. (2017). Greenhouse gas balance and carbon footprint of beef cattle in three contrasting pasture-management systems in Brazil. *J. Clean. Prod.* 142, 420–431. doi:10.1016/j.jclepro.2016.03.132

Delevatti, L. M., Cardoso, A. S., Barbero, R. P., Leite, R. G., Romanzini, E. P., Ruggieri, A. C., et al. (2019). Effect of nitrogen application rate on yield, forage quality, and animal performance in a tropical pasture. *Sci. Rep.* 9 (1), 7596. doi:10.1038/s41598-019-44138-x

Dias-Filho, M. B. (2014). Recuperação de pastagens degradadas na Amazônia: desafios, oportunidades e perspectivas. *Políticas agroambientais e sustentabilidade: desafios, oportunidades e lições aprendidas*. Brasília, DF: Ipea, 149–169.

Dias, A. V. L., Messana, J. D., Granja-Salcedo, Y. T., Alfonso, Y. F. M., Silva, L. G., Camargo, K. D. V., et al. (2023). Efficiency of amino acid utilization in nellore cattle grazing low-quality forage supplemented with different sources of nitrogen. *Life* 13 (8), 1622. doi:10.3390/life13081622

FAO (2017). *Livestock solutions for climate change*. Food and Agriculture Organization, Rome, Italy. Available online at: https://openknowledge.fao.org/items/2985e4e2-3c37-4e7c-aa7c-3655de93d53c (Accessed October 15, 2024).

FAOSTAT (2023). World food and agriculture – statistical yearbook 2023. Available online at: https://openknowledge.fao.org/items/5c272dc7-e1b8-486a-b323-6babb174eee0 (Accessed October 15, 2024).

Fiorentini, G., Messana, J. D., Dian, P. H. M., Reis, R. A., Canesin, R. C., Pires, A. V., et al. (2013). Digestibility, fermentation and rumen microbiota of crossbred heifers fed diets with different soybean oil availabilities in the rumen. *Animal Feed Sci. Technol.* 181 (1-4), 26–34. doi:10.1016/j.anifeedsci.2013.01.011

Funes-Monzote, F., Monzote, M., Lantinga, E. A., and Van Keulen, H. (2009). Conversion of specialised dairy farming systems into sustainable mixed farming systems in Cuba. *Environ. Dev. Sustain.* 11, 765–783. doi:10.1007/s10668-008-9142-7

Garcia, E., Ramos Filho, F. S. V., Mallmann, G. M., and Fonseca, F. (2017). Costs, benefits and challenges of sustainable livestock intensification in a major deforestation frontier in the Brazilian Amazon. *Sustainability* 9 (1), 158. doi:10.3390/su9010158

Gimenes, F. M. d. A., Silva, S. C., Fialho, C. A., Gomes, M. B., Berndt, A., Gerdes, L., et al. (2011). Ganho de peso e produtividade animal em capim-marandu sob pastejo rotativo e adubação nitrogenada. *Pesqui. Agropecuária Bras.* 46, 751–759. doi:10.1590/S0100-204X2011000700011

Guevara, F., Rodríguez, L. A., Ocaña, M. J., Cruz, J. O., Pinto, R., La O, A., et al. (2014). Maize stover in the relationship of maize growing and cattle production in the dry tropics of Chiapas, Mexico. *Arch. Latinoam. Prod. Anim.* 22 (1/2), 37–42.

Haddad, E. A., Araújo, I. F., Feltran-Barbieri, R., Perobelli, F. S., Rocha, A., Sass, K. S., et al. (2024). Economic drivers of deforestation in the Brazilian legal Amazon. *Nat. Sustain.* 7, 1141–1148. doi:10.1038/s41893-024-01387-7

Ianni, O. (1978). *A luta pela terra*. Editors P.-R. J. Vozes IBGE Instituto Brasileiro de geografia e estatística - IBGE. Censo Agropecuário 2017. Available online at: https://censoagro2017.ibge.gov.br/templates/censo_agro/resultadosagro/pecuaria.html?localidade=0&tema=75652 (Accessed November 27, 2024).

IBGE (2023). Instituto Brasileiro de Geografia e Estatística - IBGE. Rebanho de Bovinos (Bois e Vacas) 2023. Available online at: https://www.ibge.gov.br/explica/producao-agropecuaria/bovinos/br. (Accessed May 23, 2025).

INPE (2024). Programa de Monitoramento da Amazônia e Demais Biomas. DSEMatamento—Amazônia Legal. *TerraBrasilis PRODES (dSEMatamento)*. Available online at: https://terrabrasilis.dpi.inpe.br/app/map/deforestation?hl=pt-br (Accessed February 12, 2024).

IPS Amazônia (2023). *Índice de progresso social na amazônia brasileira: resumo executivo*. Editor Santos, D. (Belém, PA: Instituto do Homem e Meio Ambiente da Amazônia)–4. Available online at: https://amazonia2030.org.br/wp-content/uploads/2023/07/IPSAmazonia2023.pdf (Accessed May 23, 2025).

Keating, B., Carberry, P., Thomas, S., and Clark, J. (2013). "Eco-efficient agriculture and climate change: conceptual foundations and frameworks," in *Eco-Efficiency: from vision to reality* (Cali, Colombia: International Center for Tropical Agriculture CIAT), 19–28.

Keating, B. A., Carberry, P. S., Bindraban, P. S., Asseng, S., Meinke, H., and Dixon, J. (2010). Eco-efficient agriculture: concepts, challenges, and opportunities. *Crop Sci.* 50 (Suppl. 1). doi:10.2135/cropsci2009.10.0594

Köberle, A. C., Holtedahl, P., Gurgel, A., Bodirsky, B. L., Beier, F., Humpenöder, F., et al. (2023). Livestock intensification and the role of finance in the food system transformation in Brazil. *Food Syst. Econ. Comm.* Available online at: https://foodsystemeconomics.org/wp-content/uploads/Koberle-et-al.-2023.pdf (Accessed May 23, 2025).

Lambin, E. F., Gibbs, H. K., Ferreira, L., Grau, R., Mayaux, P., Meyfroidt, P., et al. (2013). Estimating the world's potentially available cropland using a bottom-up approach. *Glob. Environ. Change* 23 (5), 892–901. doi:10.1016/j.gloenvcha.2013.05.005

Larrea-Alcázar, D. M., Cuvi, N., Valentim, J. F., Diaz, L., Vidal, S., and Palacio, G. (2021). "Economic drivers in the Amazon after European colonization from the nineteenth century to the middle of the 19th century to the 1970s," in *Amazon assessment report 2021* (New York, USA: United Nations Sustainable Development Solutions Network). Available online at: https://www.theamazonwewant.org/spa-reports/ (Accessed March 22, 2024).

Latawiec, A. E., Strassburg, B. B. N., Valentim, J. F., Ramos, F., and Alves-Pinto, H. N. (2014). Intensification of cattle ranching production systems: Socioeconomic and environmental synergies and risks in Brazil. *Animal* 8 (8), 1255–1263. doi:10.1017/S1751731114001566

Lenoir, M. (2022). Éco-efficience de fermes d'élevage bovin dans 2 zones d'étude d'Amazonie Brésilienne. *Mémoire fin d'étude, Ingénieur Agron. Spécialité Systèmes d'élevage, Montp. SupAgro*.

Lira, M. d. A., Mello, A. C. L. d., da Cunha, M. V., dos Santos, M. V., Dubeux Júnior, J. C. P., Lira Junior, MdA, et al. (2017). Produção animal em pastagens tropicais da América Latina. *Archivos Latinoamericanos de Producción Animal.* 25 (1-2).

Manzano, P., Pereira, M. A., and Windisch, W. (2024). Vast extension but positive outcomes, reduced but negative: Complexity and nuances in evaluating land use by livestock and crops. *Anim. Front.* 15 (1), 43–54. doi:10.1093/af/vfae051

Mapbiomas (2024). Projeto MapBiomas-Coleção 4.1 da Série Anual de Mapas de Cobertura e Uso de Solo do Brasil. Available online at: https://brasil.mapbiomas.org/map/colecao-4/ (Accessed March 15, 2024).

Martorano, L. G., Moraes, J. R. d. S. C. d., Silva, L. K. X., Fernandes, P. C. C., Júnior, J. M. d. A., Lisboa, L. S., et al. (2021). Agricultural and livestock production in the Amazon: A reflection on the necessityof adoption of integrated production strategies in the western region of the state of Pará. *Aust. J. Crop Sci.* 15 (8), 1102–1109. doi:10.21475/ajcs.21.15.08.p2908

Mauricio, R. M., Ribeiro, R. S., Paciullo, D. S. C., Cangussú, M. A., Murgueitio, E., Chará, J., et al. (2019). *Silvopastoral systems in Latin America for biodiversity, environmental, and socioeconomic improvements*. Agroecosystem diversity, Academic Press, 287–297. doi:10.1016/B978-0-12-811050-8.00018-2

MCTI (2022). "Ministério da Ciência, Tecnologia, Inovações e Comunicações – MCTI," in *Estimativas anuais de emissões de gases de efeito estufa no Brasil. 6ª Edição – 2022*. Brasília, DF. Available online at: https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/publicacoes/estimativas-anuais-de-emissoes-gee (Accessed August 30, 2023).

Moffette, F., and Gibbs, H. K. (2021). Agricultural displacement and deforestation leakage in the Brazilian Legal Amazon. *Land Econ.* 97 (1), 155–179. doi:10.3368/le.97.1.040219-0045R

Molossi, L., Hoshide, A. K., Pedrosa, L. M., Oliveira, A. S. D., and Abreu, D. C. D. (2020). Improve pasture or feed grain? Greenhouse gas emissions, profitability, and resource use for nelore beef cattle in Brazil's Cerrado and Amazon Biomes. *Animals*, 10 (8), 1386. doi:10.3390/ani10081386

Moniot, M. (2021). "Efficience environnementale de l'élevage bovin en Amazonie brésilienne," in *Mémoire de fin d'étude, Ingénieur agronome, Spécialité Systèmes d'élevage, Montpellier SupAgro*. Available online at: https://dumas.ccsd.cnrs.fr/dumas-04552220v1 (Accessed May 26, 2022).

Moran, D., and Wall, E. (2011). Livestock production and greenhouse gas emissions: defining the problem and specifying solutions. *Anim. Front.* 1 (1), 19–25. doi:10.2527/af.2011-0012

Navegantes-Alves, L. (2011). Interactions entre pratiques de gestion du pâturage et envahissement par les adventices chez les éleveurs bovins en Amazonie Orientale. Ph. D. Thesis. Montpellier SupAgro. Available online at: www.supagro.fr/theses/extranet/11-0027_Nevegantes_Alves.pdf.pdf (Accessed March 20, 2022).

Neto, A. J., Messana, J. D., Granja-Salcedo, Y. T., Castagnino, P. S., Fiorentini, G., Reis, R. A., et al. (2017). Effect of starch level in supplement with or without oil source on diet and apparent digestibility, rumen fermentation and microbial population of Nellore steers grazing tropical grass. *Livest. Sci.* 202, 171–179. doi:10.1016/j.livsci.2017.06.007

Oliveira, A. A., Azenha, M. V., Santana, S. S., Costa, J. P. R., Ruggieri, A. C., Berchielli, T. T., et al. (2014). "Effects of Marandu pastures heights and sources of energy supplements on the weights gains per animal and per area," in *Annual animal science meeting, 2014, Kansas. Proceedings of annual animal science meeting* (Kansas: American Animal Science Society), 1.

Oliveira, J. K. S. d., Corrêa, D. C. d. C., Cunha, A. M., Rêgo, A. C. d., Faturi, C., Silva, W. L. D., et al. (2020). Effect of nitrogen fertilization on production, chemical composition and morphogenesis of Guinea grass in the humid tropics. *Agronomy* 10 (11), 1840. doi:10.3390/agronomy10111840

Oliveira, L. O. F., Gomes, R. C., Costa, T. G., Carvalho, T. A., and Caramalac, L. S. (2024). Adubação de pastagens degradadas. *Arch. zootec.* 73 (284), 223–232

Osis, R., Laurent, F., and Poccard-Chapuis, R. (2019). Spatial determinants and future land use scenarios of Paragominas municipality, an old agricultural frontier in Amazonia. *J. Land Use Sci.* 14 (3), 258–279. doi:10.1080/1747423X.2019.1643422

Pacheco, P., Piketty, M. G., Poccard-Chapuis, R., Garcia-Drigo, I., El Husny, J. C., Gomes, M., et al. (2017). Beyond zero deforestation in the Brazilian Amazon. *CIFOR Infobr.* 167, 1–6. doi:10.17528/cifor/006394

Pelletier, N., Audsley, E., Brodt, S., Garnett, T., Henriksson, P., Kendall, A., et al. (2011). Energy intensity of agriculture and food systems. *Annu. Rev. Environ. Resour.* 36 (1), 223–246. doi:10.1146/annurev-environ-081710-161014

Perez-Neira, D., Soler, M., and Fernandez, X. (2014). Energy indicators for organic livestock production: A case study from andalucia, southern Spain. *Agroecol. Sust. Food.* 38, 317–335. doi:10.1080/21683565.2013.833154

Pervanchon, F., Bockstaller, C., and Girardin, P. (2002). Assessment of energy use in arable farming systems by means of an agro-ecological indicator: The energy indicator. *Agric. Syst.* 72, 149–172. doi:10.1016/S0308-521X(01)00073-7

Piketty, M. G., Poccard-Chapuis, R., Drigo, I., Coudel, E., Plassin, S., Laurent, F., et al. (2015). Multi-level governance of land use changes in the Brazilian Amazon: lessons from Paragominas, state of Pará. *Forests* 6 (5), 1516–1536. doi:10.3390/f6051516

Pimentel, D., Hepperly, P., Hanson, J., Seidel, R., and Douds, D. (2005). Environmental, energetic, and economic comparisons of organic and conventional farming systems. *Bioscience* 55, 573–582. doi:10.1641/0006-3568(2005)055[0573:eeaeco]2.0.co;2

Pinillos, D., Bianchi, F. J. J. A., Poccard-Chapuis, R., Corbeels, M., Tittonell, P., and Schulte, R. P. O. (2020). Understanding landscape multifunctionality in a post-forest frontier: supply and demand of ecosystem services in Eastern Amazonia. *Front. Environ. Sci.* 7. doi:10.3389/fenvs.2019.00206

Pinillos, D., Poccard-Chapuis, R., Bianchi, F. J. J. A., Corbeels, M., Timler, C. J., Tittonell, P., et al. (2021). Landholders' perceptions on legal reserves and agricultural intensification: diversity and implications for forest conservation in the eastern Brazilian Amazon, *For. Policy Econ., Landholders' perceptions Leg. reserves Agric. Intensif. Divers. Implic. For. conservation East. Braz. Amaz. Policy Econ.* 129. 102504. doi:10.1016/j.forpol.2021.102504

Pinto, A., Amaral, P., Souza Junior, C., Veríssimo, A., Salomão, R., Gomes, G., et al. (2009). "Diagnóstico socioeconômico e florestal do município de Paragominas," in *Belém, Brazil: research report*. Instituto do Homem e Meio Ambiente da Amazônia - Imazon, 1–65. Available online at: https://imazon.org.br/publicacoes/diagnostico-socioeconomico-e-florestal-do-municipio-de-paragominas/ (Accessed February 16, 2022).

Plassin, S. (2018). Élever des bovins dans des paysages éco-efficients. *Comprendre modéliser le Process. d'intensification dans les fermes d'élevage d'Amazonie Orient. brésilienne. Ph. D. Thesis Institut agronomique, vétérinaire For. de France*. Available online at: https://theses.fr/2018IAVF0028 (Accessed January 7, 2022).

Poccard-Chapuis, R., Carvalho, S. A., Burlamaqui Bendahan, A., Navegantes-Alves, L. D. F., Plassin, S., El Husny, J. C., et al. (2015). Des cendres de la forêt à l'économie verte, l'évolution agraire en Amazonie orientale traduit-elle un mouvement d'intensification écologique? *Fourrages* 222, 125–133.

Poccard-Chapuis, R., Thalês, M. C., Peçanha, J. D. C., and Piketty, M. G. (2020). Os Territórios de desmatamento na Amazônia. Uma análise geográfica no Estado do Pará. *Confins* 48. doi:10.4000/confins.34636

Richards, P. D., Walker, R. T., and Arima, E. Y. (2014). Spatially complex land change: the Indirect effect of Brazil's agricultural sector on land use in Amazonia. *Glob. Environ. Change* 29, 1–9. doi:10.1016/j.gloenvcha.2014.06.011

Rodrigues, A. E., Titan, G. D. N. A., Bronze, A. B. d. S., Dias, G. N., Silva, M. C. d., Saraiva, M. P., et al. (2020). Diagnóstico da pecuária leiteira do município de paragominas, mesorregião sudeste, estado do pará, brasil/ diagnosis of dairy farming in the county of paragominas, southeastern mesoregion, state of pará, Brazil. *Braz. J. Dev.* 6 (9), 73253–73269. doi:10.34117/bjdv6n9-690

Rouquette, F. M., Jr (2016). Invited review: the roles of forage management, forage quality, and forage allowance in grazing research. *Prof. Animal Sci.* 32 (1), 10–18. doi:10.15232/pas.2015-01408

Ruggieri, A. C., Cardoso, A. D. S., Ongaratto, F., Casagrande, D. R., Barbero, R. P., Brito, L. D. F., et al. (2020). Grazing intensity impacts on herbage mass, sward structure, greenhouse gas emissions, and animal performance: Analysis of *Brachiaria* pastureland. *Agronomy* 10 (11), 1750. doi:10.3390/agronomy10111750

Sales, A., Silva, A. R., Veloso, C. A. C., Carvalho, E. J. M., and Miranda, B. M. (2018). Carbono orgânico e atributos físicos do solo sob manejo agropecuário sustentável na Amaz©nia Legal. *In Colloquium Agrariae*. 14 (1), 1–5.

Sá, J. M., Urquiaga, S., Jantalia, C. P., Soares, L. H. D. B., Alves, B. J. R., Boddey, R. M., et al. (2013). Balanço energético da produção de grãos, carne e biocombustíveis em sistemas especializados e mistos. *Pesqui. Agropecuária Bras.* 48, 1323–1331. doi:10.1590/S0100-204X2013001000003

Schmink, M., and Wood, C. H. (1992). *Contested frontiers in the Amazon*. New york: Columbia University Press.

Scoones, I. (2023). Livestock, methane, and climate change: the politics of global assessments. *Wiley Interdiscip. Rev. Clim. change* 14 (1), e790. doi:10.1002/wcc.790

Seeg (2024). Análise das emissões de gases de efeito estufa e suas implicações para as metas climáticas do Brasil. Available online at: https://seeg.eco.br/wp-content/uploads/2024/11/seeg-relatorio-analitico-12.pdf (Accessed May 23, 2025).

Silveira, J. G. d., Oliveira Neto, S. N. d., Canto, A. C. B. d., Leite, F. F. G. D., Cordeiro, F. R., Assad, L. T., et al. (2022). Land use, land cover change and sustainable intensification of agriculture and livestock in the amazon and the atlantic forest in brazil. *Sustainability*, 14, 2563. doi:10.3390/su14052563

Simioni, T. A., Messana, J. D., Silva, L. G., Brito, L. F., Torrecihas, J. A., Granja-Salcedo, Y. T., et al. (2022). Performance and enteric methane emission of growing beef bulls from different genetic groups subjected to two supplementation strategies grazing tropical grass in the rainy season. *Animal Feed Sci. Technol.* 293, 115470. doi:10.1016/j.anifeedsci.2022.115470

Solagro (2002). Planete: Méthode pour l'analyse énergétique de l'exploitation agricole et l'évaluation des émissions de gaz à effet de serre. Available online at: https://solagro.org/medias/publications/f56_014planeteooct02.pdf (Accessed January 28, 2022).

Solagro (2013). ACCTool - ACCT (simplified version), ACCT DOM. Available online at: https://solagro.org/travaux-et-productions/outils/acctool-acct-simplified-version-acct-dom (Accessed January 28, 2022).

Tyukavina, A., Hansen, M. C., Potapov, P. V., Stehman, S. V., Smith-Rodriguez, K., Okpa, C., et al. (2017). Types and rates of forest disturbance in Brazilian Legal Amazon, 2000–2013. *Sci. Adv.* 3 (4), e1601047. doi:10.1126/sciadv.1601047

Vayssières, J., Thevenot, A., Vigne, M., Cano, M., Broc, A., Bellino, R., et al. (2011). Evaluation des inefficiences zootechnique et environnementale pour intensifier écologiquement les systèmes d'élevage tropicaux. Etude de cas à la Réunion. *Revue d'élevage de médecine vétérinaire des pays tropicaux* 64 (1-4), 73–79. doi:10.19182/remvt.10117

Vaz, V. (2013). "A formação dos latifúndios no sul do Estado do Pará: Terra, Pecuária e desflorestamento," in *PhD tesis, Centro de Desenvolvimento Sustentável*. Universidade de Brasília, 129.

Vázquez, O. O. S. (2020). Eficiencia energética y económica en sistemas ganaderos de engorde de bovinos de la SPR de RL Pecuaria Hermanos Vázquez Cruz. *Tesis prof. Como requisito obtener el título Ing. Agrofor. Univ. Ciencias Artes Chiapas. Fac. Ing. Subsede Villa Corzo*. Available online at: https://repositorio.unicach.mx/handle/20.500.12753/2362 (Accessed January 8, 2024).

Viana, C., Coudel, E., Barlow, J., Ferreira, J., Gardner, T., and Parry, L. (2016). How does hybrid governance emerge? Role of the elite in building a Green Municipality in the Eastern Brazilian Amazon. Environ. Policy Govern. 26, 337–350. doi:10.1002/eet.1720

Pastoralism
Research, Policy
and Practice

TYPE Original Research
PUBLISHED 13 August 2025
DOI 10.3389/past.2025.14926

OPEN ACCESS

EDITED BY
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RECEIVED 19 May 2025
ACCEPTED 11 July 2025
PUBLISHED 13 August 2025

CITATION
Banka IA, Rashid M and Sahani R (2025) Rethinking climate impacts and livestock emissions through transhumant pastoralism in Jammu and Kashmir.
Pastoralism 15:14926.
doi: 10.3389/past.2025.14926

Rethinking climate impacts and livestock emissions through transhumant pastoralism in Jammu and Kashmir

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This article reconsiders the climate implications of transhumant pastoralism through an ethnographic case study of the Chopan pastoralists in the alpine grasslands of Jammu and Kashmir, India. Amid dominant global climate narratives that homogenize livestock systems and often portray them as ecologically harmful, this study highlights the need for differentiated assessments that recognize the distinctiveness of extensive, low-input systems. Drawing on fieldwork conducted in the high-altitude Trajan pasture, we demonstrate how Chopan pastoralism makes ecologically efficient use of marginal environments through adaptive mobility, rotational grazing, and traditional ecological knowledge. Contrary to assumptions of overgrazing and degradation, our analysis—grounded in forage yield estimates and carrying capacity calculations—suggests that current grazing pressure remains well within sustainable limits. Moreover, the Chopans contribute to regional food security, mediate human-wildlife interactions, and promote soil fertility through natural nutrient cycling. Yet, these pastoralists remain structurally marginalized in policy frameworks and face increasing constraints from land-use change, forest restrictions, and infrastructural encroachments. We argue for the inclusion of pastoralist perspectives in climate policy debates and for a revaluation of transhumant systems as viable models of low-impact, climate-resilient land use. The study advances broader discussions on sustainability, ecological justice, and the role of traditional livelihoods in contemporary environmental governance.

KEYWORDS

climate change, transhumant pastoralism, greenhouse gas emissions, Chopan pastoralists, Jammu and Kashmir, livestock emissions, Forest Rights Act (FRA)

Introduction

The debate regarding emissions from livestock production has gained momentum since the UN Food and Agriculture Organization's 2006 report *Livestock's Long Shadow* estimated that 17.8% of greenhouse gas (GHG) emissions came from livestock (Steinfeld et al. 2006). Subsequent assessments have provided varying figures: Gerber et al. (2013) suggested 14.5%, Poore and Nemecek (2018) about 15%, Xu et al. (2021) proposed 19.6%,

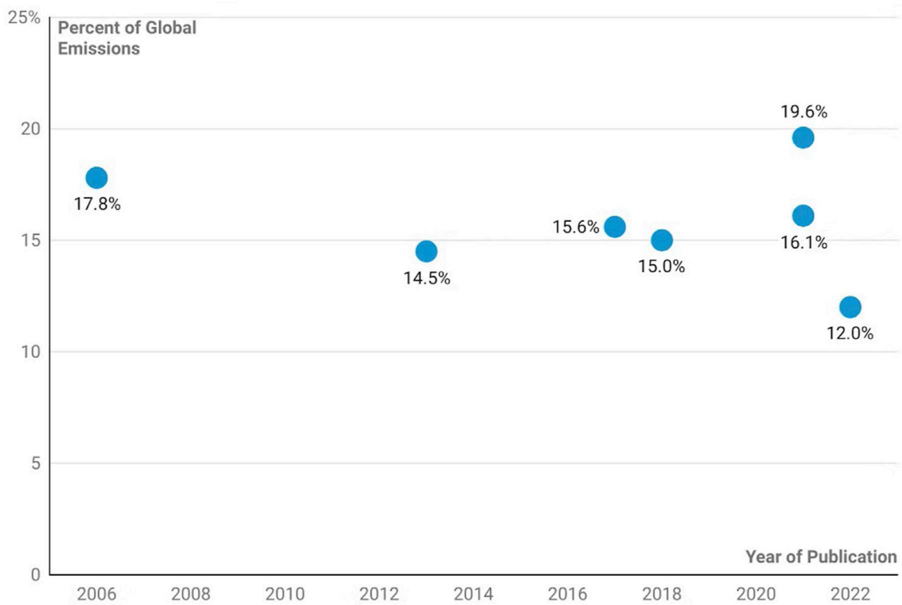

FIGURE 1
Estimated percentages of greenhouse gas emissions from livestock across different studies and years of publication. Adapted from Blaustein-Rejto and Gambino (2023).

while the latest GLEAM 3 estimate indicates 12% which is lower than previous GLEAM estimates (FAO 2023). Figure 1 presents the wide variation in estimates of greenhouse gas emissions from livestock, organized by their respective years of publication. These differences arise primarily from variations in the reference year of measurement, the emission sources included in the analysis, and the methodological approaches used to assess and compare the climate impact of different greenhouse gases (Blaustein-Rejto and Gambino 2023). The most widely cited estimate so far is of Gerber et al. (2013) which says that livestock emissions contribute 14.5% to the global anthropogenic greenhouse gas (GHG) emissions primarily through enteric fermentation producing methane, manure management and land use changes.

Most of the data used in greenhouse gas emission assessments are derived from intensive livestock systems, primarily located in the Global North and other developed regions; however, these assessments have contributed to media narratives that frequently depict pastoralism—an extensive and context-specific livestock system—as environmentally detrimental (Scoones 2023). The narrative advocating for alternatives to animal-based foods is prominently endorsed by influential individuals, including David Attenborough and Greta Thunberg, and is widely disseminated through media channels, while its commercial viability is further reinforced by the support of key actors such as Bill Gates and the World Economic Forum (García-Dory, Houzer, and Scoones 2022). However, such narratives typically fail to differentiate between intensive and extensive livestock systems, overlooking the unique characteristics and potential environmental benefits of traditional pastoralism. The assessments are affected by biases in the data, inconsistencies in how livestock systems are defined, and methodological challenges related to how baselines are established and evaluated within the models (STEPS Centre, 2023). Houser and Ian (2021) have advocated for systems analysis rather than life cycle analysis when calculating emissions from pastoral systems, arguing that mainstream climate policies unjustly portray all livestock systems as harmful while overlooking the low-impact nature and socio-environmental value of pastoralist systems, which leads to systematic marginalization of extensive livestock keepers (García-Dory, Houzer, and Scoones 2022). The most recent FAO report (2023), along with earlier studies, proposes various mitigation strategies, many of which are impractical to implement; those that are applicable are often already embedded within extensive pastoral systems globally. Addressing emission challenges effectively therefore requires the active involvement of pastoral communities and the integration of their traditional knowledge into policy and strategy development.

This study focuses on Chopan pastoralists in Jammu and Kashmir, India, who practice transhumant pastoralism in highland pastures above the tree line. As specialized sheep herders who do not own their own sheep or land, Chopans represent a marginalized community whose practices and knowledge have been largely absent from climate policy discussions. The prioritization of intensified production systems has historically excluded pastoralist communities—such as the Chopans—who have received limited support from government programs, subsidies, and financial services, thereby raising important questions about the equitable distribution of benefits in the future expansion of alternative and industrial protein sectors, particularly given the state's previous inability to address their needs in ways that also encompass cultural preservation, sustainable livelihoods, food security, and biodiversity protection. Through ethnographic research in the Trajan pasture, we explore how these pastoralists navigate environmental variability, contribute to local food security, and potentially enhance carbon sequestration in alpine grasslands.

The study addresses the research questions that examine the necessity of pastoralism for grasslands, its effects on carrying capacity, its environmental impacts and benefits, alternative land uses for highland pastures, implications of global climate narratives for local pastoral systems, effects on food security, policy impacts on pastoralists and low income countries, mitigation strategies in case of pastoralism, and the importance of indigenous knowledge and the involvement of pastoralists in climate debates.

Livestock emissions and climate change debates

The role of livestock in contributing to greenhouse gas emissions has been widely debated in both scientific and policy domains. While multiple influential studies report that livestock production significantly contributes to global emissions (Steinfeld et al. 2006; Gerber et al. 2013; Poore and Nemecek 2018; Xu et al. 2021), critics have questioned the methodologies used and their applicability across diverse production systems. The discussions need to differentiate between the systems and the situations in developing and industrialized developed countries.

In their critique of Poore and Nemecek (2018) peer-reviewed study, García-Dory, Houzer, and Scoones (2022) acknowledge its comprehensive dataset while highlighting significant limitations. They note that the research predominantly examines industrial agricultural systems in confined settings where free grazing is absent. The data collection demonstrates a distinct geographic bias, drawing primarily from European and North American contexts, with limited representation from Latin America and coastal China. Importantly, traditional subsistence production systems were explicitly excluded from the analysis. A review of 164 food production life cycle analyses revealed that a mere 0.4 percent originated from African contexts, with the vast majority examining industrial systems (Clark and Tilman 2017). The assessments assume that additional livestock result in additional emissions from an assumed neutral baseline, failing to recognize that in extensive systems, alternative land uses may not be possible as crops or trees will not grow and removal of livestock could lead to their replacement by other greenhouse gas-producing animals, whether wild ruminants or termites (Manzano and White 2019).

Research has indicated ecological advantages of extensive pastoral systems across diverse regions. Research in Sardinia, Italy showed that semi-extensive systems have potential benefits over more intensive systems due to the high carbon costs of feed imports and opportunities for carbon sequestration (Arca et al. 2021; Vagnoni et al. 2017). Researchers documented similar findings in China's Amdo Tibet region when extensive and more intensive systems were compared (Zhuang et al., 2017). In Senegal, mobile pastoral systems could achieve carbon neutrality, and occasionally even remove carbon from the atmosphere, when analyzed holistically within their ecological context (Assouma et al. 2019).

Recent studies have also challenged perceptions of particular livestock types. Kerven (2024) argues that the negative climate impact of domestic goats may be overstated, emphasizing their importance for low-income farmers, adaptability to harsh environments, and relatively low methane emissions per unit body weight compared to other ruminants, depending on feed and management systems. Loomis and Kerven (2025) challenge popular narratives of goats as agents of desertification, arguing instead that their ecological adaptability supports the resilience and food security of marginalized pastoralist communities. Dubeuf et al. (2023) highlight goat farming as a sustainable and low-emission livestock system, emphasizing its adaptability, use of marginal resources, and potential for climate impact mitigation through precision practices.

Pastoralism, uncertainty, and development

Pastoralism involves the extensive use of rangelands through mobile livestock-keeping, providing vital livelihoods globally. Rangelands cover more than half the world's land surface, supporting millions of people in harsh and highly variable environments (ILRI, IUCN, FAO, WWF, UNEP, and ILC, 2021). The provision of livestock products, such as meat, milk, wool, hides, and so on, is essential for local economies and the nutrition of often marginalized people (Manzano et al. 2021; Köhler-Rollefson 2021).

Pastoralists practice mobility to access resources, responding to variability and uncertainty (Krätli 2015; Scoones 2021; Manzano et al. 2021). This adaptability is increasingly recognized as valuable in the context of climate change, as pastoralists are well-suited to thrive under conditions of climate variability (Scoones 1995; Davies and Nori 2008; Goldman and Riosmena 2013; Pollini and Galaty 2021; Rodgers 2022; Marty et al. 2023).

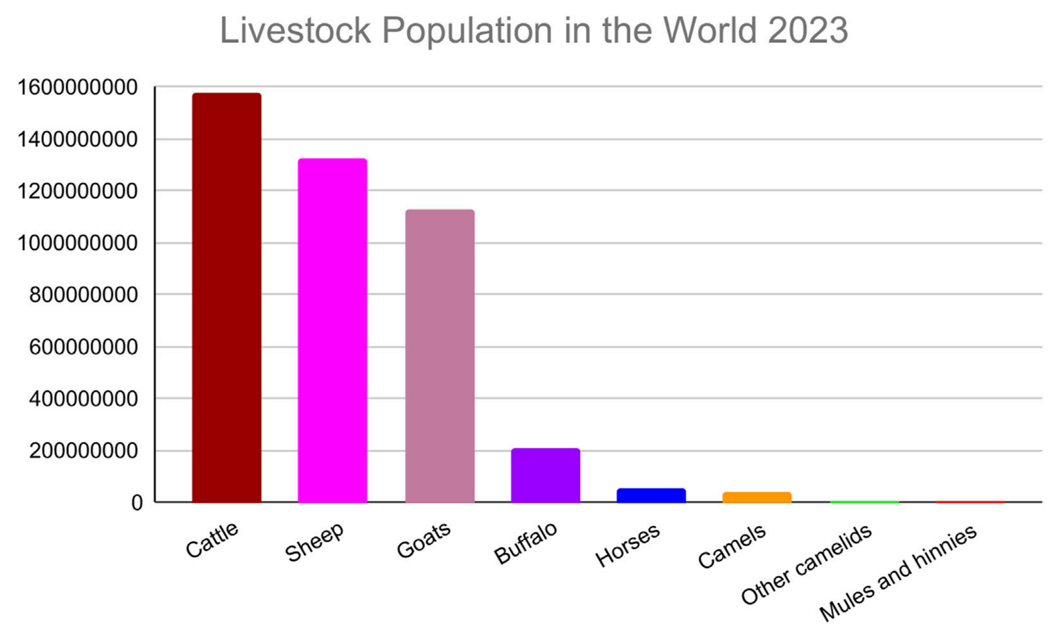

FIGURE 2
Ungulate livestock population in the world 2023. Source: FAOSTAT (2025).

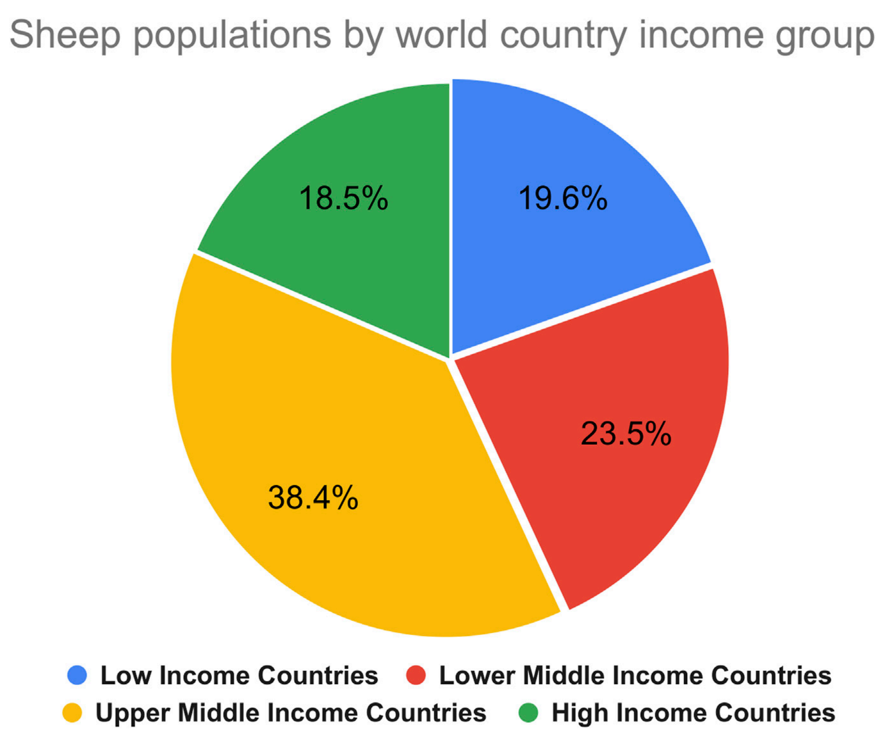

FIGURE 3
Sheep populations by world country income group. Source: World Bank Group (2025), based on gross national income (GNI) *per capita* data in U.S. dollars And FAOSTAT (2025).

Pastoral systems in Jammu and Kashmir

Sheep were among the earliest animals to be domesticated, originating in the Fertile Crescent and subsequently spreading across the globe, where they developed into numerous breeds and became integral to human societies (Zeder and Hesse 2000). The global sheep population is estimated at approximately 1.3 billion, making sheep the second most numerous ungulate livestock after cattle (FAOSTAT 2025) (see Figure 2). A majority of the global sheep population (56.9%) is concentrated in upper-middle- and high-income countries, where intensive livestock farming is predominant; in contrast, extensive pastoral systems are more common in low- and lower-middle-income countries, especially in Africa and Asia (World Bank Group 2025) (see Figure 3).

In Jammu and Kashmir, transhumant pastoralism is practiced by several communities. These include the Gaddis, who rear large flocks of sheep and goats; the Bakarwals, who are nomadic goat herders; the Gujjars, known for rearing buffaloes; and the Chopans, who specialize in sheep herding (Rao and Casimir 1982). The region's alpine and subalpine pastures—locally known as *Margs* or *Bahaks*—are ecologically significant and economically vital resources (Haq et al. 2022; Saleem et al. 2024b).

Rao and Casimir (1982) describe the Chopan as professional herders employed by sedentary agriculturalists in the Kashmir Valley and Jammu plains. They are responsible for livestock management during the summer months, moving animals to high-altitude pastures while owning minimal or no land themselves. Although the herds do not belong to them, the Chopans exercise substantial control over herd management and reproduction. Traditionally paid in kind, they are now predominantly compensated in cash.

The Chopan, the focus of this study, are socioeconomically marginalized sheep herders who manage the flocks of *zamindars* (land-owning farmers or agriculturalists) in the highland pastures between May and October each year. They are one of the many communities in India who have specialized pastoralist identities (Kishore and Köhler-Rollefson 2020; FAO 2021). Despite their central role in traditional pastoral systems, they have not been granted Scheduled Tribe status by the Government of India unlike other pastoral communities in Jammu and Kashmir. Their exclusion from official recognition has contributed to their invisibility in contemporary policy and academic discourse. Even recent studies, such as Singh and Kerven (2023), have omitted the Chopan from analysis, primarily due to underrepresentation in official datasets and limited documentation.

In comparison, Gujjar and Bakarwal pastoralists have received more scholarly attention. Rashid, Ghosh, and Ali (2024) analyze the inter- and intra-community dynamics among these groups, noting that kinship ties, shared cultural practices, and cooperative strategies enable them to adapt to socio-environmental pressures. Similarly, Banka and Sahani (2023) underscore the pressing socio-ecological and policy-related challenges faced by the Chopan, such as inadequate shelter, wildlife threats, reduced access to grazing lands, restrictions on traditional ecological knowledge, and declining economic viability of sheep-based livelihoods.

Methods

Study area

This study was conducted in the Trajan pasture (34°00′28″N 74°20′39″E) in District Baramulla, Jammu and Kashmir, India (see Figure 4). The site lies approximately 6.5 km from the well-known tourist destination of Gulmarg (34°02′58″N 74°23′35″E) and about 3 km from the border between Pakistan-administered (Muzaffarabad) and Indian-administered Kashmir. The pasture ranges in elevation from approximately 3,250 to 4,150 m above sea level and lies above the treeline, featuring a harsh climate marked by highly variable weather, including frequent rainfall and cloud cover. A topographic overview of the landscape is provided in Figure 5.

Due to the pasture's proximity to the border, access required permissions from district administration, police, and military authorities. The terrain is mountainous and challenging to traverse, necessitating a full day's journey on foot from the nearest road.

Data collection

Ethnographic fieldwork was conducted among the Chopan pastoralists, involving participant observation and extended residence with the community—from their home villages to the highland Trajan pasture. The research focused on observing daily herding practices, camp organization, and adaptive strategies employed in response to environmental conditions. Interviews were conducted in Kashmiri, the native language of the Chopan pastoralists, and recorded using a mobile phone recorder. These interviews explored their knowledge, practices, challenges, and perceptions of climate change and policy impacts. Informal focus group discussions (FGDs) provided collective perspectives on pastoralism, climate, and government policies.

Given the unpredictable weather at the fieldsite, with rain and cloud cover occurring anytime during the day, photography was a key tool for data collection. This approach aimed to capture critical moments revealing underlying tensions within uncertain pastoral landscapes and to contribute to broader debates on pastoralism, uncertainty, and development beyond conventional frameworks (Bose and Gogineni 2023). The photographs were also incorporated into the analytical process. Figure 6 presents

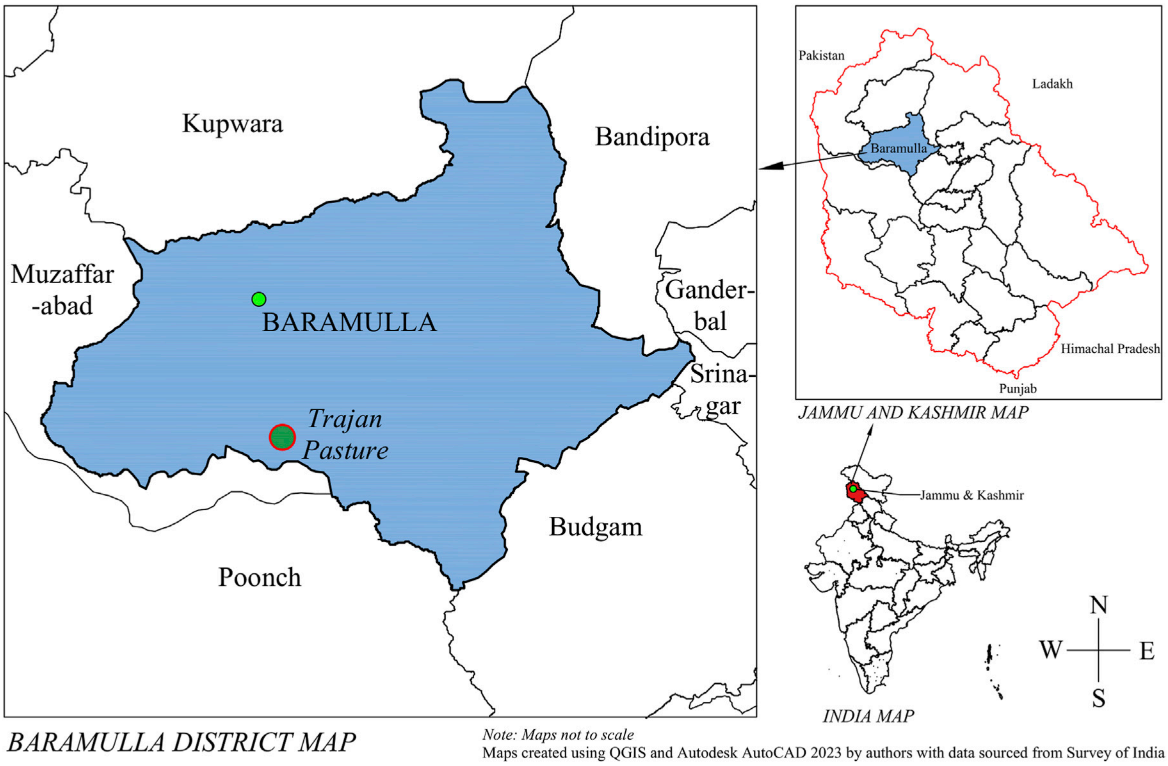

FIGURE 4
Maps showing location of Trajan Pasture (Study Area). Source: Prepared by authors (2025).

selected images taken during fieldwork that illustrate key moments and contextual elements relevant to the study.

The pasture was mapped using pencil and paper in the field, with rough elevations recorded relative to the pastoral camp (Kotha). This was later refined using QGIS and AutoCAD 2023. Mapping was facilitated by one author's prior land surveying experience. Data for mapping was obtained manually, and elevations for contour lines were supplemented by secondary sources, including Google Earth, topographic maps, and Survey of India.

Due to limitations in conducting direct biomass sampling, forage availability in Trajan was estimated using data from the Diskel pasture (33.8324°N, 74.5550°E), approximately 20 km away and ecologically similar. According to Saleem et al. (2024a), Diskel has an average dry forage yield of 3.88 metric tons per hectare.

We acknowledge that this approach introduces a limitation in precision, as variations in microclimate and grazing history between the two sites may influence forage yield. Future studies would benefit from on-site biomass sampling to improve accuracy and allow for sensitivity analysis.

Existing literature on livestock emissions, pastoralism, and climate change was reviewed to contextualize field observations and address research questions. The study focused on four Chopan groups at the Trajan site, belonging to the villages of Morishpora, Burzawacchan, and Khushi Pora, all in district Baramulla. These groups comprised seven individuals managing a total of 2,650 sheep over the 860.9-ha area of Trajan pasture. One group had relocated from the nearby Khilan pasture in July to rest their home pasture.

Data analysis

Data collected through field notes, interview transcripts, and focus group discussions were analyzed thematically to identify patterns related to pastoral practices, environmental knowledge, adaptation strategies, challenges, and perceptions of climate policies. Photographs captured during fieldwork were integrated into this process to visually interpret pastoral routines, material conditions, and moments of uncertainty. These images functioned as ethnographic tools, offering insight into the affective and embodied dimensions of Chopan pastoral life that are often less accessible through textual data alone.

To understand spatial patterns of movement and resource use within the pasture, maps and spatial data were analyzed. The area of the field site—Trajan pasture—was calculated to be approximately 8.609 square kilometers, with a perimeter of 12.597 km, using AutoCAD 2023.

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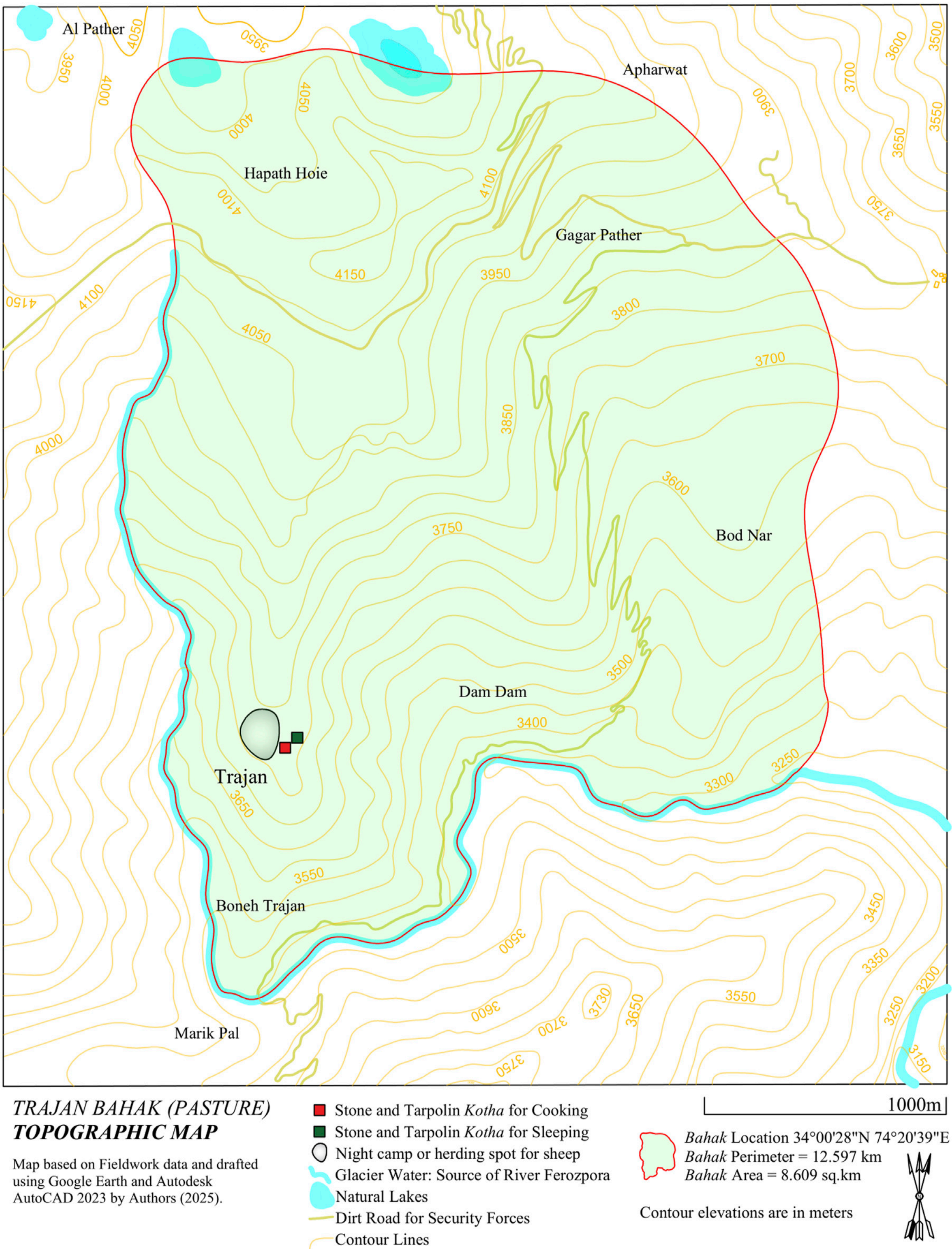

FIGURE 5
Topographic Map of the Trajan Pasture (Field Site). Source: Prepared by authors (2025).

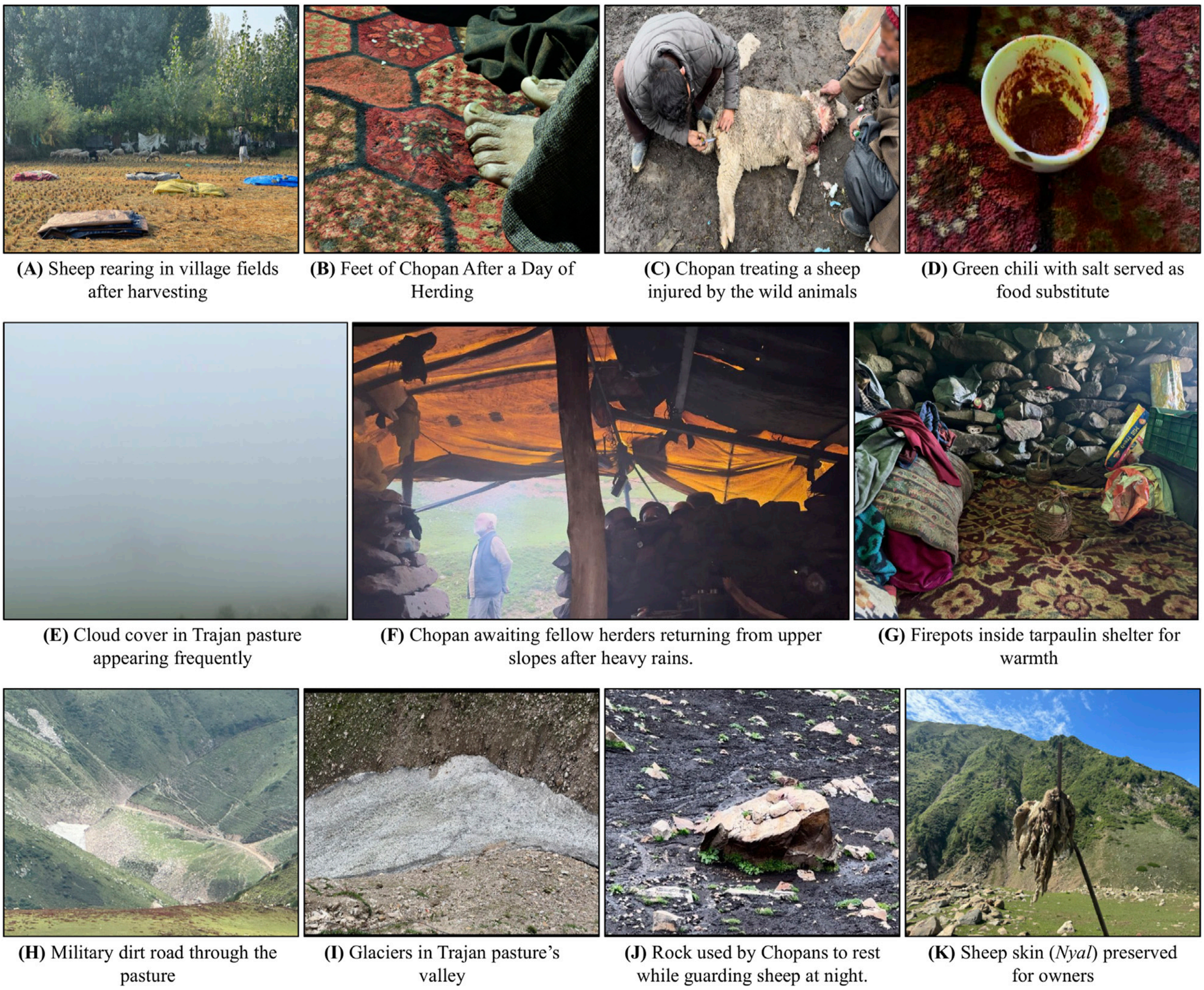

FIGURE 6
Photographic documentation **(A–K)** of pastoral life and uncertainty in the highland pastures of Kashmir. **(A)** Sheep graze in village fields post-harvest. **(B)** Close-up of a Chopan's feet on a patterned rug after a day of herding. **(C)** Chopan treats a sheep injured by wildlife. **(D)** Chili powder with salt in a cup served as food substitute to the researcher. **(E)** Cloud cover in Trajan pasture appearing frequently. **(F)** Chopan awaiting fellow herders returning from upper slopes after heavy rains. **(G)** Firepots in a stone-walled tarp shelter. **(H)** Military dirt road through the pasture. **(I)** Glaciers in Trajan pasture's valley. **(J)** Rock used by Chopans to rest while guarding sheep at night. **(K)** Sheep skin (Nyal) hung on a wooden pole, preserved for owners. Source: Fieldwork by author in 2024.

Carrying capacity and grazing pressure were estimated using rangeland management frameworks. Following established practice, a 50% utilization rate was applied to reflect the proportion of forage available for livestock use (Holechek 1988; Saleem et al. 2024a), resulting in an estimated usable forage of 1,940 kg per hectare. One animal unit (AU) was defined as a sheep with an average body weight of 52 kg, requiring 1.3 kg of dry matter per day—about 2.5% of its body weight. Based on a 50-day grazing season—aligned with the grass renewal cycle—each sheep was estimated to consume 65 kg of forage.

The carrying capacity (CC), representing the number of animals the pasture can sustainably support, was calculated using the formula:

$$CC = \frac{Usable\ Forage}{Forage\ Requirement\ per\ AU}$$

The stocking rate (SR) was computed by dividing the total number of sheep by the pasture area. The carrying rate (CR) was then derived by taking the ratio of the stocking rate to the carrying capacity.

Analysis of government data on livestock populations, meat production, and consumption in Jammu and Kashmir supplemented the ethnographic data to contextualize local pastoral practices within broader regional trends.

Reflexivity and scope

None of the authors belong to the Chopan or any other pastoralist community. However, the first two authors are from the Himalayan region and have worked closely with transhumant groups in Jammu and Kashmir since 2019. Fieldwork among Chopan herders was carried out during their seasonal migrations, with trust built over time through extended stays in high-altitude pastures and regular participation in daily routines. While the authors are not part of the community, their regional familiarity and sustained engagement supported meaningful dialogue and mutual respect.

This position—neither fully inside nor fully outside—shaped how the research was conducted and how the findings were interpreted. It required careful reflection on power, access, and responsibility, especially in a politically sensitive setting like Jammu and Kashmir. Ethical considerations such as confidentiality, informed consent, and sensitivity to local risks were central throughout the research process. The study aims to reflect the voices and experiences of Chopan pastoralists while also critically examining the institutional systems that affect their lives.

The scope of this study is intentionally narrow. It focuses on one pastoral group—the Chopans—and a single alpine pasture, Trajan, located in Baramulla District. The findings are not presented as representative of all pastoralist communities in the Himalayas. Instead, this case offers an in-depth example of how transhumant pastoralism can operate as an environmentally sustainable and socially important way of life in high-altitude settings.

The analysis is based on detailed conversations with seven Chopan herders. While this small sample is consistent with qualitative ethnographic research, it limits broader generalisations. The aim here is to offer insight rather than statistical conclusions. Future studies comparing different pastoral groups and landscapes would help build a fuller picture and guide more inclusive and context-aware policies.

This study contributes to that larger conversation by showing how local knowledge, mobility, and land use practices are tied to broader issues of climate policy, ecological sustainability, and social marginalisation.

Results

Pastoral practices and knowledge systems

In Kashmir, the Chopan pastoralists—locally referred to as *Pahael* (singular: *Pohol*)—practice transhumant pastoralism, moving seasonally between lowland villages and highland pastures. Preparations begin in March when *Zamindars* (landowning agriculturalists) entrust their sheep to the Chopans. The pastoralists refer to this seasonal movement as *bahakih khason*, meaning "moving up to the highland pasture," while *Zamindars* describe it as *nyor sozun*, or "sending sheep to pasture."

For approximately 6 weeks, the sheep are grazed on village outskirts and uncultivated fields. By May, as temperatures rise and lowland conditions become unsuitable, Chopans initiate their upward migration toward alpine pastures. The timing of this movement is influenced by snowmelt in the highlands and irrigation cycles in the lowlands. Warmer temperatures in the villages can negatively impact sheep health, prompting even stall-based intensive livestock owners to send their animals to upland grazing zones for improved welfare.

Figure 7 summarizes the Chopans' seasonal transhumance, aligning changes in elevation with key temporal stages: entrustment, movement through intervening pastures, highland grazing, return, and winter stall feeding. The vertical scale of this migration spans from village elevations (~1750–1940 m) to alpine zones above 3,000 m.

During migration, Chopan herders make temporary halts in forested areas along traditional routes, departing early in the morning to avoid road congestion. These stopovers typically last three to 4 days and depend on vegetation availability and highland accessibility. Grazing patterns are carefully adjusted to the phenological stages of pasture vegetation, with earlier growth observed in transitional altitudinal zones. This reflects the Chopans' nuanced, experience-based knowledge of landscape and climate dynamics.

In the Trajan pasture, the Chopans establish two types of stone-and-tarpaulin structures (temporary shelters): one used for sleeping and another as a kitchen. Herding is conducted in a rotating pattern, with one individual remaining at camp while others guide the flock to different sectors of the pasture daily. This pattern, responsive to rainfall and sunlight, is designed to optimize forage intake and support vegetation regeneration.

Figure 8 illustrates the intra-pasture grazing pattern in Trajan. It includes rotational grazing locations over several days (e.g., Boneh Trajan, Dam Dam, Bod Nar, Gagar Pather, Hapath Hoie), night camps, glacial water sources, and infrastructure such as temporary shelters and military roads. This map-based representation highlights the spatial organization of daily pastoral activities and the importance of adaptive movement within a constrained alpine ecosystem. The daily grazing pattern is adapted to environmental uncertainty, particularly the sequence of rainfall followed by sunlight. Chopans observe that fresh and nutritious grass emerges rapidly after rain when followed by sun, and they adjust grazing accordingly to maximize sheep health and forage quality.

Traditional ecological knowledge is central to Chopan pastoralism and is evident in their ability to anticipate weather changes, select appropriate grazing sites, treat livestock ailments

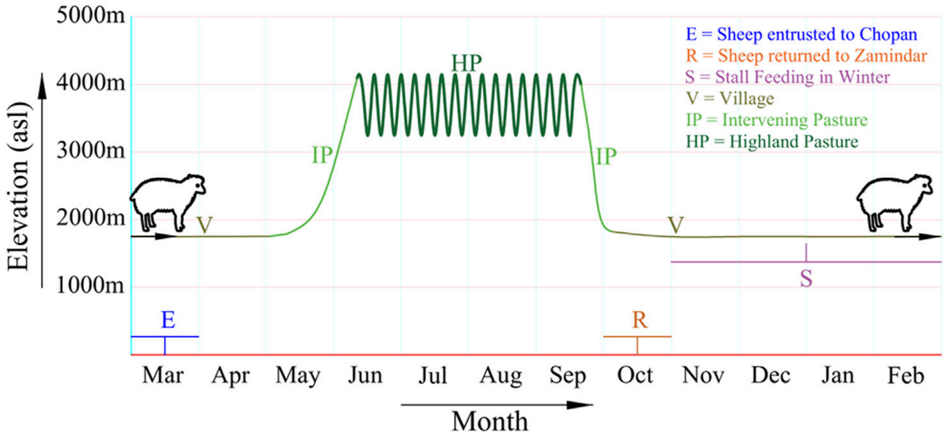

FIGURE 7
Seasonal transhumance trajectory of Chopan pastoralists in Baramulla District, showing the vertical movement of sheep from lowland villages to highland pastures (Trajan) and back. The figure aligns the migration cycle with monthly intervals and elevation changes, highlighting key stages: sheep entrustment to Chopans, temporary stops in intervening pastures, high-altitude summer grazing, and return to zamindars for winter stall feeding. Based on fieldwork data and prepared by authors using Google Earth, topographic-map.com, and Autodesk AutoCAD 2023 (2025).

using medicinal plants, and manage pasture sustainability. Grazing areas are systematically rotated to ensure optimal fodder quality and availability for the sheep. While participants emphasized that the availability of grasses is generally sufficient and that overuse is unlikely, field observations indicated that their daily grazing patterns—shaped by experiential knowledge and environmental responsiveness—naturally prevent overgrazing and contribute to ecological balance.

Environmental impacts and benefits

The findings indicate that Chopan pastoralism provides several important environmental benefits. This practice converts otherwise unused alpine grassland vegetation into protein, thereby preventing biomass loss in areas where alternative land uses are not feasible. Pastures such as Trajan, situated along the border between Pakistan-administered and Indian-administered Kashmir, are ecologically sensitive zones located above the treeline. These landscapes are unsuitable for agriculture or plantation due to their rocky terrain, steep gradients, and frequent cloud cover and rainfall. One Chopan remarked that "these pastures were created for livestock; if they do not graze here, the land will become like the neglected wetlands of Kashmir." Such comments reflect an embedded ecological ethic among herders.

The continued presence of pastoralists also mediates wildlife-human interactions. Predators—primarily wild animals—are known to take one to two sheep per week. Without pastoral presence in these zones, such animals may approach more densely populated areas, including the tourist destination of Gulmarg. As Hussain (2019) notes in his ethnographic study of snow leopard conservation in the Western Himalaya, such interactions reveal the limitations of dichotomous framings that separate the wild from the domestic or the ecological from the cultural. Snow leopards, for example, frequently rely on domestic livestock for sustenance, particularly in areas where human populations and pastoral herding are present, suggesting that the survival of such predators is entangled with pastoral livelihoods rather than threatened by them. This perspective complicates dominant conservation discourses that often portray herders as ecologically detrimental. In the case of the Chopans, managing predation involves not only physical practices of protection but also embodied knowledge of terrain, seasonal patterns, and animal behavior—forms of environmental engagement that are largely overlooked in formal conservation policy but are critical to sustaining coexistence in these frontier landscapes.

In lowland areas, Chopans provide ecosystem services to farmers and orchard owners by grazing sheep on grasses that harbor pests, reducing rat populations near apple trees. Sheep manure contributes to soil fertility in both highland pastures and village agricultural systems. Because herders guide animals across wide areas, manure is evenly distributed, eliminating the need for manual labor for fertilization.

Contrary to common assumptions about overgrazing, Chopans reported sufficient fodder availability in the Trajan pasture, attributed to the rapid regrowth of grasses due to frequent rainfall and their rotational grazing practices that help preserve vegetation cover. Based on the proxy yield from the ecologically similar Diskel pasture and applying a standard 50% utilization rate, the estimated usable forage in Trajan is 1,940 kg per hectare.

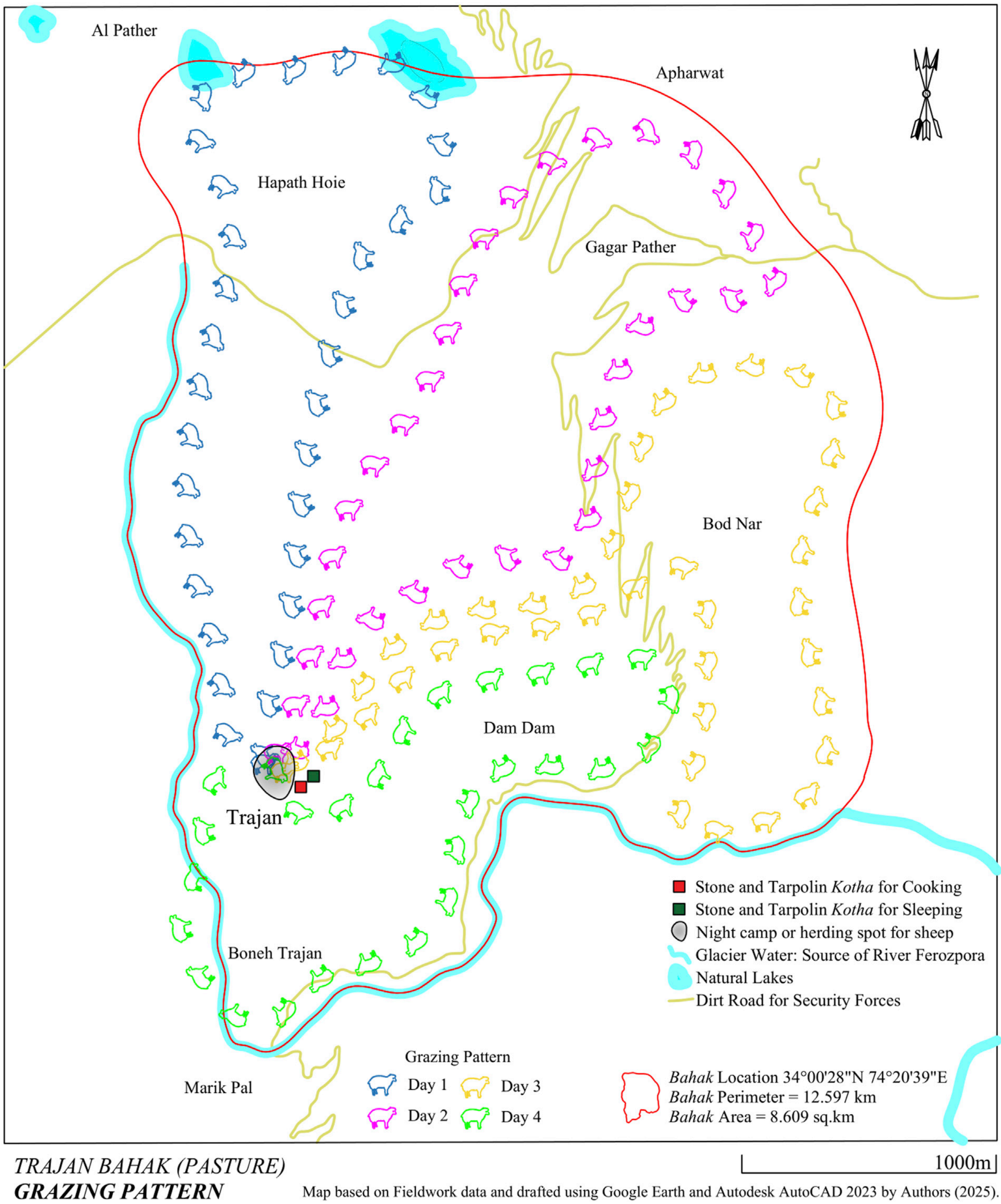

FIGURE 8
Intra-pasture grazing pattern of Chopan pastoralists in Trajan Bahak, showing rotational movement across key zones (e.g., Boneh Trajan, Dam Dam, Bod Nar, Gagar Pather, Hapath Hoie) over a 4-day cycle. The map also indicates stone-and-tarpaulin shelters, night camps, natural water sources, and dirt roads of security forces. Based on fieldwork data and drafted by authors using Google Earth and Autodesk AutoCAD 2023 (2025).

TABLE 1 Estimated grazing capacity of Trajan pasture based on forage yield and stocking data. Values are based on a 50% forage utilization rate and a seasonal grazing period of 50 days.

Indicator	Value	Source/Notes
Pasture area	860.9 ha	Mapping
Total number of sheep	2,650	Field data
Grazing season	50 days	Based on grass regrowth cycle
Forage requirement	65 kg/AU	Holechek (1988); Saleem et al. (2024a)
Dry forage yield (Diskel proxy)	3.88 t/ha	Saleem et al. (2024a)
Usable Forage (50% utilization)	1,950 kg/ha	Rangeland management standard
Carrying Capacity (based on Diskel yield)	29.85 AU/ha	Derived from above
Observed Stocking Rate	3.08 AU/ha	2,650 sheep over 860.9 ha
Carrying Rate (Diskel-based)	10.32%	(Stocking rate/Carrying capacity) × 100
Dry forage yield (regional avg.)	5.16 t/ha	Saleem et al. (2024b)
Adjusted carrying rate (regional avg.)	7.75%	Based on higher forage availability

Note: AU, Animal Unit (1 AU = 1 sheep of ~52 kg body weight). Carrying rate represents the percentage of ecological carrying capacity currently used.

Given a seasonal forage requirement of 65 kg per animal unit (AU), the carrying capacity of the Trajan pasture is calculated at 29.85 AU/ha. With 2,650 sheep grazing over an area of 860.9 ha, the observed stocking rate is 3.08 AU/ha, resulting in a carrying rate of just 10.32%. If the region-wide average yield of 5.16 t/ha (Saleem et al. 2024b) were used instead, the carrying rate would be even lower—approximately 7.75%. This suggests that only a small fraction of the pasture's productive potential is currently being utilized which is well within sustainable limits. Table 1 summarizes the key indicators used in assessing the grazing potential of the Trajan pasture.

Food security and economic importance

Livestock rearing has long been a central component of rural life in Jammu and Kashmir, historically embedded in agrarian livelihoods and local food systems (Lawrence 1895). Today, livestock continues to play a critical role in the region's rural economy and food security. Government data indicate that livestock remains the primary source of meat and milk protein, with mutton occupying a particularly central place in Kashmiri cuisine. As per the 20th Livestock Census, the livestock and poultry populations of Jammu and Kashmir and Ladakh stand at 8.32 million and 7.37 million, respectively (Hamdani et al. 2022). The region also exhibits one of the highest livestock densities in the country, with 882 animals per 1,000 people, compared to the national average of 457 (Kumar, Kher, and Dwivedi 2012), underscoring the continued socio-economic importance of pastoral and agro-pastoral livelihoods.

Census data from 2011 reveal that approximately 73% of the population resides in rural areas and remains directly or indirectly involved in agriculture and allied sectors, including livestock rearing as main occupation (Livestock Breeding Policy 2019). Despite this reliance, local meat production fails to meet demand. Of the annual 310 lakh kilograms of mutton required, only 135 lakh kilograms are produced within the region, necessitating the import of approximately 175 lakh kilograms to fill the deficit (see Figure 9). While Jammu and Kashmir historically experienced growth in livestock populations—especially sheep—outpacing human population growth in earlier decades, more recent years have shown fluctuations and even declines in sheep numbers (see Figure 10).

Land use changes further compound concerns over local food production and pastoral sustainability. Between 1990 and 2017, the total agricultural area in Jammu and Kashmir declined by 278 km^2 (a 5% decrease), while built-up areas increased from 133 km^2 to 313 km^2, marking a 3% gain (Rasool et al. 2021). These shifts not only impact food security but also alter the ecological and social landscapes upon which traditional livestock-based livelihoods have long depended.

Challenges and policy impacts

Chopan pastoralists face a range of structural and environmental challenges that directly impact their livelihoods. A major concern is the loss of traditional grazing areas, particularly village commons (*Kahcharai*), which have been increasingly appropriated by powerful individuals or converted for infrastructure development. This has significantly reduced available grazing spaces prior to seasonal migration to highland pastures. Additionally, government-imposed forest restrictions, including fencing,

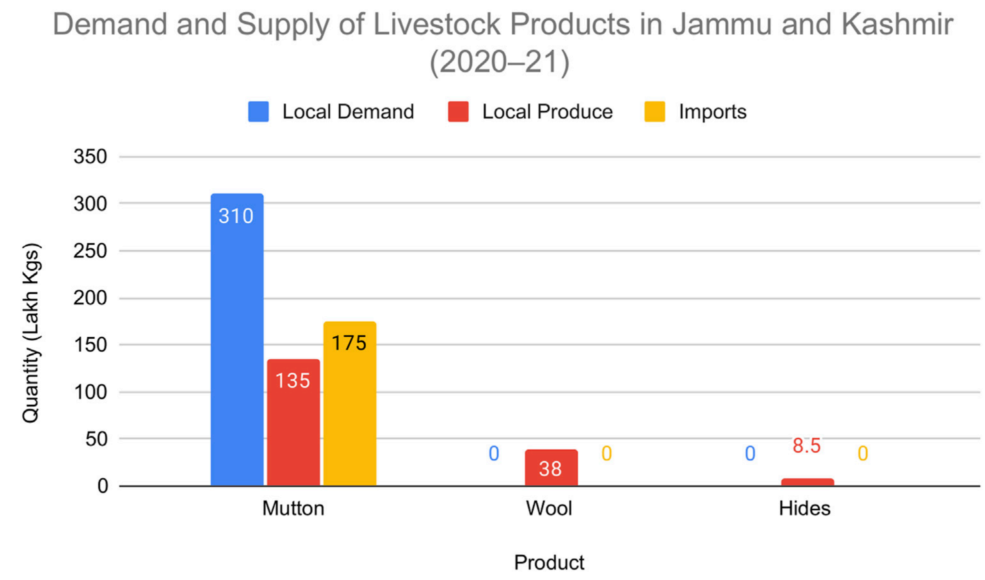

FIGURE 9
Demand and supply of livestock products in Jammu and Kashmir (2020–21). Source: Developed by authors (2025) based on data from Sheep Husbandry Department, Kashmir (https://jksheephusbandrykashmir.nic.in).

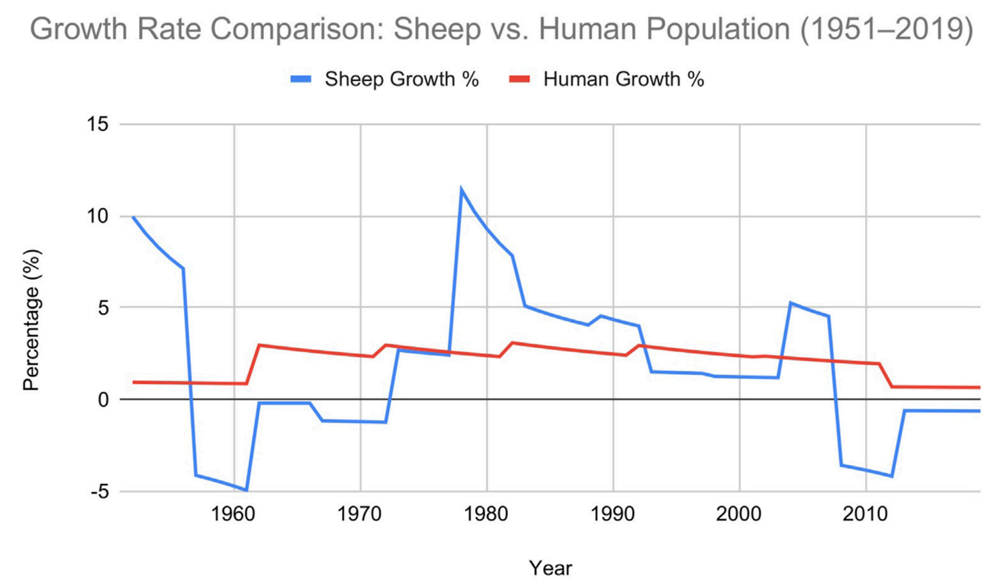

FIGURE 10
Growth rate comparison of sheep and human populations in Jammu and Kashmir (1951–2019). Developed by authors (2025) based on data from Ministry of Finance, Government of India (2022); Digest of Statistics (2019–20, 2021–22), Department of Planning, Government of Jammu and Kashmir; 20th and 18th Livestock Census (data.gov.in); and Department of Animal Husbandry, J&K (https://www.jkanimalhusbandry.net).

have limited access to traditional migration routes and resting points in intervening pastures, disrupting long-established patterns of mobility. This is seen as a serious issue by Chopan pastoralists.

Pastoralists are also exposed to risks from wild animals and feral dogs, which endanger both livestock and herders, particularly during transit and in remote grazing areas. In the Trajan pasture, the pastoralists' sheep are under threat by the dogs that they believe have been imported to the area by the Indian Security Forces.

Compounding these challenges is the lack of essential services in highland regions. There is no access to medical care for either herders or their livestock, and limited communication infrastructure further isolates these communities. There is no electric facility, no mobile networks and no road connectivity. Despite their critical role in sustaining the livestock economy, Chopans remain economically marginalized, with minimal institutional support or formal recognition. Policy frameworks have largely neglected pastoralism, focusing instead on agricultural intensification and intensive pastoralism. For example, the Jammu and Kashmir State Action Plan on Climate Change—drafted in 2011 but never implemented—misrepresents pastoral grazing as inherently destructive to forests and pastures, a view that is increasingly contradicted by contemporary scientific research emphasizing the ecological value of well-managed pastoral systems.

When this policy neglect was discussed with Chopan herders during fieldwork, they responded with resignation and irony, asking, "Have any of those policymakers ever visited these pastures? Did they ever think about us too?" Their rhetorical questions underscore the disconnect between policy narratives and lived realities on the ground, highlighting the urgent need for more inclusive, context-sensitive governance in pastoral regions.

Discussion

Rethinking pastoral impacts on highland ecosystems

The findings of this study challenge dominant narratives that depict pastoralism as inherently damaging to highland ecosystems. Despite supporting approximately 2,650 sheep, the Trajan pasture shows no visible signs of ecological degradation—an assessment confirmed both by the lived experiences of Chopan pastoralists and direct field observations. When compared with the ecologically similar Diskel pasture (33°49′55″N 74°33′45″E), Trajan appears in notably better ecological condition. This can be attributed, in part, to its remoteness: situated at 34°00′28″N 74°20′39″E near the Line of Control, the pasture remains inaccessible to tourism, agricultural development, and infrastructural encroachment.

The estimated carrying rate of just 10.32% illustrates that grazing pressure in Trajan remains well within sustainable limits. Pastoralists are thus utilizing land that would otherwise remain ecologically unproductive, demonstrating a low-impact form of land use that contributes to regional food systems. These findings are consistent with recent research by Saleem et al. (2024b) and Mugloo et al. (2023), which report high levels of aboveground biomass in Kashmir's alpine pastures, supported by favorable soil conditions, sufficient precipitation, and sustainable grazing practices.

The microclimatic features of highland pastures—frequent rainfall, cool temperatures, and variable sunlight—also promote rapid regrowth of herbaceous vegetation. Furthermore, temperate environments are known to store significant amounts of soil organic carbon due to slower decomposition rates in colder climates (Ding et al. 2017), suggesting that well-managed pastures such as Trajan may contribute to carbon sequestration and broader climate mitigation goals.

Importantly, these alpine pastures lie above the tree line, rendering them unsuitable for forestry or conventional agriculture. Attempts by the Forest Department to cultivate tree species in similar zones have repeatedly failed. In addition, the militarized status of the border region precludes tourism and commercial expansion. In this context, pastoralism emerges not only as a viable land use but arguably the most sustainable and ecologically compatible form of human activity in these fragile landscapes.

These findings align with broader ecological research suggesting that pastoralism can play a potentially important role in shaping grassland ecosystems. Managed grazing has been shown to influence plant species composition, promote habitat diversity, and enhance ecosystem functioning (Scasta et al. 2016). In the case of Trajan, Chopan pastoralists suggest the value of traditional ecological knowledge in sustaining landscapes that are otherwise marginalized in land use policy and development planning.

Pastoralism and climate change mitigation

This study reinforces the growing call to differentiate between intensive and extensive livestock systems in climate policy and emissions accounting. As García-Dory, Houzer, and Scoones (2022) argue, dominant climate discourses tend to homogenize all livestock systems as environmentally harmful, often ignoring the relatively low-impact nature and socio-ecological value of pastoralist systems. Such generalizations obscure critical distinctions in land use, energy input, and ecosystem interaction.

Most greenhouse gas assessments are based on data from industrial livestock systems, where animals are confined, feed is externally sourced, and emissions are concentrated. These models often overlook the complexities of carbon and nitrogen cycles inherent in extensive grazing systems, including natural carbon sequestration through pasture regrowth and soil enrichment. In the context of northern India, Panwar et al. (2022) report high carbon sequestration potential in pastoral landscapes, including those in Jammu and Kashmir, due to substantial aboveground biomass productivity.

Furthermore, many commonly proposed methane mitigation strategies (FAO 2023)—such as methane inhibitors, dietary additives, electron sinks, and anaerobic digesters—are designed for controlled feedlot environments and are impractical or irrelevant in open, extensive pastoral systems (Mukherji et al. 2023). Applying such strategies without adaptation risks further marginalizing pastoralist communities and distorting emissions estimates.

These findings underscore the importance of involving pastoralists in the development of climate mitigation strategies that are appropriate to their ecological and cultural contexts. Recognizing the environmental services embedded in pastoralist practices—such as nutrient cycling, soil fertility maintenance, and sustainable land use—is critical for crafting equitable and effective climate policies. Extensive livestock systems, when rooted in traditional ecological knowledge and adaptive mobility, can form part of the solution to climate change rather than being cast solely as a problem.

Food security and socioeconomic implications

Any policy that restricts pastoral practices in Jammu and Kashmir is likely to have significant implications for regional food security. The region already imports approximately 56% of its annual mutton requirement, and agricultural land is steadily declining due to urban expansion and land-use change. Further constraints on livestock production—particularly extensive pastoralism—would exacerbate the existing protein deficit, compromising both dietary diversity and nutritional adequacy.

The socioeconomic impacts of such restrictions would be particularly severe for Chopan pastoralists, who already occupy a marginalized position within state development frameworks and receive minimal institutional support. Following the abrogation of Article 370 and the reorganisation of Jammu and Kashmir as a Union Territory, the Forest Rights Act (FRA) of 2006 was formally extended to the region. While this was initially seen as a progressive step (Ashiq 2021), the absence of operational mechanisms—such as Forest Rights Committees, Sub-Divisional Level Committees, and effective claim verification—has rendered the Act largely non-functional in practice. Chopans encountered during fieldwork were unaware of their rights under the FRA, despite fulfilling the criteria of "other traditional forest dwellers" under Section 2(o), and engaging in transhumant grazing covered under Section 3(1)(d) of the Indian FRA 2006. This exclusion is rooted in institutional neglect, lack of Scheduled Tribe status, and state imaginaries that continue to privilege sedentary agriculture over mobile livelihoods. In several areas, the Forest Department has demolished seasonal mud-and-log huts (*kothas*) used by pastoralists during their summer migrations. As one pastoralist remarked, "We have not occupied these lands . . . we live there only for 6 months in the summer, so why is this being done now?" (Sharma 2021)—highlighting the disjuncture between legal definitions of occupation and pastoralist rhythms of land use. In 2021, although the Lieutenant Governor distributed FRA certificates to Gujjar, Bakarwal, Gaddi, and Sippi communities, the Chopans—despite qualifying under the Act—were neither invited nor acknowledged (Bhat 2021). Their prolonged exclusion from ST status can be attributed not only to the absence of political will, but also to their scattered settlement pattern, continued mobility, and weak collective organisation. Unlike Gujjars and Bakarwals, who benefit from cohesive community networks and political representation, the Chopans remain largely outside formal advocacy spaces and welfare schemes. This structural marginalisation within both policy and social hierarchies contributes to their limited engagement with state institutions, leaving them especially vulnerable to eviction and exclusion from forest governance frameworks.

This exclusion has material consequences. In violation of Section 4(5) of the Indian FRA, eviction notices have been issued to Chopans and other pastoralists prior to the resolution of land claims (Bhat 2023). Many are unable to furnish the required documentation despite long-standing pastoral use, and some now express willingness to abandon mobility and settle permanently (Sharma 2021). Of over 46,000 claims filed under the FRA, more than 39,000 have been rejected as of March 2025—primarily at the Gram sabha level—often due to procedural ambiguities and lack of institutional support. Approved land titles have been overwhelmingly concentrated in the Jammu region, mainly among Scheduled Tribe beneficiaries, while Kashmir has seen minimal recognition, with no titles issued in districts such as Baramulla or Srinagar (Deccan Herald 2025). An RTI inquiry found that none of the 81 approved community claims in districts like Kupwara and Budgam included Chopans or Other Traditional Forest Dwellers (OTFD) groups, highlighting their continued exclusion from FRA implementation (Bhat 2022). These disparities reflect deeper epistemological and bureaucratic biases that fail to acknowledge mobility, seasonality, and customary land use as legitimate forms of forest dependence. As Singh et al. (2022) show in the context of Khangchendzonga National Park, such frameworks disproportionately affect economically vulnerable herders, while better-resourced actors often navigate these constraints through informal or political channels. The Chopans' experience illustrates how the extension of legal protections, in the absence of structural reform, can reproduce entrenched patterns of spatial and political marginalisation.

At the same time, global policy shifts toward plant-based and alternative proteins raise questions about equity, cultural appropriateness, and accessibility. While these alternatives may serve as sustainable options in some contexts, e.g., in certain parts of the global north, their affordability and availability remain limited in regions like Jammu and Kashmir, where animal-source foods continue to play a critical role in both nutrition and cultural identity (Beal et al.

2017; Ryckman et al. 2021). Meat, in particular, holds significant cultural value, featuring prominently in traditional Kashmiri cuisine—most notably in *Wazwan*, a ceremonial multi-course meal central to social and religious celebrations in Kashmir.

Despite the ecological sustainability of pastoralism in highland regions, local livestock production does not meet existing demand. On average, approximately 1.47 million heads of small ruminants are imported annually from Rajasthan to supply the mutton market in Jammu and Kashmir (Shah et al. 2020). With population growth and dietary preferences showing no signs of shifting away from meat consumption, this supply-demand gap is expected to widen in the future. In this context, supporting pastoralism is not only a matter of livelihood preservation but also of nutritional sovereignty and cultural continuity.

Traditional ecological knowledge and policy development

This study underscores the importance of traditional ecological knowledge (TEK) in shaping sustainable practices within pastoral landscapes. Chopan pastoralists possess a nuanced understanding of microclimatic variability, vegetation cycles, and animal movement, which enables them to manage alpine grazing systems in ways that optimize forage use while minimizing ecological degradation. What may appear to external observers as marginal or fragile land is, in practice, adaptively managed through longstanding experiential knowledge. These findings align with broader research that highlights the value of integrating TEK with scientific monitoring. Reid-Shaw et al. (2021), for instance, suggested that combining Mongolian herders' knowledge with ecological data significantly enhanced the understanding of environmental trends across ecological zones. Similarly, Reid et al. (2004) emphasize that climate mitigation strategies are most effective when grounded in traditional pastoral institutions, particularly when they offer co-benefits such as food security, social cohesion, and environmentally appropriate land use.

Despite this, current policy approaches in Jammu and Kashmir—like in many pastoral contexts—tend to privilege externally generated data and global narratives over local insight. The Jammu and Kashmir State Action Plan on Climate Change exemplifies this disjuncture; it characterizes pastoral grazing as uniformly destructive, despite ethnographic and ecological evidence to the contrary, including findings presented in this article. The Livestock Breeding Policy (2019) in Jammu and Kashmir also supports primarily unemployed youth establishing intensive livestock units, overlooking the foundational role that extensive pastoralism plays in sustaining such systems. As shown in this study, even intensive livestock production in the region remains ecologically and economically dependent on seasonal access to highland pastures managed by Chopan pastoralists, whose contributions remain unrecognized in policy frameworks. Such policies risk marginalizing pastoralists further by failing to recognize the ecological services embedded in their adaptive practices.

As Jasanoff (2004) argues, meaningful and equitable environmental governance requires the co-production of knowledge, in which scientific and local epistemologies are brought into dialogue. For such co-production to occur, pastoralists must be included not merely as stakeholders but as co-designers of policy frameworks. A bottom-up, pilot-based approach—grounded in local institutions, knowledge systems, and needs—offers a more promising pathway toward context-sensitive and effective climate adaptation strategies. Recognizing and institutionalizing TEK is therefore essential not only for ecological stewardship but also for the socio-political inclusion of pastoralist communities in future decision-making processes.

Conclusion

This study suggests that transhumant pastoralism, as practiced by Chopan communities in the highland pastures of Jammu and Kashmir, is not a relic of the past but a dynamic, sustainable adaptation to variable and ecologically marginal environments. Far from contributing to degradation, Chopan pastoralism supports multiple environmental and social functions: converting underutilized biomass into high-value protein, maintaining soil fertility through natural manure distribution both in highlands and lowlands, managing human-wildlife interactions, and contributing to regional food security in a context of declining agricultural land and growing protein deficits.

Our ethnographic and ecological findings challenge prevailing policy narratives and climate discourses that portray all livestock systems as environmentally harmful. The case of the Trajan pasture—where the observed carrying rate is only 10.32%—suggests that Chopan grazing practices are ecologically balanced and well within sustainable limits. These landscapes, located above the treeline and unsuitable for agriculture or plantation, are managed by herders who rely on deep environmental knowledge, rotational grazing, and microclimatic sensitivity. The Chopans' presence not only sustains livelihoods but also actively shapes the resilience of alpine ecosystems that would otherwise remain ecologically underutilized.

This research underscores the importance of distinguishing between intensive, industrial livestock systems and extensive, low-emission pastoral practices. Applying uniform emission metrics and mitigation strategies—such as methane inhibitors or controlled feed systems—risks mischaracterizing the climate impact of pastoralism and marginalizing those whose practices already align with sustainable land use. The climate benefits of grassland-based systems, including carbon sequestration in soils and reduced dependence on fossil-fuel-based inputs, remain underexplored and undervalued.

Despite these contributions, pastoralists remain structurally excluded from policy processes. Institutional frameworks—such as the Jammu and Kashmir State Action Plan on Climate Change and the post-370 implementation of the Forest Rights Act—have overlooked or undermined pastoral livelihoods. Policies designed without pastoralist input often misrepresent their role in ecosystem dynamics and restrict access to commons and migration corridors. As one Chopan poignantly asked, "*Did any of the policymakers ever visit these pastures?*" This reflects not only exclusion but a missed opportunity to ground climate and development policy in lived ecological knowledge.

The findings of this study also align with recent global frameworks such as the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 6 Synthesis Report, which emphasises the value of integrating diverse knowledge systems—scientific, Indigenous, and local—into climate adaptation strategies (IPCC 2023). The adaptive practices of Chopan pastoralists demonstrate the kind of situated environmental knowledge that is often undervalued in formal policy. As the AR6 highlights, climate justice entails not only *distributive justice* (the fair sharing of risks and benefits), but also *procedural justice* (meaningful participation in governance), and *recognition* (respect for different ways of knowing and being). Supporting mobile pastoralists through inclusive governance, protection of migratory corridors, and legal recognition of traditional use rights is not only ecologically sound but also essential to just and equitable climate adaptation.

To address these gaps, we recommend the following multilevel policy actions.

(A) At the national level (Ministry of Tribal Affairs, MoEFCC):
  I. Legally differentiate between intensive and extensive livestock systems in climate assessments and livestock-related policies.
  II. Ensure the effective implementation of the Forest Rights Act for transhumant communities, including recognition of OTFD status for Chopans and protection from eviction.
  III. Designate the Tribal Affairs Department—not the Forest Department—as the nodal agency for FRA implementation in Jammu and Kashmir to better align institutional priorities with tribal rights.
(B) At the regional level (Jammu and Kashmir administration):
  IV. Integrate traditional ecological knowledge into rangeland monitoring and adaptation strategies specific to high-altitude ecosystems.
  V. Secure pastoral mobility and legal access to alpine and subalpine grazing lands through inclusive commons governance and tenure reforms.
  VI. Provide context-sensitive livestock development programs that reflect the ecological, cultural, and migratory specificity of pastoral systems in Kashmir.
(C) At the global level (FAO, IPCC, UNFCCC, development donors):
  VII. Incorporate the contributions of mobile pastoralists into climate adaptation and biodiversity frameworks, particularly in relation to low-emission protein production, ecosystem stewardship, and resilience in marginal environments.
  VIII. Establish mechanisms for meaningful pastoralist participation in climate governance, including local representation in planning, implementation, and monitoring processes.

Ultimately, this case study contributes to a growing body of research suggesting that pastoralism in high-altitude, marginal environments can offer sustainable livelihoods and serve as a model for resilient, low-impact land use under conditions of climate uncertainty. However, we emphasise that these findings emerge from a single, context-specific study of Chopan pastoralists in the Trajan pasture of Baramulla District, Jammu and Kashmir. While the ecological and institutional insights presented here are valuable, they are not intended to represent the diversity of pastoral systems across the broader Himalayan region. As such, the policy recommendations outlined in this study should be viewed as entry points for more inclusive, differentiated, and locally informed dialogue. Recognising the heterogeneity of pastoral communities and the context-specific nature of their adaptive strategies is essential to crafting just and ecologically appropriate climate and land-use policies.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for the studies involving humans because Ethical approval was not required under the policies of the authors' institutions, as the study did not involve biomedical interventions, sensitive personal data, or research with minors or legally vulnerable individuals. The research complied with standard ethical protocols in anthropology, including voluntary participation, confidentiality, and cultural sensitivity. In addition, prior permission was obtained from the relevant authorities in Jammu and Kashmir to conduct research in the high-altitude Trajan pasture, a sensitive border area near the Line of Control. These permissions were essential for access to the field site and were secured before the commencement of fieldwork. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

IB was responsible for the methodology, conducted the fieldwork, reviewed relevant literature, and collected secondary data. IB also carried out the results and analysis, and prepared the initial draft of the manuscript. IB, RS, and MR jointly contributed to the review, editing, and final approval of the manuscript for submission. All authors reviewed the results and approved the final version of the manuscript.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

References

Arca, P., Vagnoni, E., Duce, P., and Franca, A. (2021). How does soil carbon sequestration affect greenhouse gas emissions from a sheep farming system? Results of a life cycle assessment case study. *Italian J. Agron.* 16 (3), 1789. doi:10.4081/ija.2021.1789

Ashiq, P. (2021). J&K to implement forest rights act, 2006: move will elevate socio-economic status of tribal communities. National Newspaper in India. Available online at: https://www.thehindu.com/news/national/other-states/jk-to-implement-forest-rights-act-2006/article36446427.ece (Accessed June 29, 2025).

Assouma, M. H., Lecomte, P., Corniaux, C., Hiernaux, P., Ickowicz, A., and Vayssières, J. (2019). Pastoral landscapes in the Sahel: A carbon balance with unexpected potential for climate change mitigation. *Perspective* 52, 1–4. doi:10.19182/agritrop/00083

Banka, I. A., and Sahani, R. (2023). "Challenges faced by Pohul (Chopan) shepherds in Kashmiri highland pastures: a case study," accepted panels," in *19th IUAES - WAU world anthropology congress 2023* (New Delhi, India: IUAES). Available online at: https://iuaes2023delhi.org/panelabstractsdetail.aspx?vrd=1267 (Accessed June 29, 2025).

Beal, Ty, Massiot, E., Arsenault, J. E., Smith, M. R., and Hijmans, R. J. (2017). Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. *PLoS ONE* 12 (4), e0175554. doi:10.1371/journal.pone.0175554

Bhat, R. M. (2021). Chopans of J&K continue to be excluded from forest rights act. Available online at: https://theleaflet.in/environment/chopans-of-jk-continue-to-be-excluded-from-forest-rights-act.

Bhat, R. M. (2022). Kashmir's chopans denied the right to graze freely. *India Dev. Rev.* Available online at: https://idronline.org/ground-up-stories/the-forest-rights-act-must-be-implemented-for-the-chopans-in-jammu-and-kashmir/ (Accessed June 28, 2025).

Bhat, R. M. (2023). Issuing eviction notices to forest dwellers violates apex court ruling. *Kashmir Obs.* Available online at: https://kashmirobserver.net/2023/07/24/issuing-eviction-notices-to-forest-dwellers-violates-apex-court-ruling/ (Accessed June 29, 2025).

Blaustein-Rejto, D., and Gambino, C. (2023). Livestock don't contribute 14.5% of global greenhouse gas emissions. *Breakthr. Inst.* Available online at: https://thebreakthrough.org/issues/food-agriculture-environment/livestock-dont-contribute-14-5-of-global-greenhouse-gas-emissions (Accessed June 20, 2025).

Bose, S., and Gogineni, R. (2023). "Decoding uncertainty in pastoral context through visual methods," in *Pastoralism, uncertainty and development*. Editor I. Scoones (Rugby, UK: Practical Action Publishing), 21–38. doi:10.3362/9781788532457

Clark, M., and Tilman, D. (2017). Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environ. Res. Lett.* 12 (6), 064016. doi:10.1088/1748-9326/aa6cd5

Davies, J., and Nori, M. (2008). Managing and mitigating climate change through pastoralism. *Policy Matters* 16, 127–141. Available online at: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=41be468021b63534e02ebd86b560053f5945efa6 (Accessed May 10, 2025).

Deccan Herald (2025). J&K govt rejects over 39000 land claims under forest rights act. Available online at: https://www.deccanherald.com/india/jammu-and-kashmir/jk-govt-rejects-over-39000-land-claims-under-forest-rights-act-3463525 (Accessed March 26, 2025).

Ding, J., Chen, L., Ji, C., Hugelius, G., Li, Y., Liu, Li, et al. (2017). Decadal soil carbon accumulation across Tibetan permafrost regions. *Nat. Geosci.* 10, 420–424. doi:10.1038/ngeo2945

Dubeuf, J. – P., Genis, J. C., Morand-Fehr, P., and Ruiz Morales, F. d. A. (2023). The contribution of goats in the future redesigning of livestock activities and value chains. *Small Ruminant Res.* 227, 107065. doi:10.1016/j.smallrumres.2023.107065

FAO (2021). "Pastoralism – making variability work," in *FAO animal production and health paper no. 185*. Rome. doi:10.4060/cb5855en

FAO (2023). *Pathways towards lower emissions – a global assessment of the greenhouse gas emissions and mitigation options from livestock agrifood systems*. Rome. doi:10.4060/cc9029en

FAOSTAT (2025). Crops and livestock products. *Food Agric. Organ. U. N.* Available online at: https://www.fao.org/faostat/en/#data/QCL (Accessed March 20, 2025).

García-Dory, F., Houzer, E., and Scoones, I. (2022). Livestock and climate justice: challenging mainstream policy narratives. *IDS Bull.* 53 (4), 47–64. doi:10.19088/1968-2022.138

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., et al. (2013). *Tackling climate change through livestock – a global assessment of emissions and mitigation opportunities*. Rome: Food and Agriculture Organization of the United Nations FAO. Available online at: https://www.fao.org/4/i3437e/i3437e.pdf.

Goldman, M. J., and Riosmena, F. (2013). Adaptive capacity in Tanzanian maasailand: changing strategies to cope with drought in fragmented landscapes. *Glob. Environ. Change* 23 (3), 588–597. doi:10.1016/j.gloenvcha.2013.02.010

Hamdani, A., Ganai, N. A., Rather, M. A., Shanaz, S., Ayaz, A., Mansoor, S., et al. (2022). Livestock and poultry breeds of Jammu and Kashmir and Ladakh. *Indian J. Animal Sci.* 92 (3), 283–288. doi:10.56093/ijans.v92i4.124009

Haq, S. M., Hassan, M., Jan, H. A., Al-Ghamdi, A. A., Ahmad, K., and Abbasi, A. M. (2022). Traditions for future cross-national food security—food and foraging practices among different native communities in the Western himalayas. *Biology* 11 (455), 455. doi:10.3390/biology11030455

Holechek, J. L. (1988). An approach for setting the stocking rate. *Rangelands* 10 (1), 10–14. Available online at: https://repository.arizona.edu/bitstream/handle/10150/640265/10362-9902-1-PB.pdf?sequence=1&isAllowed=y (Accessed June 28, 2025).

Houser, E., and Ian, S. (2021). Are livestock always bad for the planet? Rethinking the protein transition and climate change debate. *Brighton PASTRES*. doi:10.19088/STEPS.2021.003

Hussain, S. (2019). *The snow leopard and the goat: politics of conservation in the Western himalayas*. Editor K. Sivaramakrishnan (Seattle: University of Washington Press). Available online at: https://uwapress.uw.edu/book/9780295746579/the-snow-leopard-and-the-goat/.

ILRI, IUCN, FAO, WWF, UNEP, and ILC (2021). *Rangelands atlas*. Nairobi, Kenya: ILRI. Available online at: https://hdl.handle.net/10568/114064.

Intergovernmental Panel on Climate Change (IPCC) (2023). "Summary for policymakers," in *Climate change 2022 – impacts, adaptation and vulnerability: Working group II contribution to the sixth assessment report of the intergovernmental panel on climate change* (Cambridge: Cambridge University Press), 3–34. doi:10.1017/9781009325844.001

Jasanoff, S. (2004). *States of knowledge: the Co-production of science and the social order* (London: Routledge). doi:10.4324/9780203413845

Kerven, C. (2024). Contribution of goats to climate change: How and where? *Pastor. Res. Policy Pract.* 14, 13988. doi:10.3389/past.2024.13988

Kishore, K., and Köhler-Rollefson, I. (2020). Accounting for pastoralists in India. *Ober-Ramstadt, Ger. Leag. Pastor. Peoples Endogenous Livest. Dev*. Available online at: https://www.pastoralpeoples.org/wp-content/uploads/2020/09/Accounting4pastoralists-IN.pdf (Accessed March 15, 2025).

Köhler-Rollefson, I. (2021). Livestock for a small planet. *Ober-Ramstadt, Ger. Leag. Pastor. Peoples Endogenous Livest. Dev*. Available online at: https://www.ilse-koehler-rollefson.com/wp-content/uploads/2021/10/livestock-for-a-small-planet_web.pdf (Accessed May 5, 2025).

Krätli, S. (2015). *Valuing variability: new perspectives on climate resilient drylands development*. London: IIED. Available online at: https://www.iied.org/10128iied.

Kumar, P., Kher, S. K., and Dwivedi, S. (2012). An analytical study of livestock in Jammu and Kashmir. *Int. J. Plant, Animal Environ. Sci.* 2 (3). Available online at: https://www.fortunejournals.com/ijpaes/admin/php/uploads/217_pdf.pdf. (Accessed May 10, 2025).

Lawrence, W. R. (1895). The Valley of kashmir. *Amen corner, E.C.* Oxford University Press Warehouse. Available online at: https://archive.org/details/in.ernet.dli.2015.234537/page/n3/mode/2up.

Livestock Breeding Policy (2019). "Approval of jammu and kashmir state livestock breeding policy," in *Animal/sheep husbandry and fisheries department*. Available online at: https://jkash.nic.in/Acts%20and%20Rules/Livestock%20Breeding%20Policy,%202019.pdf.

Loomis, C., and Kerven, C. (2025). The environmental impact of goats: Uprooting the narrative. *Front. Animal Sci.* 6, 1544366. doi:10.3389/fanim.2025.1544366

Manzano, P., Burgas, D., Cadahía, L., Eronen, J. T., Fernández-Llamazares, Á., Bencherif, S., et al. (2021). Toward a holistic understanding of pastoralism. *One Earth* 4 (5), 651–665. doi:10.1016/j.oneear.2021.04.012

Manzano, P., and White, S. R. (2019). Intensifying pastoralism May not reduce greenhouse gas emissions: Wildlife-dominated landscape scenarios as a baseline in life-cycle analysis. *Clim. Res.* 77, 91–97. doi:10.3354/cr01555

Marty, E., Bullock, R., Cashmore, M., Crane, T., and Eriksen, S. (2023). Adapting to climate change among transitioning Maasai pastoralists in southern Kenya: An intersectional analysis of differentiated abilities to benefit from diversification processes. *J. Peasant Stud.* 50 (1), 136–161. doi:10.1080/03066150.2022.2121918

Ministry of Finance, Government of India (2022). Economic survey 2021-22 statistical appendix. Available online at: https://www.indiabudget.gov.in/budget2022-23/economicsurvey/doc/Statistical-Appendix-in-English.pdf.

Mukherji, A., Arndt, C., Arango, J., Derera, J., Flintan, F., Francesconi, W., et al. (2023). Achieving agricultural breakthrough: a deep dive into seven technological areas. Montpellier France: CGIAR, Available online at: https://hdl.handle.net/10568/131852 (Accessed May 10, 2025).

Mugloo, J. A., Khanday, M. u., Dar, M. u., Saleem, I., Alharby, H. F., Bamagoos, A. A., et al. (2023). Biomass and leaf nutrition contents of selected grass and legume species in high altitude rangelands of Kashmir Himalaya Valley (Jammu & Kashmir), India. *Plants* 12, 1448. doi:10.3390/plants12071448

Panwar, P., Mahalingappa, D. G., Kaushal, R., Bhardwaj, D. R., Chakravarty, S., Shukla, G., et al. (2022). Biomass production and carbon sequestration potential of different agroforestry systems in India: a critical review. *Forests* 13 (8), 1274. doi:10.3390/f13081274

Pollini, J., and Galaty, J. G. (2021). Resilience through adaptation: Innovations in Maasai livelihood strategies. *Nomadic Peoples* 25 (2), 278–311. doi:10.3197/np.2021.250206

Poore, J., and Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science* 360 (6392), 987–992. doi:10.1126/science.aaq0216

Rao, A., and Casimir, M. J. (1982). Mobile pastoralists of jammu and kashmir: a preliminary report. *Nomadic Peoples* 10, 40–50. Available online at: https://www.jstor.org/stable/43124001 (Accessed May 11, 2025).

Rashid, M., Ghosh, A., and Ali, I. (2024). Pastoral lives in motion: inter-community and intra-community relations among the gujjar and bakerwal. *Int. J. All Res. Educ. Sci. Methods (IJARESM)* 12 (12), 2746–2757. Available online at: https://www.ijaresm.com/uploaded_files/document_file/Muzamil_Rashid7GfY.pdf (Accessed May 12, 2025).

Rasool, R., Fayaz, A., Shafiq, M. u., Singh, H., and Ahmed, P. (2021). Land use land cover change in kashmir himalaya: linking remote sensing with an indicator based DPSIR approach. *Ecol. Indic.* 125, 107447. doi:10.1016/j.ecolind.2021.107447

Reid, R. S., Thornton, P. K., McCrabb, G. J., Kruska, R. L., Atieno, F., and Jones, P. G. (2004). "Is it possible to mitigate greenhouse gas emissions in pastoral ecosystems of the tropics?," in *Tropical agriculture in transition — opportunities for mitigating greenhouse gas emissions?* Editors R. Wassmann and P. L. G. Vlek (Dordrecht: Springer), 91–109. doi:10.1007/978-94-017-3604-6_5

Reid-Shaw, I., Jargalsaihan, A., Reid, R. S., Jamsranjav, C., and Fernández-Giménez, M. E. (2021). Social-ecological change on the Mongolian steppe: herder perceptions of causes, impacts, and adaptive strategies. *Hum. Ecol.* 49, 631–648. doi:10.1007/s10745-021-00256-7

Rodgers, C. (2022). *Equipped to adapt? A review of climate hazards and pastoralists' responses in the IGAD region*. Nairobi: IOM and ICPALD. Available online at: https://icpald.org/wp-content/uploads/2022/09/ICPALD-IOM-Pastoralism-Report.pdf.

Ryckman, T., Beal, Ty, Nordhagen, S., Murira, Z., and Torlesse, H. (2021). Affordability of nutritious foods for complementary feeding in south Asia. *Nutr. Rev.* 79 (S1), 52–68. doi:10.1093/nutrit/nuaa139

Saleem, S., Rather, J. A., Ahmad, S., Ahmed, R., and Hajam, L. A. (2024a). Assessment of livestock carrying capacity in the alpine grasslands of the kashmir himalayas. *Pastor. Res. policy Pract.* 14, 13541. doi:10.3389/past.2024.13541

Saleem, S., Rather, J. A., Ahmed, S., Mushtaq, S., Ahmed, R., and Malik, I. H. (2024b). Above ground biomass estimation for alpine grasslands of kashmir himalayas using remote sensing and field-data. *Rangel. Ecol. and Manag.* 96, 117–127. doi:10.1016/j.rama.2024.06.001

Scasta, J. D., Duchardt, C., Engle, D. M., Miller, J. R., Debinski, D. M., and Harr, R. N. (2016). Constraints to restoring fire and grazing ecological processes to optimize grassland vegetation structural diversity. *Ecol. Eng.* 95, 865–875. doi:10.1016/j.ecoleng.2016.06.096

Scoones, I. (1995). *Living with uncertainty: new directions in pastoral development in Africa* (London: Intermediate Technology Publications). Available online at: https://practicalactionpublishing.com/book/1264/living-with-uncertainty.

Scoones, I. (2021). Pastoralists and peasants: Perspectives on agrarian change. *J. Peasant Stud.* 48 (1), 1–47. doi:10.1080/03066150.2020.1802249

Scoones, I. (2023). Livestock, methane, and climate change: the politics of global assessments. *Wiley Interdiscip. Rev. Clim. change* 14 (1), e790. doi:10.1002/wcc.790

Shah, M. M., Ahanger, S. A., Rather, T. A., Rather, M. A., Hamdani, A., and Bashir, I. (2020). Mutton production, demand and supply in Jammu and Kashmir and its augmentation. *Int. J. Curr. Adv. Res.* 9 (5), 22095–22102. doi:10.24327/ijcar.2020.22102.4355

Sharma, A. (2021). Communications from the field: the tale of two gujjar communities. *Nomadic Peoples* 25 (1), 137–140. doi:10.3197/np.2021.250116

Singh, R., Bhutia, K. S., Bhutia, T. U., and Babu, S. (2022). Rangeland conservation, pastoralist displacement, and long-term implications of a grazing ban in the Indian himalaya. *Ecol. Econ. Society–the INSEE J.* 5 (1), 195–221. doi:10.37773/ees.v5i1.335

Singh, R., and Kerven, C. (2023). Pastoralism in south Asia: contemporary stresses and adaptations of Himalayan pastoralists. *Pastoralism* 13 (21), 21. doi:10.1186/s13570-023-00283-7

Steinfeld, H., Gerber, P., Wassenaar, T., Vincent, C., Rosales, M., and Haan, C. d. (2006). *Livestock's long shadow*. Rome: FAO. Available online at: https://www.fao.org/4/a0701e/a0701e00.htm.

STEPS Centre (2023). Livestock and climate change: pastoralism and uncertainty online course. *YouTube video*. Available online at: https://www.youtube.com/watch?v=_CmX8D4gCfY (Accessed May 13, 2025).

Vagnoni, E., Franca, A., Porqueddu, C., and Duce, P. (2017). Environmental profile of Sardinian sheep milk cheese supply chain: a comparison between two contrasting dairy systems. *J. Clean. Prod.* 165, 1078–1089. doi:10.1016/j.jclepro.2017.07.115

World Bank Group (2025). *The world by income and region*. NW Washington, DC: The World Bank. Available online at: https://datatopics.worldbank.org/world-developmentindicators/the-world-by-income-and-region.html (Accessed May 13, 2025).

Xu, X., Sharma, P., Shu, S., Lin, T.-S., Ciais, P., Tubiello, F. N., et al. (2021). Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. *Nat. Food* 2, 724–732. doi:10.1038/s43016-021-00358-x

Zeder, M. A., and Hesse, B. (2000). The initial domestication of goats (*Capra hircus*) in the zagros Mountains 10,000 years ago. *SCIENCE* 287, 2254–2257. doi:10.1126/science.287.5461.2254

Zhuang, M., Gongbuzeren, and Li, W. (2017). Greenhouse gas emission of pastoralism is lower than combined extensive/intensive livestock husbandry: a case study on the Qinghai-Tibet Plateau of China. *J. Clean. Prod.* 147, 514–522. doi:10.1016/j.jclepro.2017.01.126

Pastoralism Research, Policy and Practice

TYPE Original Research
PUBLISHED 13 August 2025
DOI 10.3389/past.2025.14939

Goat transhumance in Mediterranean Turkey: characterization and key factors driving its transformation

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OPEN ACCESS

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RECEIVED 21 May 2025
ACCEPTED 11 July 2025
PUBLISHED 13 August 2025

CITATION
Ocak Yetişgin S and Canan S (2025) Goat transhumance in Mediterranean Turkey: characterization and key factors driving its transformation.
Pastoralism 15:14939.
doi: 10.3389/past.2025.14939

Goat transhumance in Mediterranean Turkey is undergoing significant transformation due to intersecting political, economic, institutional, and environmental pressures. This study explores these changes by identifying the primary forces driving transformation and by analyzing the adaptive responses developed by transhumant pastoralists in this evolving context. Specifically, the research aims to both document and describe current goat transhumance practices and to assess how they are being reshaped by policy frameworks, market integration, ecological shifts, and socio-political dynamics. Through field-based ethnographic and ecological research conducted over two full migration seasons (2019–2023), the study offers insights into how traditional knowledge systems interact with sustainability paradigms—particularly green and circular economy principles—to manage uncertainty, maintain mobility, and support pastoral resilience. Data were gathered through participant observation, semi-structured "walk-and-talk" interviews with 15 families, and ecological surveys of migration routes, stopover areas, and herd-environment interactions. Ethnographic findings emphasized labor dynamics, gender roles, and mobility structures, while ecological data addressed pasture conditions and grazing impacts. Triangulating these data revealed the socio-ecological logic of transhumance under shifting conditions. Six core drivers were identified: rural urbanization and demographic trends, economic pressures and market integration, governmental and policy frameworks, impact of climate change, COVID-19 pandemic and the emergence of circular and green economic frameworks. Despite mounting pressures, the study highlights that pastoralists continue to engage in strategic adaptations—such as rotational grazing, breed diversification, and labor reorganization—grounded in long-standing ecological knowledge. The findings demonstrate that transhumance persists not as a relic of the past, but as a dynamic and ecologically efficient livelihood system capable of responding to multi-scalar rural challenges.

KEYWORDS

goat pastoralism, green and circular economy, Mediterranean Turkey, transformation, transhumance

Introduction

Transhumance, practiced by pastoral communities across remote regions of the world, is a sophisticated life management model developed through generations of ecological knowledge and adaptive resilience (Easdale et al., 2023; Manzano-Baena and Casas, 2010; Ocak, 2016; Oteros-Rozas et al., 2013; Zanon et al., 2022). It operates on a low-input, low-output system while making intensive use of natural, human, and social capital to generate economic, environmental, and cultural benefits. Globally, transhumance is recognized for its contribution to biodiversity conservation (Hilty et al., 2020), sustainable land use (Zanon et al., 2022), maintenance of cultural landscapes (Azcárate and Hevia, 2023; Hevia et al., 2013), reduced reliance on fossil fuels, minimal waste generation, and the provision of high-quality animal products (Easdale et al., 2023). These systems exemplify long-standing forms of human–environment interaction shaped by mobility, adaptation, and collective governance.

In the Mediterranean and Alpine regions, transhumance has also received institutional recognition. In 2019, it was inscribed on UNESCO's Representative List of the Intangible Cultural Heritage of Humanity, based on a joint nomination by Italy, Austria, and Greece. This recognition was reaffirmed in 2023 at the 18th session of the Intergovernmental Committee in Botswana, underscoring global concern for the preservation of mobile pastoral systems. While the inscription applies to select European contexts, it reflects a broader appreciation of transhumance as a living cultural heritage that fosters ecological stewardship and intergenerational continuity.

In Turkey, transhumance has a deep historical legacy and remains vital for rural livelihoods in ecologically marginal yet resource-rich upland regions. Particularly in Mediterranean Turkey, seasonal livestock mobility—especially goat transhumance—has shaped social institutions, cultural memory, and rangeland ecology. The practice represents an adaptive social-ecological system that evolves in response to climatic, topographic, and institutional dynamics (Coppock et al., 1986). Over centuries, transhumant communities have tailored livestock practices to highly variable environments, contributing to spatial diversity, ecological resilience, and resource-sharing regimes (Manzano-Baena and Casas, 2010). Routes used by transhumants often function as ecological corridors, linking high-value habitats and reducing landscape fragmentation (Hevia et al., 2013; Azcárate and Hevia, 2023; Hilty et al., 2020).

While often framed as a declining tradition, transhumance is increasingly being reinterpreted through the lens of innovation. Transhumant communities also exemplify what Zagata et al. (2020) define as "retro-innovators"—actors who consciously revive and recontextualize historic practices, ecological knowledge, and communal technologies to address contemporary sustainability challenges. Retro-innovation reflects a conscious process involving the critique of modernist paradigms, the recovery of long-forgotten experiential knowledge, and its integration with current socio-technical conditions. From this perspective, transhumance is not a disappearing tradition but a dynamic and future-oriented practice that aligns with green economy models, circular resource use, and climate adaptation strategies. These potential benefits, however, are highly contingent on the policy and institutional contexts in which pastoralists operate. These retro-innovative benefits, however, depend on careful stewardship, including the maintenance of traditional grazing thresholds to prevent overuse and ecological degradation.

Despite its significance, transhumance in Mediterranean Turkey is under pressure from a range of structural and policy-related challenges that merit closer investigation. The absence of a national mountain area management plan has left pastoral communities without proper institutional support. At the same time, weak representation at the governmental level has resulted in a lack of coordinated efforts to safeguard pastoralist rights. Inefficiencies in implementing pasture laws, coupled with limited success in rural development projects, have exacerbated the situation. Additionally, persisting rural poverty, frequent shifts in agricultural policies, and mismanagement of pasturelands have placed further strain on transhumant communities. Overgrazing and declining productivity, coupled with difficulties in marketing livestock products and security concerns in remote mountain areas, have further discouraged younger generations from continuing this way of life (Akbas and Baykal, 2022). However, there is limited research on how these transformations are being negotiated in practice—particularly in the western Taurus region—and what this means for the future of transhumance as a viable livelihood system.

While academic interest in transhumance has grown, most studies in Turkey focus on Eastern Anatolian practices (Albayrak, 2020; Siddiq and Şanlı, 2020; Thevenin, 2011) or the socio-economic transformation of pastures in Southeastern Anatolia (Bakırcı, 2019). Notably, Ertas (2020) explores the impact of pasture bans and land privatization on pastoral sheep farming in Eastern Turkey, offerimfng valuable insights for policymakers. Important archaeological studies have explored the origins of pastoralism in Anatolia (Arbuckle, 2012; Hammer and Arbuckle, 2017), yet there remains limited research on contemporary goat transhumance in the western Taurus region, particularly through the lens of institutional transformation and adaptive governance.

This study aims to document goat transhumance and investigate the transformation by identifying the main political, economic, socio-ecological, and institutional drivers interact to reshape transhumant mobility, and how herders develop adaptive strategies in response. Drawing on ethnographic fieldwork and ecological observations conducted over two full migration cycles (2019–2023), the study contributes to scholarship on contemporary transhumance practices between

Mediterranean region and Anatolia, also explores the role of green and circular economy models in ensuring the sustainability of transhumance, emphasizing local strategies for managing uncertaintys, market integration dynamics, and adaptive pastoral practices.

Timeline of Turkish transhumance and state of the art

The term transhumance originates from the Latin words "*trans*" (across) and "*humus*" (ground) (Bhasin, 2011) and is believed to have emerged in the Mesopotamian region during the Mesolithic Period (Arnold and Greenfield, 2006; Nandris, 1985). Livestock domestication began around 10,000 BC, particularly in the Fertile Crescent, which spans present-day Turkey and Iran (Arbuckle et al., 2014). In Anatolia, the transition from hunting-based economies to livestock-based systems during the Neolithic period marked the origins of pastoralism (Arbuckle, 2014). Transhumance predates the arrival of Turkic communities in the 11th century, as historical accounts describe mobile pastoralism in the region long before their settlement. Herodotus (fifth century BC) observed nomadic groups wintering in Bodrum (a town in Western Turkey), describing their way of life as distinct from urbanized civilizations.

Historically, Anatolian highlands served as summer pastures, while Mediterranean coastal rangelands provided winter grazing grounds. Transhumance spread throughout the Fertile Crescent, influencing regional cultures and production systems. During the Ottoman period, transhumant communities, referred to as "Turkomen" and later "Yörük" (meaning "those who walk"), maintained their pastoral traditions despite state-imposed efforts to settle them (Sahin, 2006). The Ottoman Empire attempted to regulate transhumance by registering nomadic groups as "konar göçer" (seasonal migrants) in the 16th–18th centuries. These groups were assigned various economic roles, such as mine workers, lumberjacks, bridge and road constructors, and suppliers for the Ottoman army, which relied heavily on their livestock (İnalcık, 2014). Judicial records from 1672 indicate that the Aleppo Turkomens were required to provide 17,000 sheep for the army (İnalcık, 2014). Transhumant groups in Rumelia, a division of the empire that included present-day Albania, North Macedonia, and Thrace, were also employed in mines and fortresses (Gokbilgin, 1957). The Ottoman administration sought to curb nomadism by promoting urbanization and taxation, as mobile pastoralists were difficult to govern and tax efficiently (Oksay and Çelik, 2011). Policies were designed to either sedentarize these groups or restrict their migration patterns to ensure administrative control (Lindner, 1983). Both the Ottoman Empire and the Republic of Turkey implemented policies that progressively curtailed transhumant mobility in Anatolia. In the Ottoman period, nomadic communities such as the Yörüks were registered as *konar-göçer* (seasonal migrants) and gradually subjected to administrative control, taxation, and labor obligations, which aimed to integrate them into sedentary frameworks (İnalcık, 2014; Sahin, 2006; Lindner, 1983). This sedentarization agenda persisted into the Republican era, where state-led modernization projects—particularly under the 1926 Settlement Law—sought to transform mobile pastoralists into settled agriculturalists, viewing mobility as incompatible with centralized governance and national development goals (Bates, 1973; Barkey, 2008). These historical continuities underscore a long-standing institutional tendency to "slow" or suppress transhumance in favor of fixed settlement.

Contemporary Turkey remains home to various pastoral and nomadic communities, including the Laz and Georgian nomads in the Black Sea region, the Turkic, Turkomen, and Tahtacı groups in Western Anatolia and the Taurus Mountains, and predominantly Kurdish pastoralists in Eastern Anatolia (Büyükcan Sayılır, 2012). The Mediterranean region, with its unique bioclimatic conditions, has historically been a primary habitat for goat transhumance, providing vital sustenance for local communities. However, in recent decades, traditional goat transhumance has declined due to socio-economic shifts, insufficient governmental support, restrictive pasture laws, limited subsidies, land-use changes, and climate variability. Additionally, conflicts between transhumants and local villagers, as well as restricted access to essential services such as healthcare, education, and security, have further exacerbated challenges for these communities.

Despite these adversities, transhumance persists in Turkey, albeit on a reduced scale with a distinctive social structure (Table 1). Unlike most European countries, where transhumant movements over 10 km typically involve trucks (Malzac et al., 2024), on-foot goat transhumance remains prevalent in Mediterranean Turkey. Goat pastoralists cover approximately 400–450 km in 30–45 days during the spring migration from Mediterranean highlands to Central Anatolian pastures (Ocak, 2016). However, shrinking migration routes and agricultural expansion force communities to traverse narrow corridors, accelerating the migration process to avoid conflicts. Conversely, the autumn migration follows a more regulated pace, as harvested fields present fewer constraints. Migration routes, traditionally passed down through generations, remain stable unless disrupted by land-use changes or access restrictions (Ates et al., 2024). In the Mediterranean region, goat pastoralists continue to migrate on foot, whereas sheep pastoralists in central, western, and southeastern Anatolia increasingly rely on transportation by truck. Community names often reflect the breeds they raise, such as Beritan, Şavak, Akkeçili, Sarıkeçili, Karakeçili, Akkoyunlu, and Karatekeli. Determining the precise population of transhumant communities remains challenging due to gaps in the national livestock inventory, which does not differentiate between production systems. However, fieldwork interviews indicate that the Sarıkeçililer community comprises approximately 150 families, each living in its own tent

TABLE 1 Main transhumance communities and their location in Turkey.

Transhumant communities	Region	Raised animals
The Laz and Georgian	Black Sea Region	Goat
Turkomen and Tahtacı	West Anatolia	Sheep
Kurdish	South East and East Anatolia	Sheep
Turkish	Central and West Anatolia and Mediterranean	Goat

TABLE 2 Data collection and analysis.

Data source	Data analysis	Period
Semi-structured walk and talk interviews with transhumant herders (n: 15)	Interviews have been recorded and transcribed, analyzed as text	2019 April, May, June, July, October, November
Participant observation (n: 140)	Documented into field notes, analyzed as text	2019–2023
Taking photos (n: 868)	Analysis of visual materials	2019–2023
Archival data (n = 120)	Analysis of verbal and visual materials	2014–2023

with five to six households. The Sarıkeçililer are notable for their organized structure, which includes an association dedicated to preserving their production practices and traditional way of life.

Goat transhumance in the Mediterranean region relies on locally adapted Hair and Honamlı goat breeds, which are well suited to the area's environmental conditions and grazing systems. This traditional practice plays a crucial role in food security by ensuring a stable supply of animal-derived products. However, seasonal migration, commencing in April, frequently disrupts education, limiting many community members to primary schooling. Furthermore, inadequate healthcare facilities in both summer and winter pastures, as well as along migration routes, pose significant hardships. Given these dynamics, this study aims to analyze not only the historical and contemporary aspects of transhumance in Turkey but also the transformations it has undergone in recent years and the underlying drivers of these changes.

Materials and methods

Study area

This study examines the seasonal transhumant practices of the Sarıkeçililer community in southern Turkey, who migrate annually between coastal highlands near Aydıncık (Mersin Province) and upland pastures near Seydişehir (Konya Province) (Figure 1). The region encompasses both Mediterranean and continental mountain climates. Coastal zones experience annual precipitation between 600 and 1,100 mm, with warm, arid summers and mild, wet winters. In contrast, the upland pastures—located between 1,500 and 2,200 m near Seydişehir—receive approximately 1,100 to 1,300 mm of annual precipitation (TSMS, 2024), most of which falls as snow from November through March (Sensoy and Demircan, 2016). This climatic diversity supports a wide range of ecosystems. Accordingly, the Anatolian biogeographical region harbors 28 protected areas and sustains significant biodiversity across various ecoregions (Ambarli et al., 2016; Sekercioglu et al., 2011). Vegetation displays clear altitudinal stratification. Lower elevations (0–800 m) are dominated by maquis shrublands and secondary growth, including *Arbutus andrachne, Quercus coccifera, and Laurus nobilis*. At mid-altitudes, mixed coniferous forests, especially *Pinus brutia, Pinus nigra, and Juniperus* species, are prevalent. Subalpine zones above 1,500 m support species-rich grasslands alongside *Cedrus libani and Abies cilicica* stands.

The Sarıkeçililer follow a biannual migratory cycle. From November to April, they winter in the coastal highlands, where forage remains accessible. During April and May, they ascend along traditional northward routes to reach summer pastures. From May through October, they graze flocks in high-altitude areas before descending gradually to winter settlements in late October. These seasonal migraation, covering 400–450 km and last aproximatelly in 30 days. National agricultural statistics do not distinguish transhumance from other livestock production systems, limiting the resolution and relevance of available figures. Consequently, most insights into flock size, migration patterns, and community demographics stem from independent research efforts, local observations and community knowledge rather than official data collection. Current estimates, based on field interviews (2016–2020), local administrative records (2020) and data from Sarıkeçililer Association for Solidarity and Mutual Aid (2019), suggest that approximately

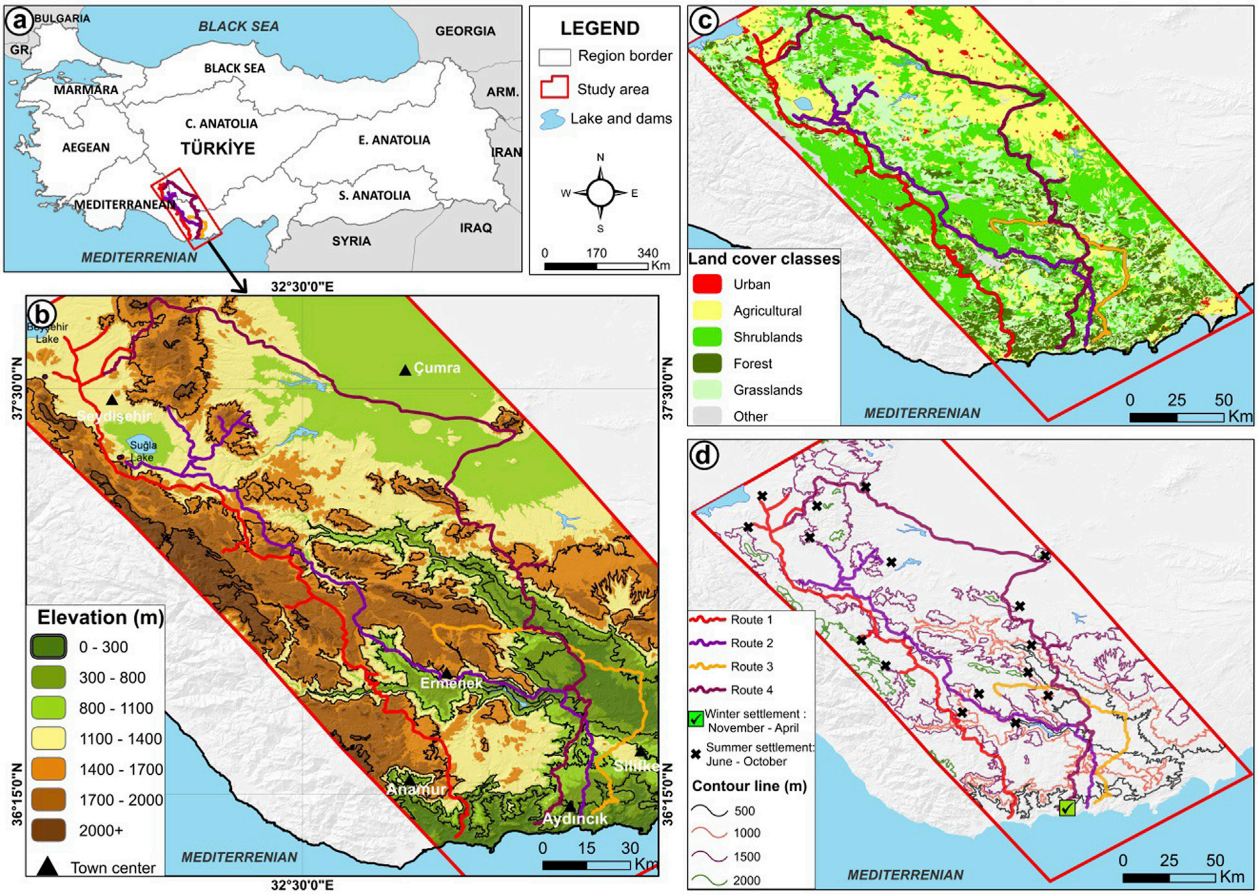

FIGURE 1
Study area **(a)** location, **(b)** elevation map, **(c)** land cover classes adapted from CORINE 2018 maps, and **(d)** the temporal and spatial dynamics of migration routes.

150 households continue to practice goat transhumance, managing an estimated 90,000 goats along these routes.

Data collection

Field data were gathered over two consecutive years (2019–2020) along transhumant migration routes from Mersin Province to the Konya region, encompassing both settlement areas and cultural festivals (Table 2). The Sarıkeçililer community comprises approximately 150 families. Fifteen households were selected using snowball sampling—a widely employed non-probability method in ethnographic research, particularly effective for socially interconnected or hard-to-reach populations where trust is vital (Noy, 2008; Biernacki and Waldorf, 1981). Initial participants, identified based on their continued engagement in full transhumant migration, referred researchers to additional families, facilitating broader access and ensuring the inclusion of diverse household perspectives while respecting community dynamics. Households were selected to reflect diversity in flock size and geographic distribution along the traditional migration corridor. Flock sizes among surveyed households ranged between approximately 500 and 600 goats, depending on household labor availability and resource access. The migration corridor covered extends from the coastal highlands near Aydıncık (Mersin Province) to the upland pastures around Seydişehir (Konya Province), spanning diverse climatic zones and ecological conditions. Within each household, interviews were conducted with multiple family members—including adult men and women, youth, and elders—to capture varied perspectives on migration, labor roles, ecological knowledge, and adaptive strategies (Moktan et al., 2008). Interview questions were designed to explore not only pastoral practices but also perceived changes in transhumance patterns and the adaptive strategies herders employ in response to ecological and institutional pressures. Primary data sources included semi-structured walk-and-talk interviews and participant observation during full transhumant cycles from Mersin to Konya. Researchers embedded themselves within the migrating community, conducting longitudinal participant observation. Daily activities, decision-making processes, and knowledge transmission were documented. Interviews were audio-recorded with informed consent, then transcribed and translated into English. Photographic documentation and detailed field notes captured social, cultural, and gendered dynamics relevant to transhumant pastoralism.

Ecological observations aimed to document how herders interact with rangeland environments. Key indicators included vegetation condition, pasture use, water availability, and stopover site characteristics. Observations covered dominant plant species, ground cover, overgrazing signs (e.g., erosion, trampling), and herder-reported forage quality. Grazing intensity, dung accumulation, site selection, and spatial behavior were recorded systematically. Stopover sites (*konalga*) were assessed for vegetation density, shade, and water proximity. Observations spanned two migration cycles (spring and autumn of 2019 and 2020). According to Turkish State Meteorological Service data, the Taurus uplands received 950–1,050 mm of precipitation in 2019 and 850–950 mm in 2020, with notably drier conditions in spring 2020 (TSMS, 2024). Observation points were selected collaboratively with herders based on traditional ecological knowledge, targeting ecologically significant areas. Sites were stratified across environmental gradients (e.g., elevation, vegetation type, and soil condition), ensuring ecological and cultural representativeness. Topics discussed during interviews included migration challenges, gendered labor roles, natural resource management, livestock production, and transhumance-related products. Participants were informed about the study's aims, assured confidentiality, and provided consent for recordings and photographs. Expert consultation with anthropologist Dr. Atilla Erden offered valuable guidance on historical and contextual aspects of transhumance.

Data analysis

Interview transcripts and field notes were analyzed using inductive thematic coding, applying a grounded theory approach to identify recurring patterns and key themes. Codes were iteratively refined through constant comparison. Ecological data were analyzed using standard indicators of pasture condition, grazing pressure, and water availability. These data were cross-verified with ethnographic findings through triangulation—a qualitative strategy that enhances credibility by validating insights across multiple data sources (Denzin, 1978; Patton, 1999). This triangulated analysis integrated interviews, observations, and photographic evidence to ensure interpretive accuracy and reduce potential bias. SPSS software supported the organization of qualitative data, assisting in synthesizing household-level narratives and ecological observations. Expert input from Dr. Erden further contributed to contextualizing the findings, particularly in relation to historical migration patterns and socio-environmental changes. By combining ethnographic, ecological, and documentary data—and incorporating intra-household diversity—the study provides a holistic understanding of the socio-ecological dynamics shaping contemporary pastoralism in Mediterranean Turkey.

While the study employed inductive thematic coding to identify patterns from interview transcripts and observational field notes, not all transformation drivers were derived solely from this grounded process. In particular, themes such as climate change, the COVID-19 pandemic, and the relevance of Green and Circular Economy frameworks were included as analytically significant drivers based on their prominence in international literature and policy discourse on pastoralism. Their inclusion reflects a triangulated methodology, wherein empirical field data were cross-referenced with macro-contextual dynamics. Participants frequently referenced unpredictable seasonal weather, mobility restrictions during the pandemic, and adaptive shifts in livestock and resource use aligned with sustainability concepts—substantiating the relevance of these broader drivers in the localized context of Mediterranean Turkey.

Results

Characteristics of goat transhumance

Migration and pastoral practices

The spring migration spans six to 7 weeks, covering 8–10 km per day, totaling 400–450 km. It begins in mid-April in Mersin (Mediterranean region) and concludes in the summer pastures of Konya (Central Anatolia) around June (Figure 1). These highland pastures serve as summer grazing areas for approximately 4.5–5 months. By mid-October, the transhumant communities gradually descend to lower altitudes, returning to their winter settlements in Mersin province. The migration route requires prior approval from local authorities, including the Regional Municipality and the Ministry of Environment, Urbaniszation and Climate Change. This seasonal pattern has persisted for centuries, with minor route modifications driven by administrative decisions or environmental factors. Each year, the number of stops, duration of stay at each site, and specific migration paths are subject to change based on governmental permissions and ecological conditions. These stopover locations, known as "konalga," are individually named, often reflecting historical or cultural associations. Hearthstones mark the tent settlement areas, symbolizing the community's temporary homes during migration (Figure 2). These waypoints function as cultural landmarks, forming an ancient navigational system akin to a traditional GPS. The location of each stop is strategically chosen

FIGURE 2
Heart stones on the migration route.

FIGURE 3
Typical cistern and wells along the route.

based on the availability of water sources, such as wells and fountains (Figure 3). As families depart, they leave the hearthstones undisturbed, enabling them to recognize their previous settlements upon their return.

Migration begins early in the morning, with family roles clearly defined in advance. Experienced young male and female shepherds are responsible for guiding the goats along the route, ensuring that herds remain cohesive and avoid cultivated fields. Damage to crops can lead to conflicts with settled communities, which are typically mediated by elders or women through monetary compensation or livestock donations. Traditionally, personal belongings and tents were transported on camels, accompanied by donkeys and horses. While modern days transhumants increasingly rely on tractors and trucks, challenging mountainous roads often limit their practicality. Historically, camels were adorned with decorative face bells "*Gübürdek*" and beaded ornaments "*Keydirme*" before embarking on their journey (Figure 4). They were also covered with colorful sacks "*Alaçuval*" and intricately woven kilims "*Cicim*." Until the 1990s, settled populations would gather along migration routes to witness this spectacle, which resembled a ceremonial procession. However, such displays have largely disappeared. Today, only a few remaining camel convoys persist, led by a respected female figure within the transhumant group. This tradition underscores the matriarchal structure of the community, where women hold a prominent role in decision-making and social organization (Figure 5).

All the transhumant communities demonstrate a profound awareness of natural resource limitations and the environmental impacts of overgrazing, vegetation loss, and erosion. These concerns, frequently expressed in interviews, reflect a deliberate strategy to mitigate ecological degradation. To ensure sustainability, they employ rotational grazing, minimizing the time spent in a single location to prevent land exhaustion. This practice aligns with traditional agroecological methods documented in Ottoman records, which highlight the resource management expertise of Anatolian pastoralists (Sahin, 2006). By synchronizing grazing with the flowering periods of shrubs and selectively browsing understory vegetation in forested areas, they contribute to ecosystem stability. Additionally, the

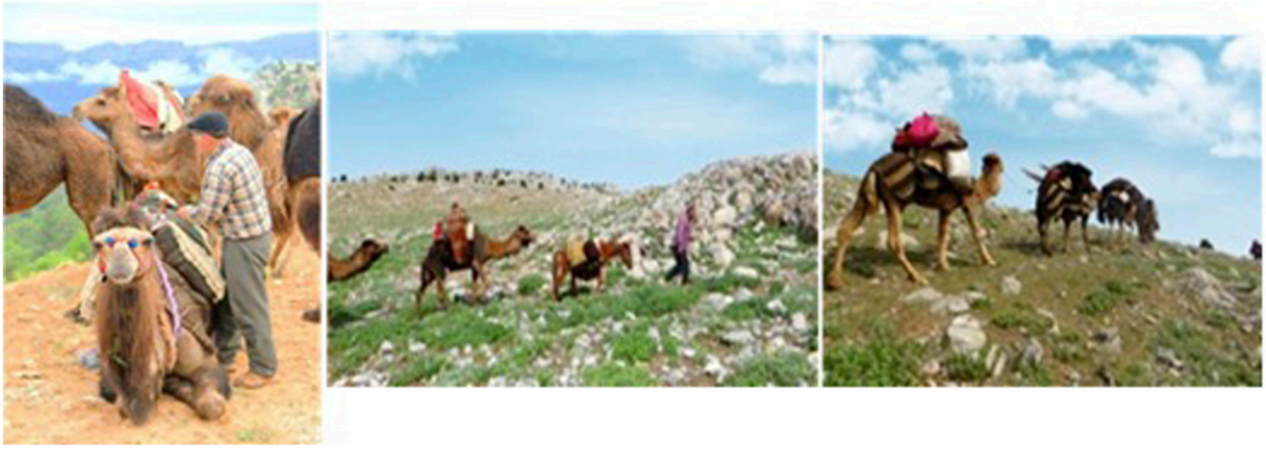

FIGURE 4
Camel convoy on the migration route decorated with face bells.

FIGURE 5
Woman leading the camel convoy.

natural deposition of urine and manure enhances soil fertility, reduces erosion, and improves water quality in catchment areas (Mediterranean Consortium for Nature and Culture, 2013). Transhumant goat grazing also plays a crucial role in forest management. The pastoral goat communities closely monitor herd movement to minimize damage to young trees and bark. Grazed reforested areas benefit from natural fertilization, promoting forest regeneration. Furthermore, transhumant flocks significantly reduces wildfire risk compared to ungrazed areas. By consuming understory vegetation and low shrubs, goats limit the accumulation of flammable biomass, decreasing fire intensity and spread. Their trampling also buries volatile pine needles, further reducing fire hazards. The effectiveness of goat grazing in fire prevention has been widely documented (Rosa García et al., 2012). Beyond vegetation management, transhumant flocks interact with broader ecological processes. As herbivores, they utilize natural forage and water sources while serving as prey for predators such as foxes, wolves, and occasionally bears. Predator protection in the communities relies primarily on Anatolian shepherd dogs and, in some cases, rifles. Despite these measures, predator attacks remain a significant challenge. In accordance with ecological traditions, livestock attacked and killed by predators are not buried or consumed by the community but are left for scavengers, contributing to nutrient cycling within the ecosystem (Figure 6).

These evolving patterns of mobility, influenced by both ecological conditions and administrative oversight, highlight emerging pressures on the continuity of traditional transhumant routes—issues explored further in the discussion of environmental and institutional drivers. At the same time, these shifting practices reflect a deeper transformation in the spatial and temporal logic of transhumant mobility. Rather than

FIGURE 6
Goat died by a predator attack and hung on a tree for natural recycling.

merely reacting to external constraints, herders increasingly engage in situational mobility—a flexible, real-time recalibration of routes, timing, and labor roles in response to dynamic ecological conditions and administrative regulations. This marks a transition from traditional fixed-route pastoralism to a more contingent and adaptive mobility regime, grounded in localized knowledge and responsive decision-making. These changes, therefore, represent not only adaptation but a structural reconfiguration of the mobility system itself.

Gender role

Transhumant societies are generally male-dominated and paternalistic, reinforcing male supremacy and the subjugation of women (Bhasin, 2011). However, the role of women varies across cultures, with a common characteristic being their ability to perform multiple tasks simultaneously, drawing on ancestral knowledge and specialized skills. In Turkish transhumance, particularly among the Sarıkeçililer, women occupy a distinctive position due to the community's shamanistic heritage and matriarchal family structure. They form the backbone of the household economy, as livestock production and processing depend heavily on their labor. Unlike many other Turkish transhumance groups, Sarıkeçililer women exert considerable influence over household decision-making.

Their primary responsibilities include childcare, animal product processing, livestock breeding, firewood collection, and meal preparation. As integral contributors to the socio-economic structure, they bear a substantial workload. Marriage patterns further reinforce their role, as pastoralist men, often from shepherding families, typically marry women raised in similar environments. These women acquire a deep understanding of pastoral life from an early age and are well-prepared for its demands. While livestock production requires the cooperation of both men and women, female involvement is particularly pronounced. Men primarily construct shelters to protect livestock from predators and harsh weather and are responsible for dismantling and rebuilding homes during migration. They also collaborate with women in twisting and spinning goat hair into thread, whereas women predominantly weave textiles for clothing, food containers, and tent coverings. Beyond their economic contributions, women play a crucial role in conflict resolution within transhumance communities. Nevertheless, despite their active participation in economic and social life, they are generally excluded from independently making decisions regarding the marketing of livestock and animal products, as such matters require their husbands' consent. This reflects broader gender disparities in disadvantaged regions of developing countries, where women often have limited decision-making authority and unequal access to resources. The expanding roles of women within the Sarıkeçililer community—especially under growing labor shortages and shifting household structures—reflect broader socio-economic transformations and gendered adaptations discussed in the following section.

The black tent

The black tent serves as the central living space for transhumant communities, fulfilling multiple functions, including accommodation, meal preparation, guest reception, and storage. The tent floor is covered with felt, providing insulation and comfort (Figure 7). Its thick, heavy structure offers shade in summer and effective protection against the cold in winter. Tents are typically spaced fairly apart from each other, ensuring privacy while mitigating overgrazing, reducing

FIGURE 7
Tent weawing woman and central pole in the tent.

competition, and minimizing environmental impact (Figure 8). Woven by the women of the household, these tents have a lifespan of 7–10 years (Ocak, 2016). Goat hair, the primary material for tent construction, is shorn and cleaned in July before being spun into yarn for weaving. The distinctive thick weave pattern allows visibility from the inside while preventing outsiders from seeing in. However, traditional handicrafts such as rug weaving are declining, primarily due to the heavy workload associated with large livestock herds. Weaving is traditionally performed on a loom known as the ıstar (Figure 7a). The tent is supported by five poles: a central pole, measuring 2.5 m in height, positioned at the structure's core, and four outer poles, each 20 cm shorter, arranged in a square formation approximately 4 m apart (Figure 7b). Both the warp and weft of the tent fabric are made from yarn that is twisted twice, ensuring durability in adverse weather conditions, such as strong winds. The entrance consistently faces east, with bedding placed to the right. Opposite the entrance, sacks containing clothing and valuables are stored, including *Alaçuval*—special sacks used for foodstuffs and valuables. Measuring approximately 2 m by 70 cm, *Alaçuval* are traditionally adorned with woven motifs to distinguish their contents. Additionally, these sacks serve as part of a young girl's dowry in preparation for marriage. The diminishing practice of tent weaving among Sarıkeçililer women, driven by shifting labor demands and herd management pressures, signals broader changes in cultural continuity and gendered labor roles—dimensions explored further in the discussion of socio-economic transformation.

Flock management and economic significance

The Hair and Honamlı goat breeds (Figure 9) and their crossbreeds constitute the predominant local goat population, primarily raised for meat production. While some families also maintain small flocks of sheep and a few camels, goats remain central to their livestock management practices. Hair and Honamlı goats are recognized as the hardiest among Turkish goat breeds due to their exceptional adaptability to extreme climatic conditions, rugged terrain, limited forage availability, endemic diseases, and traditional, non-specialized handling practices (Yilmaz et al., 2012). These breeds play a significant role in the livelihoods of rural communities, providing essential sources of protein, economic stability, and traditional dairy products. Despite challenges these goats remain highly resilient and integral to local agricultural systems.

The average flock size per household ranges between 500 and 600 goats. These flocks are managed along a 400–450 km migration route stretching from Mersin's coastal highlands to the upland summer pastures of Seydişehir in Konya Province, traversing varying altitudes and bioclimatic zones. The average milk yield is approximately 110lt/goat (Toplu and Altınel, 2008). However, milk production is not a primary objective and is mainly reserved for household consumption, particularly in the form of cheese and yogurt. Goat hair holds no commercial value, and the primary sources of dietary protein for the community are goat meat and milk. Flocks rely exclusively on rangeland pastures and shrubs, with supplementary feeding limited to a small quantity of grain during the final trimester of pregnancy. All family members actively participate in livestock management, particularly during the kidding season. After birth, does remain close to the family tent for several days under observation, receiving provided feed rather than grazing freely. Newborn kids remain with their dams until they are sufficiently strong to join the flock. Kids are marked with ear notches for identification and further distinguished through unique names or symbols based on ear shape, hair color, age, or other physical characteristics. Young family members, often serving as shepherds, can individually recognize goats based on these distinguishing features. Additionally, Anatolian Shepherd dogs are commonly kept to protect flocks from predators.

FIGURE 8
The Black tent.

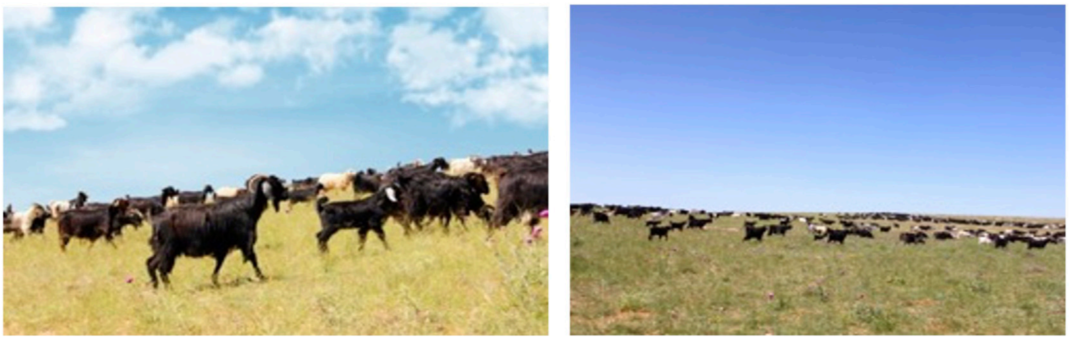

FIGURE 9
Hair and Honamlı goats on the migration route.

The mating season occurs between August and October, with kidding taking place in January and February. Kids remain with their dams until June or July, when natural weaning occurs as milk production ceases. The community does not engage in commercial dairy production; milking is practiced only in late June and July for household consumption. There is no strictly defined weaning period, as kids continue nursing until milk supply naturally diminishes. Milking is conducted only after ensuring that kids have suckled adequately.

Goat hair is sheared annually in July and August, with an average yield of approximately 1 kg per one-year-old goat. Traditionally, the fiber was combed into yarn, dyed, and woven into tents and clothing. However, this labor-intensive process, historically performed by women, has declined due to shrinking household sizes and evolving socioeconomic conditions. As a result, goat hair is now primarily repurposed as fertilizer for banana plantations and as an insulation material in the construction industry (Ates et al., 2024). The availability of ready-made products has further diminished the necessity of hair processing, which is no longer prioritized over other, more pressing tasks.

The recognition of goat manure as a valuable byproduct has only emerged in the past two decades. However, within the community, manure remains secondary to overall livestock production. The shift toward manure utilization is primarily driven by reductions in grazing areas, which have constrained seasonal migrations and reduced herd mobility. In the past, when pastures were more extensive, manure collection was impractical. With the current limitation of grazing lands, families can now gather manure from stationary resting areas of their flocks. The collected manure is primarily utilized as organic fertilizer in greenhouse agriculture (Ates et al., 2024).

The evolving uses of livestock products—from declining goat hair utilization to increased manure valorization—illustrate adaptive strategies shaped by shifting market conditions and land-use constraints, themes analyzed in detail in the discussion on economic transformation. These evolving practices suggest that transhumance is not static; rather, it is undergoing transformation shaped by economic marginalization and limited institutional support. Herders' adjustments in breed preferences, seasonal labor distribution, and manure usage exemplify localized adaptation strategies within a dynamic pastoral system.

Meat and dairy production

Following the gradual weaning period in June and July, kids are sold to butchers in summer pastures, providing families with crucial income after a year of labor. However, due to their mobile lifestyle and limited market access, families are unable to engage in meat processing themselves. Goat sales, particularly culled ones and male kids for traditional feasts, serve as the primary source of cash income.

Dairy production, specifically the preparation of tuluk cheese—a traditional cheese aged in treated goat hide—represents another vital economic activity. Goats are milked in June and August for the production of tuluk cheese and salted yogurt, both of which are highly valued for their long shelf life. Milking and dairy processing are primarily carried out by women. The labor-intensive cheese-making process preserves both traditional knowledge and economic sustainability. The production of tuluk cheese involves several preparatory stages. Goat hides must be carefully removed in one piece, salted, and sun-dried before undergoing repeated treatments with strained yogurt and salt over several weeks. Once the hide is fully processed, it is stitched back into its original shape and used to store fresh cheese. The cheese itself is produced by adding rennet to fresh milk. After 12 h of draining, the curd is transferred to woven bags, salted, and stored for 2 weeks. It is then crumbled, mixed with additional salt and black caraway seeds, and packed tightly into the prepared goat hides. The cheese is aged for several months in caves or cold storage before being sold in village markets, where its value increases with age.

The continued reliance on traditional dairy processing and limited meat market integration underscores the tension between cultural continuity and economic marginalization—pressures that shape the evolving livelihood strategies analyzed in the following discussion.

Emerging drivers of transformation: ethnographic and ecological insights

The transformation of transhumant pastoralism in Mediterranean Turkey is not a consequence of isolated factors but rather the cumulative result of interacting structural pressures. Field data collected through longitudinal ethnographic immersion and ecological monitoring during two migration cycles (2019–2020) identified six principal drivers reshaping the practices, viability, and resilience of goat transhumance: demographic transition, market marginalization, institutional constraints, climate variability, pandemic-induced disruption, and the unrealized potential of sustainability frameworks.

Demographic transition and rural urbanization

Interviews revealed a widespread concern over intergenerational discontinuity in transhumance. Younger family members increasingly prioritize formal education and urban employment over pastoral livelihoods, perceiving them as physically arduous and socially devalued. This demographic shift has resulted in diminished household labor capacity and weakened traditional knowledge transmission. Consequently, elderly and female household members now bear increased responsibilities for herd management and migration logistics. These findings align with broader regional trends in the devaluation of pastoral identity and the feminization of agricultural labor under rural depopulation dynamics.

Market marginalization and economic constraints

Respondents underscored multiple economic stressors: volatile livestock prices, lack of formal market infrastructure in upland zones, and rising input costs, including veterinary care and transportation. Transhumant families primarily sell kids post-weaning but lack access to meat processing, cold chain logistics, or niche markets. This economic precarity is compounded by their exclusion from subsidy schemes designed for sedentary producers. The data confirm that market pressures are driving shifts toward semi-sedentary systems and herd downsizing, undermining the ecological and economic rationale for long-distance mobility.

Institutional constraints and governance failures

Herders consistently reported difficulties in navigating fragmented and inconsistent regulatory frameworks. Permit acquisition for migration routes is bureaucratically burdensome and often subject to changing local and national directives. Protected area designations and conservation policies have increasingly restricted access to seasonal pastures, without offering viable alternatives or compensation. Interviewees described a governance landscape that privileges sedentary agricultural models, with limited legal recognition for the spatial-temporal logic of pastoral mobility. These constraints have led to route compression, intensified pasture use, and conflict with settled communities.

Climate variability and environmental stressors

Ecological observations corroborate herder narratives regarding the declining reliability of seasonal vegetation and water availability. In both 2019 and 2020, early spring droughts disrupted migration timing and reduced forage productivity in mid-altitude zones. Respondents adapted by shortening stopover durations, delaying ascent, or modifying grazing intensity—responses indicative of flexible, knowledge-based ecological management. These shifts, however, impose additional stress on animal health, workload, and pasture regeneration. The findings support the view that transhumant systems are on the frontlines of climate-induced ecological instability, yet lack systemic adaptation support.

COVID-19 pandemic

The pandemic introduced acute systemic shocks, further destabilizing transhumant viability. Movement restrictions imposed during 2020 interrupted scheduled migrations, forced herd concentration in suboptimal grazing zones, and escalated conflict over pasture access. Simultaneously, closure of local livestock markets disrupted income generation and reduced cash flow. The repurposing of mountain areas for domestic tourism and recreation during lockdowns created new forms of spatial competition, increasing the vulnerability of herders operating in contested commons. These observations underscore how global crises exacerbate structural marginality in mobile pastoral systems.

Underutilization of green and circular economy synergies

Despite extensive alignment between traditional transhumant practices and sustainability principles—such as manure recycling, low fossil-fuel dependency, and rangeland stewardship—there is little institutional recognition or financial incentivization for these contributions. Interviewees expressed awareness of their ecological role but frustration at the absence of market or policy mechanisms that valorize their sustainability practices. This represents a critical missed opportunity: transhumance is a latent asset within green transition frameworks, yet remains unintegrated into environmental planning or certification schemes that could secure long-term viability.

These six interconnected drivers, derived from ethnographic fieldwork and ecological assessments, provide an integrated framework for understanding the ongoing transformation of goat transhumance in Mediterranean Turkey. They validate the thematic analysis presented in the discussion and demonstrate how herders employ innovative, grounded strategies to navigate shifting socio-ecological terrains.

Cultural continuity and perceived heritage loss

Ethnographic accounts gathered during fieldwork illuminated a profound sense of cultural precarity among transhumant communities. Many participants articulated concerns over the erosion of traditional practices—including oral histories, communal rituals, and artisanal knowledge systems such as black-tent weaving and tuluk cheese production. Elders frequently described a "disconnect" between younger generations and ancestral knowledge, noting the waning participation in seasonal festivals, storytelling, and intergenerational skills transmission. Participants also expressed ambivalence toward recent attempts by external institutions—NGOs, cultural organizations, or media—to valorize transhumance as "intangible heritage." While such efforts were seen as validating, they were also perceived as superficial or symbolic, lacking material support or structural impact. Several community members critiqued the aestheticization of transhumance in public discourse, highlighting a dissonance between celebratory representations and their lived experience of marginalization.

Moreover, participants conveyed that although practices such as transhumant migration, tent-making, and gendered labor persist, they are increasingly decoupled from the socio-ecological and spiritual meanings they historically carried. Concerns were voiced about the dilution of cultural identity under pressures from tourism, policy interventions, and shifting land-use norms. These narratives collectively underscore that transhumant pastoralism is not only under threat ecologically and economically, but also culturally. The community's sense of being active stewards of a living tradition, rather than passive subjects of heritage discourse, emerged as a key theme—providing an empirical foundation for the discussion on cultural preservation and heritage recognition that follows.

Discussion

Key drivers influencing the transformation of transhumance: a categorized analysis

The transformation of transhumance is shaped by a complex interplay of environmental, economic, social, and political factors. While historically rooted in sustainable pastoral systems, transhumance has undergone significant changes due to shifting socio-economic structures, evolving land-use patterns, climate change, policy interventions, and market dynamics. Our findings not only characterize these transformative pressures but also document how goat pastoralists have actively adapted their practices in response—through shifting migration patterns, herd management, and labor organization. These transformations, although regionally distinct, exhibit common trends across pastoralist communities—including goat herders in Mediterranean Turkey—where traditional practices are increasingly challenged by modernization and socio-ecological pressures. This section categorizes and analyzes the key drivers influencing the transformation of transhumance, emphasizing that the same forces affecting broader transhumant systems also shape the livelihoods and practices of goat pastoralists in this specific region. Recognizing these parallels enhances our understanding of how localized changes reflect global pastoral transitions and highlights the urgent need for context-specific adaptation strategies.

Socio-economic factors: rural urbanization and demographic trends

The transformation of transhumance is closely linked to socio-economic shifts, particularly the declining attractiveness of pastoralism among younger generations. Alternative livelihood options in urban centers and changing aspirations have led to a loss of interest in traditional livestock farming. Younger people increasingly view transhumance as physically demanding and economically insecure (Manzano-Baena and Salguero-Herrera, 2018), a perception that is equally evident among goat herding communities in Mediterranean Turkey. As a result, the continuity of goat transhumance is at risk, with elders struggling to transfer specialized knowledge on herd mobility, pasture use, and climate adaptation.

This generational disconnect is further deepened by formal education, which often alienates youth from pastoral knowledge systems (Oteros-Rozas et al., 2013). In the Taurus Mountains and surrounding coastal hinterlands, goat pastoralism has historically depended on intergenerational learning. Today, however, many young people leave rural areas permanently, leading to labor shortages, shrinking herd sizes, and the abandonment of traditional routes. As elder pastoralists retire without successors, valuable knowledge regarding pasture rotation, livestock health, and climate adaptation may be lost (Fernández-Giménez et al., 2017). Consequently, elderly household members and women increasingly manage herds under challenging conditions, with limited labor and institutional support—paralleling broader patterns across transhumant regions (Nori et al., 2008).

Education plays a dual role in this shift. While increased access to schooling provides opportunities beyond pastoralism, it simultaneously contributes to the erosion of traditional pastoral knowledge (Oteros-Rozas et al., 2013). Changing social aspirations have made pastoral livelihoods less desirable, especially as they are often associated with hardship and marginalization. The depopulation of rural areas, particularly in Mediterranean and Central Asian pastoral regions, has led to a diminishing labor force for livestock management as younger generations seek employment opportunities in urban centers (Lasanta et al., 2017). Demographic shifts—including rural depopulation, urban migration, and infrastructural expansion—have further influenced seasonal livestock movements. These changes result in labor shortages, disrupted family structures, and reduced access to grazing lands (Lasanta et al., 2017; Krätli and Schareika, 2010). This demographic shift has also reconfigured family structures, with women and elderly individuals increasingly assuming responsibilities for livestock care, often with inadequate support and resources (Nori et al., 2008). In Mediterranean Turkey, the reconfiguration of pastoral territories and erosion of identity is particularly visible as families relocate to urban and peri-urban areas. The expansion of agriculture, infrastructure, and tourism fragments migration routes and limits access to water and pasture (García-Ruiz and Lasanta-Martinez, 1990; Linstädter et al., 2013). Consequently, many herders have shifted toward semi-sedentary systems, leading to reduced rotational grazing, biodiversity loss, and declining animal performance.

Additionally, pastoralists now face intensified competition for resources due to growing demands from agriculture, tourism, and conservation initiatives, restricting access to grazing lands and water sources (Linstädter et al., 2013). These pressures are particularly acute for goat pastoralists in Mediterranean Turkey, where traditional upland grazing areas are increasingly encroached upon. Faced with limited access to pasture and rising resource competition, many pastoralists have shifted toward semi-sedentary systems. However, the loss of rotational grazing practices has often led to overgrazing, reduced biodiversity, and declining animal performance. While not listed as a primary driver of change in this study, the motorization of access to pastures represents an important historical inflection point in the broader transformation of transhumance. Mechanization altered migration pace, duration, and the nature of family involvement—particularly among sheep pastoralists. In the case of the Sarıkeçililer, who continue to migrate predominantly on foot, the effects of motorization have been more limited. Nonetheless, it has influenced the transport of supplies and tents and contributed to the reorganization of labor roles within migrating households. As such, motorization intersects with broader demographic and socio-economic changes, though it is not a stand-alone driver in the transformation of goat pastoralism in this region.

These socio-demographic transformations do not act in isolation. Rather, they intersect with shifting economic conditions that also influence the viability and direction of transhumant pastoralism in Mediterranean Turkey.

Economic pressures and market integration

Building on the demographic and social changes outlined above, economic pressures—particularly those related to market integration and structural exclusion—present a critical set of challenges for transhumant communities. The future of transhumance is shaped by several crucial factors, including social, economic, and political decisions at both national and regional levels. These decisions carry significant weight due to their inherent unpredictability and the lack of long-term reliability. The strategies adopted by mountain pastoralists for livestock management play a vital role in this context.

Over time, transhumance in many parts of the world has evolved from a traditional subsistence-based practice to one increasingly integrated into market economies. However, this trend is less pronounced in Turkey, where transhumance—particularly among goat pastoralists in Mediterranean regions—continues to operate largely outside formal commercial structures. It remains deeply rooted in cultural traditions, household-level subsistence, and informal local exchange networks. The partial detachment from structured markets renders these systems more vulnerable to marginalization, as they are often overlooked by policy instruments that prioritize commercially oriented and sedentary production models. As a result, the sustainability of Turkish transhumance is shaped not by market integration alone, but by a combination of policy neglect, institutional exclusion, and competition over land and resources. This economic marginalization is particularly visible among goat pastoralists in Mediterranean Turkey, whose livelihoods have historically depended on seasonal mobility and ecological knowledge. As markets expand and standardize production practices, traditional herders are increasingly subject to price volatility and policy environments that disadvantage extensive systems. Market pressures have brought both opportunity and strain, as pastoralists navigate new expectations for productivity without corresponding support for mobile systems.

Economic viability is a crucial determinant of transhumance sustainability. Pastoral communities are increasingly integrated into national and global markets, subjecting them to fluctuations in livestock prices, feed costs, and transportation expenses. The rising cost of maintaining flocks, coupled with the declining profitability of extensive livestock production, has put significant financial strain on transhumant herders. Market pressures have also influenced flock composition and grazing patterns. To remain competitive, many farmers have shifted towards high-yield breeds that require more intensive feeding and management, making traditional migratory routes less viable. This is also observed among goat keepers in Mediterranean Turkey, where pressure to adopt more productive but less resilient breeds undermines the ecological advantages of local genetic resources and traditional grazing cycles. Furthermore, large-scale commercial livestock production, supported by subsidies and infrastructure, often outcompetes transhumant pastoralism, forcing many herders to either modify their practices or abandon them altogether. Market fluctuations, increased competition, and the rising costs of livestock maintenance make transhumance less economically viable. Another economic constraint is the lack of access to financial services. In many regions in Turkey, transhumant pastoralists struggle to obtain credit, insurance, and other financial tools that could help them mitigate risks associated with climate variability, disease outbreaks, and market fluctuations. This lack of financial resilience makes pastoralists more vulnerable to external shocks, further accelerating the decline of transhumance (Krätli and Schareika, 2010). Among goat herders in the Taurus Mountains, these limitations are particularly acute. Mobile herders often operate informally or lack the legal documentation needed to access formal finance, rendering them structurally disadvantaged in adapting to market integration or climate-induced shocks. Alongside economic restructuring and demographic shifts, the role of formal governance and regulatory regimes has been decisive in shaping the changing conditions for transhumance. These institutional dynamics merit separate attention.

Government and policy frameworks

Government and policy frameworks have fundamentally reshaped the dynamics of goat transhumance in Mediterranean Turkey. Conservation initiatives, land tenure reforms, and livestock regulations—while often introduced to modernize agriculture or safeguard natural resources—have produced unintended consequences for mobile pastoralism. Specifically, protected area designations and forestry policies have limited access to critical seasonal grazing corridors, while tenure reforms have largely failed to accommodate the spatial fluidity of transhumant land use. These institutional rigidities have marginalized mobile pastoralists, embedding a structural bias that favors sedentary farming systems.

This policy orientation routinely neglects the ecological benefits of transhumance—such as sustaining habitat connectivity, promoting biodiversity, and mitigating wildfire risk—despite evidence of its adaptive and low-impact nature. In Mediterranean Turkey, goat herders navigating traditional migration routes increasingly encounter bureaucratic barriers and shrinking access to upland pastures, now often repurposed for forestry, tourism, or conservation (Gurung and Seeland, 2008).

Livestock regulations further complicate mobility. Administrative demands tied to mandatory registration systems and veterinary controls—though important for disease surveillance—are often misaligned with the flexible temporal and spatial rhythms of transhumance. These policy mismatches not only threaten pastoral socio-economic sustainability but also compromise landscape-level ecological resilience.

To maintain transhumance as a viable practice, policy frameworks must evolve toward more flexible and inclusive governance models. This involves legal recognition of seasonal mobility, integration of pastoral corridors into spatial planning, and participatory governance that includes pastoral voices. Without such structural adjustments, existing regulatory regimes risk accelerating the erosion of both traditional herding systems and their associated ecological services.

These challenges are not unique to Turkey. Comparative insights from other regions reinforce the argument that structural and institutional neglect hampers pastoral resilience. Adamou (2024), for instance, critiques agricultural policies in the Sahel for failing to address climate risks, suggesting conservation farming and diversified livestock strategies as alternatives. Primi et al. (2025) similarly note how weak policy alignment and soil degradation undercut transhumance-based livestock farming. Although these examples emerge from different geographic contexts, they illustrate a common failure to support mobile systems under changing environmental and socio-economic conditions.

In Europe, the role of policy in shaping transhumance is equally significant. Esgalhado et al. (2024) evaluate the impact of Common Agricultural Policy (CAP) payments, finding that while general CAP mechanisms are insufficient, those explicitly linked to transhumance yield better outcomes for sustaining mountain pastures. These findings underscore the importance of designing subsidies and conservation strategies that explicitly incorporate the needs of mobile livestock systems. As Krätli and Schareika (2010) argue, subsidies and services disproportionately benefit sedentary producers, exacerbating the exclusion of mobile herders—a pattern echoed in Mediterranean Turkey.

Globalization compounds these trends. While it opens market opportunities, it also redirects policy attention toward high-output, sedentary livestock production and away from traditional mobile practices (Gurung, 2019). Conservation-driven land reclassifications further reduce pasture availability, exacerbating insecurity over tenure and access. The absence of clear legal recognition for transhumant herders in Turkey has contributed to ongoing marginalization, exposing them to land-use conflicts and infrastructural neglect.

The situation is particularly acute in the Taurus Mountains and surrounding regions, where mobile herders operate within ambiguous legal environments that prioritize sedentary livestock systems. These conditions mirror challenges elsewhere in Europe, where CAP-linked payments often fail to support mobile systems unless explicitly designed to do so (Esgalhado et al., 2024). In Turkey, the absence of targeted support mechanisms heightens the vulnerability of goat pastoralists dependent on seasonal upland access.

To counter these challenges, policy instruments must prioritize the formalization of mobility rights and the inclusion of pastoral systems in rural development strategies. Recognizing transhumant herders as ecological stewards and cultural custodians is crucial for designing supportive legal and institutional frameworks. As Nori et al. (2008) and Ocak (2016) observe, the failure to formalize pastoralist rights perpetuates resource conflicts and pressures mobile communities toward sedentarization. Integrating transhumant systems into regional land-use planning is thus not only a matter of social equity but a necessary step for environmental sustainability and climate resilience. Without such integration, the long-term viability of transhumance—and the socio-ecological systems it supports—remains increasingly at risk.

Climate change

Climate change, which has led to a range of challenges affecting mountain communities worldwide, has emerged as a major driver of transformation within pastoral systems. It alters seasonal weather patterns, reduces pasture productivity, and limits water availability—factors that are central to the viability of transhumant livestock production. Climate change affects livestock in two principal ways: first, through the reduction in the quality and quantity of forage, and second, via direct physiological impacts resulting from increased temperatures. A series of related consequences are expected, as highlighted in a report by the European Environment Agency (2017). The report emphasizes that in parts of southern Europe, including the Mediterranean basin, rising temperatures, increasing drought, and elevated carbon dioxide levels will negatively affect livestock productivity and health. Conversely, in northern Europe, a more favorable impact is anticipated, such as an extended growing season and increased forage availability, potentially benefiting livestock systems in those regions.

Rising temperatures, prolonged droughts, and increasingly erratic precipitation cycles are expected to disrupt traditional migration routes, making it more difficult for pastoralists to access sufficient grazing resources (Fernández-Giménez and Fillat, 2012). These disruptions are particularly consequential in mountainous areas where vegetation growth is already seasonal and constrained by elevation. In many regions, shifting climate conditions have altered vegetation composition and reduced aboveground biomass, thereby lowering the carrying capacity of pastures. The availability of key fodder species has declined, forcing herders to either travel longer distances in search of grazing land or invest in supplementary feed—both of which increase operational and economic burdens. These outcomes are acutely felt by goat pastoralists in Mediterranean Turkey, where pasture-based systems rely heavily on altitudinal migration and seasonal forage diversity. Moreover, extreme weather events—such as heatwaves, heavy snowfalls, and flooding—have become more frequent, posing direct threats to livestock survival. In Turkey, episodes of extreme precipitation, prolonged drought, and climatic disasters like windstorms have led to mass livestock mortality, particularly within extensive transhumant systems (Ocak Yetisgin et al., 2022). These events not only reduce herd size and productivity but also undermine household resilience, especially in rural communities with limited access to veterinary services, feed reserves, and emergency infrastructure.

The increasing unpredictability of weather patterns also poses challenges for migration planning and pasture use timing. For goat herders practicing transhumance in Mediterranean Turkey, the timing of departure to and from highland pastures—historically determined by phenological and climatic cues—has become less reliable. Early drought onset in summer, delayed forage growth in spring, or unexpected snowfall in autumn can force last-minute changes to herd movement or reduce the duration of grazing periods. These changes threaten both the ecological sustainability of rangelands and the economic stability of pastoral households. As such, climate-induced disruptions not only compromise pasture access and herd health, but also increase labor demands and management uncertainty. In this context, the sustainability of transhumant goat pastoralism in Mediterranean Turkey will increasingly depend on the integration of climate risk assessments into herd mobility planning. Developing adaptive strategies—such as diversified forage systems, flexible migration calendars, and improved sheltering infrastructure—will be essential to safeguard animal welfare and ensure the continuity of transhumance under changing climatic conditions.

COVID-19 pandemic

The COVID-19 pandemic had far-reaching consequences across various sectors of the global economy, including transhumance and pastoral production systems. These traditional livestock management practices, which rely on seasonal mobility to access grazing lands, were particularly affected due to movement restrictions, economic disruptions, and shifts in policy frameworks. While the severity of the impact varied by region, common challenges emerged, including reduced access to grazing areas, disruptions in livestock markets, and increased vulnerability of pastoralist communities. One of the most striking transformations triggered by the pandemic was the shift in how mountainous regions were perceived and utilized, further compounded by the ongoing effects of climate change. Predictions made during the crisis regarding changes in land use, economic restructuring, and increased interest in remote and tranquil areas have largely materialized (Akbas and Baykal, 2022). As restrictions limited urban tourism, many turned to rural and highland areas in search of safer outdoor experiences. However, this growing interest in mountain regions for tourism and recreation has raised concerns about the potential touristic encroachment on pasturelands, further straining resources essential for transhumant communities. The expansion of farm-based experiential and educational tourism, while presenting economic opportunities, also risks altering the function of pastoral spaces, potentially marginalizing traditional livestock farming and weakening the foundations of transhumance.

Transhumance is highly dependent on the free movement of livestock between seasonal grazing lands. However, during the pandemic, many governments implemented strict lockdown measures, leading to border closures and restrictions on interregional movement. This directly affected pastoralists who rely on cross-border migration for pasture access. COVID-19 lockdowns prevented their movement, leading to severe overgrazing in limited accessible areas and increased livestock mortality due to lack of adequate fodder. Furthermore, the pandemic caused widespread economic slowdowns, reducing demand for livestock products, particularly meat, milk, and hides. With restricted market access and lower purchasing power among consumers, pastoralists experienced declining incomes and increased poverty levels. In many parts of the world, livestock markets were temporarily closed or operated at limited capacity, disrupting sales and trade. Limited transportation options meant that even when pastoralists had livestock ready for sale, reaching buyers became a challenge. Also, in some regions, livestock prices collapsed due to oversupply in local markets where movement was restricted. Many transhumant and pastoralist groups belong to marginalized communities with limited access to healthcare and government support. The pandemic exacerbated their existing vulnerabilities by restricting access to veterinary services, food supplies, and essential health resources. Remote pastoralist communities often had little access to COVID-19 testing, treatment, and vaccinations. With disrupted livestock markets and reduced grazing access, many pastoralists struggled to feed their families. Some had to slaughter their animals for subsistence, reducing their future income-generating capacity. Pandemic-related economic slowdowns eliminated these opportunities, worsening financial distress. The COVID-19 pandemic posed unprecedented challenges for transhumance and pastoral production systems worldwide. Restrictions on movement, disrupted livestock markets, and increased vulnerability among pastoralists threatened the sustainability of traditional pastoral practices.

Transhumance and the green and circular economy: a pathway to sustainable pastoralism

Green and circular economy models offer strategic opportunities to enhance the sustainability of transhumance and pastoral production systems. In the face of intensifying climate change, biodiversity loss, and rural marginalization, integrating pastoralism into these frameworks is not merely beneficial—it is essential. Historically, transhumant communities have contributed to biodiversity conservation, carbon sequestration, and sustainable land management. Yet today, they are increasingly constrained by restrictive policies, land-use conflicts, and market pressures. The green economy, as defined by Davies (2024), emphasizes low-carbon, resource-efficient, and socially inclusive growth. Within this paradigm, transhumance functions as a climate-smart practice, fostering ecosystem regeneration, maintaining habitat connectivity, and sustaining extensive livestock production. Grazing lands managed by pastoralists act as carbon sinks, helping to offset greenhouse gas emissions (Sharifian et al., 2022). In addition, well-regulated herd mobility contributes to soil fertility, prevents erosion, and supports wildlife migration routes (Hatfield and Davies, 2006). These characteristics position transhumance as a nature-based solution for climate adaptation and land restoration. Despite these ecological contributions, transhumance remains underrepresented in national and international policy agendas. Many governments continue to prioritize intensive livestock production or conservation regimes that limit pastoral mobility, often exacerbating land tenure insecurity and resource competition (Diogo et al., 2021). To realize the full potential of transhumance within a green economy, policy frameworks must acknowledge its ecological value and embed it within broader sustainability planning. Recommended actions include developing a global policy framework for sustainable livestock systems, conducting cost–benefit comparisons of extensive and intensive models, fostering ecological niche markets, and integrating pastoralist knowledge systems into innovation platforms (McGahey et al., 2017). Since green economies aim to decouple economic growth from environmental degradation while promoting equity (UICN ve UNEP, 2014), transhumant livestock systems can become a central pillar of these goals. Likewise, the principles of the circular economy—which emphasize reuse, repair, and resource efficiency—align naturally with traditional pastoral practices. Since its formal adoption by the EU in 2018 (OREE, 2019), the circular economy has gained prominence in livestock policy. Pastoralists have long operated within closed-loop systems: livestock manure is recycled as organic fertilizer, mobile structures are repaired and reused, and water is managed through strategic seasonal distribution (Ates et al., 2024; Piemontese et al., 2024; Rodríguez Rigueiro, 2021). However, emerging threats such as plastic waste, overgrazing, and land conversion increasingly challenge the ecological integrity of these systems. Innovations—such as biodegradable feed packaging, solar-powered infrastructure, and circular waste management—can strengthen the environmental resilience and viability of transhumant systems. Ensuring that transhumance thrives within green and circular models requires a fundamental shift in governance. Policymakers must move beyond exclusionary conservation policies and adopt integrated socio-ecological approaches that promote mobility, landscape connectivity, and rural equity (Easdale et al., 2023). Legal protections for grazing rights and secure tenure systems are vital to prevent displacement. Additionally, expanding organic and climate-certified livestock schemes could enhance market access for pastoralists, while reinforcing sustainable production methods (Fernández-Giménez and Wilmer, 2024). The inclusion of indigenous and local knowledge in climate adaptation strategies is equally critical, given pastoralists' extensive experiential understanding of ecological dynamics.

As retro-innovators, transhumant communities reframe traditional practices as regenerative strategies aligned with low-carbon, circular, and inclusive sustainability paradigms. The intersection of transhumance with green and circular economy principles offers a viable, forward-looking framework for sustainable livestock development. With adequate policy support, technological innovation, and market incentives, transhumance can evolve into a climate-resilient practice that contributes to food security, rural revitalization, and ecosystem restoration. Recognizing pastoralism not as a vestige of the past but as a cornerstone of sustainable agriculture is essential for building inclusive and regenerative futures. By embedding low-carbon practices, circular resource use, and adaptive governance into pastoral systems, transhumance can continue to thrive as a model of environmental stewardship in the twenty-first century.

Preserving transhumance as cultural heritage: national realities in Turkey

International organizations such as the United Nations (UN), the Food and Agriculture Organization (FAO), UNESCO, and the European Union (EU) have taken the lead in efforts to preserve and promote pastoralism as both a cultural and ecological heritage. In parallel with these global initiatives, national governments, local administrations, universities, and regional civil society organizations have also played a role in cultural preservation. Various outreach tools—such as documentaries, websites, blogs, concerts, exhibitions, festivals, and educational programs—have been employed to raise awareness and underscore the enduring value of transhumance. While technological advancements, digitalization, and circular and green economy models offer potential opportunities for revitalizing transhumance, they have yet to make a significant impact in Turkey's mountainous regions. Unlike some countries where reverse migration from cities to rural areas is reshaping pastoral economies, Turkey has not yet experienced a comparable movement. However, tourism has begun to emerge as a major challenge, particularly in the Black Sea and Taurus Mountains, where increasing visitor activity is encroaching upon traditional grazing lands.

The transformation of transhumance in Turkey began with the motorization of access to pastures (instead of walking on foot), which significantly altered traditional pastoral practices. This mechanization changed many aspects of how transhumance had been traditionally carried out—such as the pace, duration, family involvement, labor roles (e.g., men's and women's roles), the nature of migration itself, and the socio-cultural routines that accompanied the journey. Additionally, the timing and duration of seasonal migrations have been affected, leading to disruptions in established patterns of livestock movement. These transformations have also contributed to the degradation of both tangible and intangible rural cultural heritage, threatening the continuity of knowledge and traditions that have shaped Turkey's pastoral identity for centuries.

Compared to developed countries, Turkey's institutional efforts to support transhumance remain insufficient. While some developing nations share similar structural weaknesses, a key difference is that organizations such as the UN and FAO have implemented numerous projects and aid programs to support pastoralists in regions affected by ethnic conflicts, land and water disputes, theft, and livestock diseases. These challenges are particularly pronounced in African countries, where pastoralist communities rely heavily on external support to sustain their livelihoods. Despite regional differences, one universal factor remains consistent: the central role of rural women and shepherds in sustaining transhumance culture. Across all countries, however, societal perceptions of their value and contributions vary significantly, highlighting deep contrasts in how different cultures recognize and support pastoralist traditions.

The future of transhumance in Turkey hinges on stronger institutional engagement, comprehensive policy reform, and well-designed economic incentives. Without such targeted interventions, the ongoing decline of this centuries-old practice may accelerate, leading to irreversible cultural and environmental consequences. Recognizing transhumance as both a living ecological strategy and a cultural legacy is essential for its continuity. This requires an integrated approach that combines sustainability tools, adaptive governance, and the transmission of traditional pastoral knowledge.

Conclusion

Goat transhumance in Mediterranean Turkey endures as a historically rooted yet dynamically evolving system shaped by a complex interplay of ecological, cultural, economic, and political factors. This study demonstrates that while the system retains its adaptive value—particularly in maintaining pastoral livelihoods, conserving indigenous knowledge, and supporting landscape-level ecological processes—it is increasingly vulnerable to multi-scalar pressures. Key drivers of transformation include rural depopulation, loss of traditional migration corridors, weakening intergenerational knowledge transmission, and restrictive land use policies. These dynamics are further compounded by climate variability and the absence of formal recognition for mobile pastoralism within national development strategies. Despite these challenges, transhumance remains an active contributor to rural resilience. Its embeddedness in local ecologies, gendered labor organization, and low-input mobility strategies suggest that it can offer viable alternatives to sedentary livestock production, especially under mounting environmental stress. However, the system's continuity cannot be assumed in the absence of deliberate institutional support. Legal recognition of seasonal mobility rights, reintegration of traditional pastoral routes into land-use planning, and equitable access to veterinary, financial, and market services are critical for ensuring its future viability.

The study also underscores the need to reposition transhumance within broader sustainability discourses. By aligning pastoral mobility with emerging frameworks such as the green and circular economy, new opportunities may arise for creating value-added niche markets, encouraging eco-social innovation, and reinforcing the environmental legitimacy of mobile systems. Importantly, policy reform must go hand in hand with community participation and respect for culturally embedded knowledge systems. Without such integrative and adaptive approaches, the erosion of transhumant practices will not only diminish cultural heritage but also undermine the broader resilience of agro-pastoral landscapes. The continuity of transhumance in Turkey depends on robust institutional engagement, coherent policy reform, and context-specific economic support mechanisms. Without such targeted interventions, the decline of this centuries-old pastoral system is likely to accelerate, resulting in irreversible losses to both cultural heritage and ecological integrity. Recognizing transhumance not merely as a remnant of the past, but as a dynamic socio-ecological practice, is essential for its future. Its preservation requires an integrated approach that combines sustainability-oriented tools, adaptive governance models, and the intergenerational transmission of traditional pastoral knowledge. Only through such a holistic framework can transhumance continue to contribute meaningfully to rural resilience, biodiversity conservation, and sustainable land use in marginal landscapes.

Data availability statement

Requests to access the datasets should be directed to SO sezenocak1@gmail.com.

Ethics statement

Participants were informed about the study's aims, assured confidentiality, and provided consent for recordings and photographs.

Author contributions

SO conceived and designed the study, conducted the research in collaboration with SC, and both authors contributed equally to writing and revising the manuscript. All authors reviewed the results and approved the final version of the manuscript.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

We are greatful to *Sarıkeçililer* community, for allowing us to do the study in their lands and homes, for their unconditional help during the study. We thank them for field assistance and farmers who patiently anwered our question over number of years.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

References

Adamou, O. I. (2024). *Adapting to climate risks in the Sahel: strategies for smallholder farmers in Niger*. NY, United States: eCommons Cornell University. Retrieved from: https://ecommons.cornell.edu/server/api/core/bitstreams/fddc074f-c05d-447c-a6c2-1ee4aac33fe3/content.

Akbas, F., and Baykal, F. (2022). A geographical perspective on transhumance cultures in the world. *Cograf. Derg.* 45, 195–213. doi:10.26650/JGEOG2022-1171902

Albayrak, L. (2020). *Ardahan'da yaylacılık kültürü ve yaylacılık faaliyetlerinde yaşanan sorunlar, Ardahan Değerlemeleri-2: Değerler, potansiyeller ve Yaklaşımlar*. Editor İ. Kurtbaş (Basım, Ankara: Nobel Akademi Yayınları), 159–189.

Ambarlı, D., Zeydanlı, U. S., Balkız, Ö., Aslan, S., Karaçetin, E., Sözen, M., et al. (2016). An overview of biodiversity and conservation status of steppes of the anatolian biogeographical region. *Biodivers. Conservation* 25, 2491–2519. doi:10.1007/s10531-016-1172-0

Arbuckle, B. S. (2012). Pastoralism, provisioning, and power at Bronze Age acemhöyük, Turkey. *Am. Anthropol.* 114 (3), 462–476. doi:10.1111/j.1548-1433.2012.01446.x

Arbuckle, B. S. (2014). Pace and process in the emergence of animal husbandry in Neolithic southwest Asia. *Bioarchaeology Near East* 8, 53–81.

Arbuckle, B. S., Kansa, S. W., Kansa, E., Orton, D., Çakırlar, C., Gourichon, L., et al. (2014). Data sharing reveals complexity in the westward spread of domestic animals across Neolithic Turkey. *PLoS ONE* 9, 99845. doi:10.1371/journal.pone.0099845

Arnold, E. R., and Greenfield, H. J. (2006). *The origins of transhumant pastoralism in temperate southeastern Europe: a zooarchaeological perspective from the central balkans. British archaeological reports, international series*, 1538. Oxford: Archaeo Press.

Ates, B., Özkan, Ş., Yılmaz, E., Çelik, D., Kızılhan, S., Küçüknane, S., et al. (2024). Sürdürülebilir ekonomiler için retro-yenilikçi bir bakış açısı: göçebe hayvancılık. *Yolda Girişimi, Sarıkeçililer Yaşatma ve Dayanışma Derneği, Innovation Dev. (I4D)*. Available online at: https://efaidnbmnnnibpcajpcglclefindmkaj/https://yolda.org.tr/content/2024-Gocebe-Hayvancilik-Ekonomi-Rapor_spreaded_240327_A4.pdf (Accessed January 20 2025).

Azcárate, F. M., and Hevia, V. (2023). Diagnosis of the ecological condition of the drove road network in the autonomous community of Madrid (central Spain). *Landsc. Ecol.* 38, 3537–3553. doi:10.1007/s10980-023-01713-y

Bakırcı, M. (2019). *Gerger ilçesinde (adıyaman) yaylacılığın mekânsal ve sosyo-ekonomik değişimi, uluslararası yaylacılık ve yayla kültürü sempozyumu, 26-28 eylül 2019, Giresun*, 479–498.

Barkey, K. (2008). *Empire of difference: the Ottomans in comparative perspective*. Cambridge, UK: Cambridge University Press, 342.

Bates, D. G. (1973). Nomads and Farmers: A Study of the Yoruk of Southeastern Turkey. United States: University of Michigan Press. doi:10.3998/mpub.11394916

Bhasin, V. (2011). Status of women in transhumant societies. *J. Sociol. Soc. Anthropol.* 02, 1–22. doi:10.31901/24566764.2011/02.01.01

Biernacki, P., and Waldorf, D. (1981). Snowball sampling: problems and techniques of chain referral sampling. *Sociol. Methods and Res.* 10 (2), 141–163. doi:10.1177/004912418101000205

Büyükcan Sayılır, Ş. (2012). Göçebelik, konar-göçerlik meselesi ve coğrafi bakımdan konar-göçerlerin farklılaşması (the nomadism and semi-nomadism issue and differentiation of the nomads in terms of geography). *Türk Dünyası İncelemeleri Derg.* 12 (1), 563–580.

Coppock, D. L., Ellis, J. E., and Swift, D. M. (1986). Livestock feeding ecology and resource utilization in a nomadic pastoral ecosystem. *J. Appl. Ecol.* 23, 573. doi:10.2307/2404037

Davies, J. (2024). Opportunities and challenges of the green transition for pastoralism and Indigenous people in Africa. Retrieved from YRDC.

Denzin, N. K. (1978). *The research act: a theoretical introduction to sociological methods*. 2nd ed. McGraw-Hill.

Diogo, R. V. C., Dossa, L. H., Vanvanhossou, S. F. U., Abdoulaye, B. D., Dosseh, K. H., Houinato, M., et al. (2021). Farmers' and Herders' perceptions on rangeland management in two agroecological zones of Benin. *Land* 10 (4), 425. doi:10.3390/land10040425

Easdale, M. H., Michel, C. L., and Perri, D. (2023). Biocultural heritage of transhumant territories *agric. Hum. Values*. *Agric. Hum. Values* 40, 53–64. doi:10.1007/s10460-022-10361-y

Ertas, N. (2020). Yayla ve mera yasaklarının küçükbaş hayvancılık faaliyetleri üzerindeki etkisi: van örneği. *Doğu Coğrafya Derg.* 44, 183–200.

Esgalhado, C., Pinto-Correia, T., Targetti, S., Napoléone, C., and Rivera, M. (2024). Sustaining altitude pastures in Mountain Landscapes–A fuzzy cognitive model approach. *Sci. Total Environ.* 931, 172930. doi:10.1016/j.scitotenv.2024.172930

European Environment Agency, (2017). *Trends and projections in Europe 2017: tracking progress towards europe's climate and energy targets*. Luxembourg: Publications Office of the European Union. Available online at: https://www.eea.europa.eu/en/analysis/publications/trends-and-projections-in-europe-2017 (Accessed 15 May 2025).

Fernández-Giménez, M. E., and Fillat Estaque, F. (2012). Pyrenean pastoralists' EcologicalKnowledge: documentation and application to NaturalResource management and adaptation. *Hum. Ecol.* 40, 287–300. doi:10.1007/s10745-012-9463-x

Fernández-Giménez, M. E., Venable, N. H., Angerer, J., Fassnacht, S. R., Reid, R. S., and Khishigbayar, J. (2017). Exploring linked ecological and cultural tipping points in Mongolia. *Anthropocene* 17, 46–69. doi:10.1016/j.ancene.2017.01.003

Fernández-Giménez, M. E., and Wilmer, H. (2024). Towards a theory of pastoralist and rancher identity: Insights for understanding livestock systems in transformation. *Agric. Hum. Values*. doi:10.1007/s10460-024-10641-9

Garcia-Ruiz, J. M., and Lasanta-Martinez, T. (1990). Land-use changes in the Spanish pyrenees. *Mt. Res. Dev.* 10 (5), 267–279. doi:10.2307/3673606

Gokbilgin, T. (1957). Rumeli'de yörükler, tatarlar ve Evlad-ı fatihan, osman yalçın matbaası, İstanbul (In Turkish).

Gurung, D. B. (2019). Stumbling transhumance pastoralism in the shadow of globalization and the state. *Contemp. Soc. Sci.* 28 (3), 109–118.

Gurung, D. B., and Seeland, K. (2008). Ecotourism in Bhutan: extending its benefits to rural communities. *Ann. Tour. Res.* 35, 489–508. doi:10.1016/j.annals.2008.02.004

Hadjigeorgiou, I., and Casas, R. (2011). Past, present and future of transhumancia in Spain: nomadism in a developed country. *Pastor. Res. Policy Pract.* 1 (1), 24. doi:10.1186/2041-7136-1-24

Hammer, E. L., and Arbuckle, B. S. (2017). 10,000 years of pastoralism in Anatolia: A review of evidence for variability in pastoral lifeways. *Nomadic Peoples* 21 (2), 214–267. doi:10.3197/np.2017.210204

Hatfield, R., and Davies, J. (2006). *Global Review of the Economics of Pastoralism*. Nairobi, KY: World Initiative for Sustainable Pastoralism, IUCN. Available online at: https://www.iucn.org/content/report-global-review-economics-pastoralism (Acessed March 1, 2017).

"Herodotus" 5 BC. Heredot Tarihi (2016). *İstanbul, Türkiye İş bankası kültür yayınları*, 832. (In Turkish).

Hevia, V., Azcarate, F. M., Oteros-Rozas, E., and Gonzalez, J. A. (2013). Exploring the role of transhumance drove roads on the conservation of ant diversity in mediterranean agroecosystems. *Biodivers. Conserv.* 22, 2567–2581. doi:10.1007/s10531-013-0539-8

Hilty, J., Worboys, G. L., Keeley, A., Woodley, S., Lausche, B., Locke, H., et al. (2020). "Guidelines for conserving connectivity through ecological networks and corridors. *Best Pract. Prot. Area Guidel. Ser. No. 30. UICN Int. Union Conservation Nat. Nat. Resour.* Available online at: https://portals.iucn.org/library/sites/library/files/documents/PAG-030-Es.pdf.

İnalcık, H. (2014). *The Yörüks: Their Origins, Expansion And Economic Role. Cedrus,* 2, 467–495. doi:10.13113/CEDRUS.201406472

Krätli, S., and Schareika, N. (2010). Living off uncertainty: the intelligent animal production of dry land pastoralists. *Eur. J. Dev. Res.* 22, 605–622. doi:10.1057/ejdr.2010.41

Lasanta, T., Arnáez, J., Pascual, N., Ruiz-Flaño, P., Errea, M. P., and Lana-Renault, N. (2017). Space–time process and drivers of land abandonment in Europe. *Catena* 149, 810–823. doi:10.1016/j.catena.2016.02.024

Lindner, R. P. (1983). *Nomads and Ottomans in medieval Anatolia*. Bloomington: Indiana University, 51.

Linstädter, A., Kemmerling, B., Baumann, G., and Kirscht, H. (2013). The importance of being reliable – local ecological knowledge and management of forage plants in a dryland pastoral system (morocco). *J. Arid Environ.* 95 (2), 30–40. doi:10.1016/j.jaridenv.2013.03.008

Malzac, A., Jouven, M., and Fabre, P. (2024). La mobilité des troupeaux dans le sud de la France: hier, aujourd'hui et demain. *Inrae Prod. Anim.* 37, 7673. doi:10.20870/productions-animales.2024.37.1.7673

Manzano-Baena, P., and Salguero-Herrera, C. (2018). Mobile pastoralism in the mediterranean: arguments and evidence for policy reform and to combat climate change. Available online at: http://medconsortium.org/wp-content/uploads/2017/12/MobilePastoralismMotherDocument_December2017_ForWeb.pdf.

McGahey, D., Davies, J., Hagelberg, N., and Ouedraogo, R. (2017). *Pastoralisme et economie verte-un lien naturel? Etat des lieux, défis et implications en matière de politique*. Nairobi, KY: UICN et PNUE.

Mediterranean Consortium for Nature and Culture (2013). *A rapid assessment of cultural conservation practices in the mediterranean*. Editor Zogib, L. (Gland, Switzerland: DiversEarth).

Moktan, M. R., Norbu, L., Nirola, H., Dukpa, K., Rai, T. B., and Dorji, R. (2008). Ecological and social aspects of transhumant herding in Bhutan. *Mt. Res. Dev.* 28 (1), 41–48. doi:10.1659/mrd.0802

Nandris, J. G. (1985). The stina and the katun: foundations of a research design in european highland zone ethnoarchaeology. *World Archaeol.* 17, 256–268. doi:10.1080/00438243.1985.9979966

Nori, M., Taylor, M., and Sensi, A. (2008). Browsing on fences: Pastoral land rights, livelihoods and adaptation to climate change. *IIED Issue Pap.* 148. Available online at: https://pubs.iied.org/12543iied (Accessed January 10, 2025).

Noy, C. (2008). Sampling knowledge: the hermeneutics of snowball sampling in qualitative research. *Int. J. Soc. Res. Methodol.* 11 (4), 327–344. doi:10.1080/13645570701401305

Ocak, S. (2016). Transhumance in central Anatolia: a resilient interdependence between biological and cultural diversity. *J. Agric. Environ. Ethics* 29, 439–453. doi:10.1007/s10806-016-9613-z

Ocak Yetisgin, S., Önder, H., Şen, U., Piwczyński, D., Kolenda, M., Sitkowska, B., et al. (2022). Farmers' risk perception on climate change: Transhumance vs. semi intensive sheep production systems in Türkiye. *Animals* 12, 1992. doi:10.3390/ani12151992

Oksay, S., and Çelik, N. (2011). The origins of contemporary encounters between the west and turks. *Hist. Stud. Int. J. Hist.* 3 (2), 1–16.

OREE (2019). *Économie circulaire and alimentation: des ınitiatives franciliennes pour tous les goûts*. Paris: Comité Francilien de l'Economie Circulaire.

Oteros-Rozas, E., Ontillera-Sánchez, R., Sanosa, P., Gómez-Baggethun, E., Reyes-García, V., and González, J. A. (2013). Traditional ecological knowledge among transhumant pastoralists in mediterranean Spain. *Ecol. Soc.* 18 (3), art33. doi:10.5751/es-05597-180333

Patton, M. Q. (1999). Enhancing the quality and credibility of qualitative analysis. *Health Serv. Res.* 34 (5 Pt 2), 1189–1208.

Piemontese, L., Terzi, S., Di Baldassarre, G., Menestrey Schwieger, D. A., Castelli, G., and Bresci, E. (2024). Over-reliance on water infrastructure can hinder climate resilience in pastoral drylands. *Nat. Clim. Chang.* 14, 267–274. doi:10.1038/s41558-024-01929-z

Primi, R., Bernabucci, G., Evangelista, C., Viola, P., Girotti, P., Spina, R., et al. (2025). Ecosystem services linked to extensive sheep and goat farming in Mountain areas: a global literature analysis using text mining and topic analysis. *Animals* 15 (3), 350. doi:10.3390/ani15030350

Rodríguez Rigueiro, F. J. (2021). Agroforestry innovation and CAP, impact on climate change, bio-economy and circular economy. *Univ. Santiago Compostela*. Available online at: https://hdl.handle.net/10347/25210 (Accessed May 10 2025).

Rosa García, R., Celaya, R., García, U., and Osoro, K. (2012). Goat grazing, its interactions with other herbivores and biodiversity conservation issues. *Small Ruminant Res.* 107, 49–64. doi:10.1016/j.smallrumres.2012.03.021

Sahin, I. (2006). *Nomads in the ottoman empire*. İstanbul (In Turkish): Eren Yayincilik, 45.

Şekercioğlu, Ç. H., Anderson, S., Akçay, E., Bilgin, R., Can, Ö. E., Semiz, G., et al. (2011). Turkey's globally important biodiversity in crisis. *Biol. Conserv.* 144, 2752–2769. doi:10.1016/j.biocon.2011.06.025

Sensoy, S., and Demircan, M. (2016). State of the climate in Turkey in 2015. Available online at: http://www.mgm.gov.tr/files/en-US/State_of_the_Climate_in_Turkey_in_2015.pdf.

Sharifian, A., Fernández-Llamazares, Á., Wario, T., Molnár, Z., and Cabeza, M. (2022). Dynamics of pastoral traditional ecological knowledge: A global state-of-the-art review. *Ecol. Soc.* 27 (1), 14. doi:10.5751/ES-12918-270114

Siddiq, A. B., and Şanlı, S. (2020). Animals and pastoral groups in the mountainous ömerli district of southeast Anatolia. *Anthrozoös* 33 (2), 153–173. doi:10.1080/08927936.2020.1719754

Thevenin, M. (2011). Kurdish transhumance: pastoral practices in south-East Turkey. *Pastor. Res. Policy Pract.* 1, 23. doi:10.1186/2041-7136-1-23

Toplu, H. D. O., and Altınel, A. (2008). Some production traits of Indigenous hair goats bred under extensive conditions in Turkey. 1st communication: Reproduction, milk yield and hair production traits of does. *Arch. Tierz., Dummerstorf* 51 (5), 498–506. doi:10.5194/aab-51-498-2008

TSMS (2024). *Turkish state meteorological service. Climate data for seydişehir and upland regions of Konya province*. Türkiye: Ministry of Environment, Urbanization and Climate Change. Retrieved from: https://www.mgm.gov.tr.

UICN ve UNEP (2014). Le pastoralisme et l'economie verte-un lien naturel? International Union for Conservation of Nature (UICN) and UN Environment Programme (UNEP).

Yilmaz, O., Kor, A., Ertugrul, M., and Wilson, R. T. (2012). The domestic livestock resources of Turkey: Goat breeds and types and their conservation status. *Anim. Genet. Resources/Ressources génétiques animales/Recursos genéticos Anim.* 51, 105–116. doi:10.1017/s2078633612000331

Zagata, L., Sutherland, L., Hrabák, J., and Lostak, M. (2020). Mobilising the past: towards a conceptualisation of retro-innovation. *Sociol. Rural.* 60 (3), 639–660. doi:10.1111/soru.12310

Zanon, T., Gruber, M., and Gauly, M. (2022). Walking distance and maintenance energy requirements of sheep during Mountain pasturing (transhumance). *Appl. Animal Behav. Sci.* 255, 105744. doi:10.1016/j.applanim.2022.105744

Odessa centre | Pastoralism Research, Policy and Practice

TYPE Original Research
PUBLISHED 18 August 2025
DOI 10.3389/past.2025.15020

OPEN ACCESS

EDITED BY
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RECEIVED 02 June 2025
ACCEPTED 05 August 2025
PUBLISHED 18 August 2025

CITATION
Imoli N (2025) Perceiving the climate crisis: pastoral futures and ecosystem compensation in post-socialist Mongolia.
Pastoralism 15:15020.
doi: 10.3389/past.2025.15020

Perceiving the climate crisis: pastoral futures and ecosystem compensation in post-socialist Mongolia

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This paper presents findings from ethnographic research on post-socialist herding groups in Mongolia, situated within the broader context of the climate crisis. The transition to a market economy in the 1990s – marked by livestock privatization and the dissolution of herder collectives – resulted in fragmented herding practices and intensified pressure on rangelands already affected by mining and climate change. In response to these challenges, Pasture User Groups (PUGs) were established with the support and initiative of donor organisations. This study draws on fieldwork conducted among members of a PUG engaged in pasture rehabilitation and biodiversity compensation in Bayangol *sum*, Selenge *aimag*. It explores how herders perceive climate change, ecological restoration, and the narratives that underpin such interventions, particularly in relation to their livelihoods and perception of the landscape they inhabit. The findings illustrate how herders interpret and respond to environmental change through socially embedded narratives and adaptive practices, revealing the dynamic interplay between lived experience, collective memory, and global climate discourses in a context of socio-economic uncertainty.

KEYWORDS

Mongolian pastoralism, climate change, pasture user group, landscape perception, pasture rehabilitation

Introduction

In this paper, I explore the differences I observed between institutional narratives of "climate change" – particularly as embodied in rangeland management and biodiversity conservation projects – and the perceptions of these same phenomena among mobile herders involved in one such project. The paper is based on the ethnographic fieldwork I conducted for my PhD, from April to November 2023, among herding families who are members of the Dorgont Pasture User Group (PUG), located in Bayangol *sum*, Selenge *aimag*, in northern Mongolia.

I contextualise the establishment of Pasture User Groups within the broader political, economic and social transformations that followed the end of socialism in Mongolia. These include the retreat of the state from the pastoral economy after the privatisation of livestock, the dismantling of the so-called "dual control" system for managing customary pastoral production and of herders' collectives (*negdel*s), and the transition to a free-market economy, as well as the occurrence, in the 2000s, of severe *zud*s – climate-induced socio-economic disasters in which extreme cold, snow, or drought prevent livestock from accessing pasture in winter, resulting in high animal mortality. Zuds have often been framed within institutional narratives of climate change, which, while not inaccurate, tend to abstract the phenomenon from the situated knowledge and embodied experiences through which herders encounter and interpret environmental hardship. Such framings risk overlooking how climate variability is locally perceived in relation to shifting social, economic, and institutional landscapes, rather than through measurable climatic and ecological trends.

The intense rainfall during the summer of my fieldwork, which caused flooding of the Haraa River – along which most herder's summer camps were located – created the conditions to investigate herder's perceptions of the climate crisis. In particular, it allowed me to explore the contrast between their framing of the issue, grounded in phenomenologically experienced weather, and "institutional" approaches based on the more abstract and detached concept of climate. Instead of counterposing "scientific knowledge" and "traditional beliefs," I propose a more nuanced approach loosely inspired by Eduardo Viveiros De Castro's notion of *controlled equivocation* (Viveiros De Castro, 2004), which seeks out productive tensions between divergent conceptual worlds. As Viveiros De Castro (2019), p. S304 argues, these tensions can serve as generative spaces "situated in the gap between languages, the only location [. . .] where we can properly address the Anthropocene world." The goal, as the author clearly states, is neither to change *our* beliefs nor *theirs*, least of all taking them as models for our future, transforming their status from being our victims to our redeemers. Rather, anthropology must recognize others' unique socio-political realities and ontological visions as equal to our own – especially in the *patchy Anthropocene* (Tsing, 2015), where diverse ways of being inevitably intersect.

The use of the concept of "climate change," central to many institutional approaches and donor interventions, has been sharply criticised by philosopher Timothy Morton. They argue that "climate change" is not a neutral descriptor but a euphemism that fails to capture the existential gravity of the crisis (Morton, 2013). Moreover, by implying a distant and abstract phenomenon, it obscures its local manifestations and contributes to a sense of disconnection that hinders effective action. Rather than treating climate change as a clear-cut explanatory principle – an approach that inevitably oversimplifies the issue and gives the false impression that it is a manageable problem – they proposes that it should be understood as a *hyperobject* – entities that they define as so vast in temporal and spatial scale that exceeds conventional human understanding, and demands new ways of thinking and talking.

I conclude by examining how these dynamics reverberate in a key aspect of winter preparation – the accumulation of fuel used for cooking and heating the yurt – and how they are intertwined with the cooperative relationships among herders, an important component of PUGs, and more broadly, with the socio-economic uncertainty and inability to act experienced by many of my interlocutors. I interpret these final two aspects through the lens of what Arjun Appadurai terms "the capacity to aspire" – a form of navigational capacity that is "unequally distributed among wealthier and poorer communities, that allows people to make their way from more proximate needs to more distant aspirational worlds" (Appadurai, 2013, p. 213) – in dialogue with the two temporal orientations described by Lars Højer, namely "apathy" and "revolution" (Højer, 2018), which help further contextualise herders' responses.

These theorists were chosen because their works offer conceptual frameworks attuned to ambiguity, fragmentation, and asymmetry – conditions that reflect the lived experiences of my interlocutors navigating environmental change and socio-economic uncertainty. Eduardo Viveiros de Castro's notion of *controlled equivocation* allows for a non-reductive engagement with divergent ontologies, helping to interpret the tensions between institutional climate narratives and herders' phenomenological weather talk not as misunderstandings, but as generative differences. Anna Tsing's concept of the *patchy Anthropocene* underscores the uneven, contingent nature of global ecological processes, providing a way to understand how herders' situated practices and perceptions emerge within disrupted but interconnected landscapes. Timothy Morton's framing of climate change as a *hyperobject* highlights its overwhelming scale and temporal abstraction, which contrasts with herders' focus on tangible variations in weather and pasture conditions. This emphasis on abstraction in dominant climate discourse can also obscure the extent to which climate-related challenges are deeply entangled with structural economic hardship and the retreat of the state in the post-socialist context. Arjun Appadurai's idea of the *capacity to aspire* illuminates how economic precarity and institutional abandonment – only partially addressed by the creation of new institutions such as the PUGs – constrain my interlocutors' imaginative horizon and ability to act, while Lars Højer's temporal orientations of *apathy* and *revolution* help to interpret the affective registers through which uncertainty and deferred agency are experienced.

Post-socialist institutional transformation

One of the reasons I selected Bayangol *sum* in Selenge *aimag* as the site for my fieldwork was to examine how cooperation unfolds among herding families in post-socialist Mongolian pastoralism, with particular attention to the interplay between informal, neighbourhood- and kinship-based exchanges of labour and more institutionalised forms of cooperation facilitated by formal structures such as the Pasture User Groups. The household that hosted me, along with others I engaged and worked with, are members of the Dorgont Pasture User Group. PUGs are a type of community-based rangeland management institution (CBRM)[1] (Allegretti et al., 2015; Tumur et al., 2020) embedded within local government structures, that have been created under the initiative and with the support of donor organisations – such as the Swiss Agency for Development and Cooperation (SDC) – across Mongolia in the last couple of decades. These groups, composed of herders who share access to specific pastures, are formalized through a participatory process that establishes territorial boundaries and is approved by the *sum*[2] government. A central element of PUG formation involves drafting pasture management plans, which serve as basis for land-use contracts for herders. These plans regulate seasonal rotation, resting of pasture, water point maintenance, and the fencing of areas designated for haymaking (Allegretti et al., 2015).

The emergence of institutions capable of implementing collective land management regulations must be understood within the broader historical, economic and political context of Mongolia's post-socialist transition[3]. Following the collapse of the Soviet Union and the disintegration of the Council for Mutual Economic Assistance (COMECON) – Mongolia's primary economic partner – the country underwent a rapid neoliberal transformation in the early 1990s, often referred to as "shock therapy." These reforms, called in Mongolian *shinjilgee*[4], "thrusted Mongolia and other post-socialist states into a situation marked by the near virtual society-wide collapse of state-based institutions, entitlements, social services, and property regimes rupturing the channels of social and economic life" (Murphy, 2011, p. 48). The effects of this transition included deep economic crisis, hyperinflation[5], soaring poverty, and mass unemployment (Sneath, 2018).

Among the most significant changes that happened in Mongolian pastoralism during the 1990s were the privatisation of livestock – which, apart from a small number of privately owned animals for domestic use, had been state-owned during the collective period – and the dissolution of the herder collectives (*negdel*s), which had long formed the institutional foundation of Mongolia's pastoral economy. At a deeper level, the reforms entailed the dismantling of the so-called "dual control" system for managing customary pastoral production (*ulamjlalt mal aj ahui*). Inherited from the pre-collective period, this system integrated the management of the key components of pastoral productions – livestock, labour and land – through interdependent forms of control: formal control, exercised by the state through jurisdictional residency and taxation of production; and informal control, whereby herders managed production and pasture use. It enabled flexibility of movement and the coordination of the components of production, helping to maintain a balanced ratio between livestock and pastoral resources within a given jurisdiction. The dismantling of the integrated management of the components, however, "disembedded the pastoral economy from its social, political, and ecological foundations" (Undargaa and McCarthy, 2016, p. 377).

Following the economic crisis and the ensuing unemployment, many former workers from the collapsed economic sectors and uneconomic state-owned enterprises migrated into the countryside and took up herding as livelihood (Griffin, 1995; Rossabi, 2005). This process was facilitated by new policies that liberalised the labour market and granted the citizens the right to move freely (Undargaa, 2023). As a result, the livestock population, which had remained almost constant during the last 20 years of socialism, increased by 36% in just 10 years (from 24.7 million in 1989 to 33.6 million in 1999)[6], while the number of herding households doubled between 1990 and 1997 (Mearns, 2004).

Despite calls from international development institutions – such as the Asian Development Bank and the World Bank – and domestic political actors for the private ownership of land (Goldstein and Beall, 1994; Sneath, 2002), the state maintained exclusive control over land. Indeed Mongolia's 1992 Constitution states that natural resources such as pasture must remain as a people's asset and state property (Undargaa, 2023). The 1994 Land Law upheld this

1 For a broader analysis on community-based natural resource management (CBNRM) see Brosius, Tsing and Zerner (2005).

2 *Sums*, often translated as "districts," are the intermediate administrative divisions of Mongolia. They are smaller than the twenty-one "provinces" (*aimags*) and comprise multiple *bags*. Their role includes overseeing community services, organising local development and managing resources within the area.

3 See Sneath (2002) for a critique of the idea of *transition* from the inefficient socialist system to the dynamic market economy based on the notion that the economic sphere should be emancipated from the political structure. My use of the term *transition* follows Daniel Murphy's formulation in his doctoral dissertation on the impacts of neo-liberal political transformations on household vulnerability in the context of hazardous events. Murphy clarifies that his use of *transition* "implies not some naturalized, unquestioned path to capitalism envisioned by neo-liberals but rather the practices that attempt to *produce* such a path" (2011, p. 47, emphasis in original).

4 These reforms, similar to those promoted in poor countries during the 1970s and the 1980s by the International Monetary Fund and the World Bank, included the "privatization of public assets, price liberalization, cutting state subsidies and expenditure, currency convertibility, and the rapid introduction of markets" (Sneath, 2003, p. 441).

5 Reaching 268,4% in 1993, according to the International Monetary Fund, https://www.imf.org/en/Countries/MNG, last accessed on 04/04/2025.

6 The same number then peaked at 71.1 million in 2022. All data on livestock numbers were retrieved from the National Statistics Office of Mongolia (*Ündesnii Statistikiin Horoo*), available at https://1212.mn, last accessed on 03/04/2025.

principle while introducing statutory exclusive private rights in the form of leases, which allowed herders to obtain exclusive use of winter and spring encampments (Fernández-Giménez and Batbuyan, 2004). In a context of shrinking available pastoral areas – linked to the aforementioned surge in livestock and herder numbers, as well as urban-to-rural migration – this encouraged herders to increase the number of encampments as families sought to secure access to more pasture (Undargaa, 2016).

Andrei Marin argues that the retreat of the state that happened after the fall of socialism led "Mongolian pastoralism to "fall back on itself" in order to adapt to the new economic system" (Marin, 2008, p. 76). As Undargaa and McCarthy (2016) note, the state developed a decentralized co-management system, sharing responsibility for managing resources between government offices (at the *bag*, *sum*, and *aimag* levels) and local self-governing bodies like the public meeting (*hural*). In practice, *sum* governments kept the power "to arbitrarily interpret and enforce the land law" (p. 372). However, they were mostly ineffective or inactive in managing herders' customary pasture use (Fernández-Giménez, 2001).

The disbanding of the *negdel*s – which among their functions had regulated pastureland use minimising environmental damage, often respecting pre-existing customary rights – and the end of the "dual control" system, left a regulatory void in the area of pasture management (Tumur et al., 2020). This issue was addressed by donor agencies through the creation of new institutions, in an attempt to establish a new nested relationship between state and customary system. However, this strategy overlooked the fact that "the state and customary forms had already been integrated into a single, historically tested and socially embedded form of pastoral production and resource management" (Undargaa and McCarthy, 2016, p. 375). This approach became especially evident after a consecutive series of *zud*s struck the Mongolian pastoral economy between 1999 and 2002.

*Zud*s and land management policies

A *zud* is a climate-induced socio-economic disaster in which extreme winter conditions[7] – particularly when following a summer draught (*gan*) – lead to abnormally high livestock mortality (Janes and Chuluundorj, 2015; Kang et al., 2015). Between 1999 and 2002, the total number of livestock dropped by almost 10 million (from 33.6 million to 23.9 million), forcing approximately 50 thousand households out of the pastoral economy. Such a high impact must be understood in the context of the aforementioned surge in the number of herding households after the transition, the limited herding experience of many of these new herders, and the absence of adequate support. Many of those affected migrated to urban areas in search of employment (Murphy, 2011). Due to the deep interconnections between rural and urban social systems and economies (Humphrey and Sneath, 1999), the impacts of the *zud*s extended beyond herding communities, triggering broader socio-economic disruptions. Having lost their livestock to the *zud*, many of these new herders were forced to abandon pastoralism – which had served as an alternative to unemployment – and return to urban areas, now without prospects for work or support. The effect on the economy manifested in a substantial drop in Mongolia's GDP and high poverty rate. Crucially, these developments were not the result of herders' individual choices of failures, but of structural vulnerabilities exacerbated by the withdrawal of state support enacted during the "shock therapy." This situation exposed already precarious populations to significant health problems (Janes et al., 2006), as well as increases in crime and violence, malnutrition, maternal mortality, depression and suicide (Rossabi, 2005; Janes and Chuluundorj, 2015).

While *zud*s have always been part of Mongolia's ecological history, the increased frequence of major *zud*s that happened in the last thirty years (Janes and Chuluundorj, 2015, p. 28) – along with their scale, the difficulty for herders to rely on traditional knowledge to predict *zud*s due to changing climatic conditions (Soma and Schlecht, 2018), and the social problems caused by the 1999–2002 and 2009–2010 *zuds* – has generated multiple explanations. These range from long-term climate variability, anthropogenic climate change, environmental degradation and desertification. The latter is attributed by some to the broader climate crisis, and by others to more immediate human-induced causes, such as overpopulation, overstocking and grazing mismanagement (Murphy, 2011).

In the context of the aforementioned retreat of the state from the pastoral sector, the dismantling of the "dual control" system, and the new role herders are expected to play in the free-market economy, the important argument put forward by Janes and Chuluundorj (2015), p. 29 – that *zud*s are not "natural" hazards independent of human agency, but rather the result of interacting ecological and social forces – has somehow been distorted in policy discourse, shifting the responsibility for the dire consequences of *zud*s onto the herders themselves. They have been blamed for either their supposed laziness and consequent poor management or excessive greed, resulting in pasture overuse and degradation (Ericksen, 2014).

7 Mongolian herders speak of different kind of *zud* depending on the weather conditions that cause livestock deaths. Heavy snowfalls that prevent animals to reach the underneath grass cause a "white *zud*" (*tsagaan zud*); a "black *zud*" (*har zud*) happens for a lack of water in snowless winters that follow summer droughts; during an "iron *zud*" (*tömör zud*) livestock cannot graze because of the hard ice sheet caused by the thawing and subsequent refreezing of the snow cover; in a "cold *zud*" (*hüiten zud*) animals die for the extreme low temperature, often combined with strong winds that weaken the herds; a "hoof *zud*" (*tuurain zud*), not characterised by weather but by human induced conditions, results from overgrazing or pasture degradation resulting from trampling, often by animals coming from other *sums* or *aimags*; a "combined *zud*" (*havsarsan zud*) happens with a combination of adverse conditions, like the white and cold *zuds* of 1999–2000.

This framing – based on a misreading of the Mongolian landscape that misconstrued the natural resource problem as one of "open access" or a lack of property rights – has supported renewed calls for the privatisation of rural land as a means to address these issues by curbing perceived "bad behaviours." Development agencies and aid organisations have proposed interventions that draw on narratives of climate change and herder-induced degradation (Murphy, 2011). These followed a period (1993–2006) during which the Mongolian government joined fourteen international environmental conventions and developed twenty-seven environmental policies and programmes, prompting a proliferation of conservation initiatives (Ichinkhorloo et al., 2017). However, as Ahearn et al. (2017) observe, many of these interventions are shaped by international development discourses skewed by misconceptions about mobile pastoralists' livelihoods and land-use practices. Drawing upon static-equilibrium model's concepts of "tragedy of the commons" (Hardin, 1968; cfr. Ostrom, 1990) and carrying capacity, these projects often fail to recognise "that the Mongolian steppe ecosystem is for the most part a highly variable ecosystem in disequilibrium" (Okayasu et al., 2011; Janes and Chuluundorj, 2015). Moreover, they are not informed on recent studies on the beneficial impact of light to moderate grazing on carbon sequestration (Deng et al., 2023), on soil health (Byrnes et al., 2018) and the reassessment of its previously overestimated negative impact on species richness and diversity (Herrero-Jáuregui and Oesterheld, 2018).

It was in this context that community-based rangeland management institutions like the PUGs were established across the rural countryside. In 2015, the Mongolian National Federation of Pasture User Groups (MNFPUG, *Mongolyn belcheer ashiglagchdyn negdsen holboo*) was founded under the Green Gold Pasture Ecosystem Management Project, funded by the Swiss Agency for Development and Cooperation (SDC).

At the core of its rangeland restoration policy, is the voluntary "rangeland user agreement" (RUA), that is established between local government and PUGs, where they negotiate on seasonal grazing boundaries, livestock stocking rates, and herd age structure and composition. The RUA serves as the foundation for creating yearly grazing and livestock management plans, defining the duties of herders and local authorities, and outlining mechanisms for enforcement. RUAs are expected to reduce stocking rates, alter age structure via the offtake of old and unproductive animals, and encourage diversification of herd composition.

Beyond the development and implementation of a model organisation to assist herders in building their institutions, MNFPUG's work also include a research component focused on rangeland monitoring and management; the improvement of the legal framework; the establishment of credit and savings cooperatives; and a certification and tracking system called "Responsible Nomads," which ensures the origin, quality and safety of livestock products based on various indicators such as pastures condition, animal health and wellbeing, raw materials quality and environmental sustainability.

On its website[8], MNFPUG states that it represents over 80 thousand members, and coordinates a nationwide network of 1,445 PUGs, 156 *Sum* Association Pasture User Groups (APUGs) and 18 *Aimag* Federation of Pasture User Groups (AFEDs). Dashbal et al. (2023) report that 1,575 PUGs had been established at the time of their writing across 184 *sums* (56% of all *sums*). They add that Rangeland Use Agreement (RUAs) had been signed with the soum governor for 1,262 PUGs (80%). However, only about 60% of PUGs with RUAs had successfully implemented management practices informed by monitoring data. Beyond the difficulty of assessing how many of these PUGs are actually operational and how effectively they function, an independent audit conducted in 2021 (Borsy et al., 2021) observed that rangeland improvements remained localised. The audit further noted that while some PUGs were considered sustainable, many were financially very weak and lacked operational capacity, leaving them dependent on continued donor support.

MNFPUG also collaborates with mining companies in implementing land reclamation and biodiversity projects. One such initiative – the Dorgont Pastureland and Bortolgoi Range Forest Ecosystem Compensation Project – involves the Dorgont PUG herders with whom I lived during fieldwork. Funded by Boroo Gold[9], a gold mine located about 40 km south of my research site, the project aims to enhance the quality and productivity of pastures through activities such as rotational grazing, haymaking and green fodder planting. It also supports smaller sub-projects, such as leather crafting, dairy processing (*tsagaan idee*) and beekeeping, involving few selected families.

Fieldwork and methods

After learning about the "Dorgont Pastureland and Bortolgoi Range Forest Ecosystem Compensation Project" on the MNFPUG's website, I reached out to the organisation to inquire about the possibility of conducting fieldwork with herders involved in the initiative. Following a series of email exchanges and conversations, they kindly agreed to put me in contact with participating families. This is how I was introduced to Yadamjav, the father of the household that hosted me during my fieldwork in Bayangol *sum*, Selenge *aimag*, from April to November 2023. He and his wife, Enh-Oyuun, both in their late

8 http://en.greenmongolia.mn/scope-of-work; last accessed on 29/06/25.

9 Boroo Gold was operated until 2018 by the Canadian mining company Centerra Gold Inc. and is now a subsidiary of OZD ASIA PTE Ltd., a Singapore-based private company.

40s, lived there by themselves, occasionally joined on weekends and during the summer by their three younger children, two daughters and a son, who live and study in Darhan, one of Mongolia's largest cities, about an hour's drive away. Their eldest daughter lived in Ulaanbaatar, where she graduated in psychology during the year I stayed in Bayangol *sum*. The other herders I mention by name in this paper, Batnyam and Otgon, are two of the household heads with whom I interacted the most, initially due to their friendship with my host father and the proximity of our encampments. Over the months of the fieldwork, I developed deeper relationships with both of them that extended beyond our shared connection to Yadamjav. Batnyam, a *myangat malchin* (a herder with more than a thousand heads of livestock), often came to visit me early in the morning for a chat and a cup of moka coffee. Especially after the flooding, when he and his family relocated their two yurts near my host family's, Otgon spent many summer afternoons with me playing chess, drinking, smoking, and talking about a wide range of topics. His family, much less wealthy than Batnyam's, is related to Yadamjav's older sister's mother-in-law.

This fieldwork period was preceded by a 4-month stay in the capital (from June to October 2022) to refresh my Mongolian language skills, which had grown quite rusty after an 8-year hiatus since I first studied the language for my master's thesis research. This preparation proved essential, as all my interlocutors spoke only Mongolian and, given the length and immersive nature of the fieldwork, I did not rely on interpreters.

The agreement with my host family was that I would attempt to "repay" their hospitality and the sharing of their knowledge by contributing to the household in various ways: helping with herding tasks as my initially non-existent skills gradually improved; teaching English to their children (alongside two of Otgon's daughters) when they returned home from school on weekends and during the summer, and by buying groceries. My daily chores included helping Enh-Oyuun with milking the cows in the morning and evening, cleaning dung from around the milking pen, and watering the sheep and goats at the Haraa river. I also frequently assisted Enh-Oyuun with cooking and participated in tasks that required cooperation with other herders – such as collecting compressed and dried dung used as fuel, castrating animals, and shearing sheep – or with urban-dwelling relatives, including goats combing for cashmere and haymaking.

The Dorgont PUG is divided into three smaller sections – Eriin Nuruu, Bayangol, and 179th Pass - based on geographical area and the type of livestock kept. These divisions do not correspond to the administrative subdistricts (*bag*s) of Bayangol *sum*. The group consists of 20 herding households, half of whom are not originally from the area, but migrated to Bayangol *sum* from the western Uvs *aimag* over the past two decades. They are part of the wave of migration toward the central *aimag*s and the cities of Erdenet and Darhan that occurred after the *zud*s of the 2000s. Like my host family, all of these "newcomers" belong to the Bayad *yastan*[10] rather than the Halha, Mongolia's major subethnic group. As I will elaborate in the Findings section, the majority of daily visits between herders, instances of shared labour, and participation in social events that I observed during fieldwork took place among these ten Bayad families, with only one or two other herders occasionally involved.

My primary research method was participant observation: I immersed myself in the daily lives of my interlocutors, assisted with herding tasks, took part in social events and community gatherings, and engaged in informal conversations with both neighbouring herders and visitors. Fieldnotes were taken regularly, sometime immediately, but more often the next morning, during brief moments of spare time following the completion of morning tasks. Due to limited access to electricity at the field site, fieldnotes were typed upon my return to Italy, then organised thematically and analysed to identify recurring themes relevant to the scope of my research. Oral informed consent was obtained informally throughout the research. I was always straightforward with the interlocutors about my research interests and positionality, conscious of the dynamics of power and representation as a foreign researcher with basic Mongolian language skills. My outsider status, limited herding skills, and the fact that I engaged in activities associated with both female roles – such as cooking and assisting with milking – and male roles often sparked curiosity, especially among herders from other families and visiting guests, prompting and shaping many of the exchanges that emerged.

I also engaged in several in-depth conversations with members of MNFPUG, both at their headquarters in Ulaanbaatar and during their field visits to Bayangol *sum*. When discussing their role in reclamation and biodiversity programmes led by mining companies, they were keen to highlight how their approach differs from that typically adopted by the extractive industry. Mining companies, particularly since the launch of the "One Billion Trees Project" in 2021 – an initiative spearheaded by President Khürelsükh Ukhnaa – prioritise tree planting as a form of environmental compensation. The "One Billion Trees Project" public and private actors, especially those with environmentally damaging operations, to commit to large-scale reforestation.

While acknowledging the value of tree planting in mitigating desertification processes, my MNFPUG interlocutors stressed that, following mine closures, what was formerly used as grazing land should return to herders as rangeland. This stance is driven by growing concern over the shrinking of grazing areas that is happening all over the country, a process that they link to

10 Derived from *yas* "bones," *yastan* is an emic term used to denote an ethnic group, typically understood as defined by common ancestry, language, and customs.

competing land uses, ambiguous land tenure policies, environmental degradation, and the expansion of mining activities. Their perspective on land degradation is informed not only by the Federation's own monitoring efforts – carried out by the Department of Research and Development – but also by recent ecological research on grazing impacts and rangeland health (Sasaki et al., 2008; Fujita et al., 2009; Liang et al., 2009; Yoshihara et al., 2009; Zemmrich et al., 2010).

As Ichinkhorloo et al. (2017) notes, the 2015 report by the Green Gold Ecosystem Project identified overgrazing, poor herd rotation practices and mining operations as major drivers of rangeland degradation, with climate change exacerbating their effects. The topic of climate change – and its current and projected effects on Mongolian rangelands – featured prominently at the VI National Rangeland Forum, initiated by MNFPUG and held at the Parliament House in Ulaanbaatar in June 2023, which I attended with Yadamjav. There, much attention was devoted to the role of pastoralism in delivering ecosystem services that can help mitigate the effects of climate change.

A recurring concern – and an important thrust for some of their initiatives – voiced by Ulaanbaatar based MNFPUG members was what they perceived as a lack of preparedness among herders to face the challenges posed by a changing climate. One contributing factor, they suggested, is a widespread "misunderstanding" of the phenomenon – particularly the "belief" among many herders that the current changes are temporary and that the climate will eventually revert to its former state.

In the following section, I explore this issue in more detail, without attempting to counterpose a single, coherent perception of climate change among Mongolian herders – which I neither encountered in conversations with my interlocutors nor believe exists – to a scientifically grounded perspective adopted by MNFPUG and other institutional actors, which ultimately aligns closely with what could be called the mainstream international narrative. Given the length and scope of my fieldwork, my aim is not to offer generalisations, nor to fall into the unproductive binary between "scientific knowledge" and "traditional belief." Instead, I argue that a more fruitful approach is to seek out productive tensions between divergent conceptual worlds, following Eduardo Viveiros De Castro's notion of *controlled equivocation* (Viveiros De Castro, 2004).

Findings

Changing climate or changing weather?

Ahearn (2019) cites a remark made by former President Elbegdorj during his speech at the 2014 UN Secretary-General's Climate Summit: "If you have doubts about whether climate change is happening or not, come to Mongolia. Ask a herdsman, "Is climate change happening?" Our herdsman will give you a true answer. They've already told me that it is happening, and happening for real." A similar sentiment emerged during my conversation with Bulgamaa, head of the Research and Development Department at MNFPUG, when she spoke about how herders perceive climate change:

> They very much talk about climate change, because they really are . . . the persons who spend most of their life out in the open. In general, herders are very observative people, observing everything. The flower colour is changed . . . So they are able to observe different changes. So they talk about that, that is getting more dry because of climate change (D. Bulgamaa, 20/09/2023).

Since her English was stronger than my Mongolian, our conversation took place in English. The term she used, "climate change" – the same expression quoted in Elbegdorj's speech – is most commonly translated into Mongolian as *uur am'sgalyn öörchlölt*, a phrase typically found in official discourse, scientific publications, and national or international development projects. It appears, for instance, in the name of institutions such as the Ministry of Environment and Climate Change (*Baigal' orchin, uur am'sgalyn öörchlöltiin yam*) and in policy instruments like the National Climate Change Programme (*Uur am'sgalyn öörchlöltiin ündesnii hötölbör*). However, during my fieldwork in Bayangol *sum*, I never heard herders use this formal term in everyday conversations – particularly when speaking among themselves. The phrase only emerged in response to my questions, in which I had introduced it first. While discussions about unusual weather patterns[11], shifting pasture conditions, and changes in floral composition were indeed very common, these phenomena were never explicitly linked to *uur am'sgalyn öörchlölt*. The root of *öörchlölt* (change) occasionally appeared in verbal form, but instead of referring to *uur am'sgal* (climate), when I heard it, it was usually coupled with *tsag agaar* (weather) and often preceded – or replaced entirely – by the verb *dulaarah* (to warm)[12]. Beside the lexical choice – possibly reflecting an avoidance of formal terminology – it is important to note that my interlocutors were far less concerned with abstract discussions about climate than with articulating the changes they perceived around them through

11 For example, 1 day toward the end of April, I heard Enh-Oyuun complaining about the cold winds that kept blowing, asking out loud: "When will summer come? There has been a cold winter, and this long spring is not ending!" (*Zun hezee boloh yum be? Övöl hüiten baisan, urt havar duusahgüi!*).

12 In their investigation into children's perceptions of environmental transformation, Irvine et al. (2019) report that the Mongolian children who participated in the study associated the reduced flow of rivers with a lack of rain, with several attributing this to "global warming" (*delhiin dulaaral*), a phenomenon they had learned about through television and school lessons.

phenomenologically experienced weather, shifts in pasture quality and changes in floral composition.

"The Russians shot the clouds"

An opportunity to engage more deeply with these themes emerged in July, when heavy rainfall caused the Haraa River to flood the area where most of the summer camps (*zuslan*) were situated. At the time, I was travelling in Dornod *aimag*, in the eastern part of the country, and on my return journey to Bayangol *sum*, I received a stream of memes and images circulating online. Among them were photos of inundated neighbourhoods in Ulaanbaatar–humorously dubbed "the Mongolian Venice" – along with scenes of submerged roads from various provinces and a widely shared video showing the collapse of a bridge that had once crossed the Haraa River.

When I returned to my fieldwork site about a week after the flooding, I found that every household had moved their *zuslan* away from the river, relocating either to their spring (*havarjaa*) or winter encampments (*övöljöö*). Of my host family, only Bayasaahüü, the second daughter, was present; her parents and younger siblings had left 2 days before my arrival to visit relatives in Uvs *aimag*, the western province where most of my adult interlocutors were born and raised. Bayasaahüü described how hard it had been to pack up and move both their *gers*[13] and belongings to the *havarjaa* in a single day – something that is usually done over a couple of days – amid relentless rain and the rapidly rising river. There had been no time to rest, not even to eat some food.

Summer is the season when most of the precipitations falls in Mongolia, so rainfall itself was not unusual. However, the intensity of the rains that occurred across the country during that season marked them as extraordinary. Several herders later told me that the flooding had been caused by the most intense rainfall the region had experienced in 60 years. The increased intensity and amount of rainfall that tends to be concentrated in shorter events is a recurrent observation reported by herders across the country (Reid-Shaw et al., 2021). Initially, I perceived this as contradicting the earlier-mentioned focus on weather rather than long-term climatic patterns. However, at least two further considerations complicate this apparent contradiction.

Firstly, none of the herders who described the event as "the most intense rainfall in this area in the last 60 years" had actually lived there 60 years ago – nor had their parents. As previously mentioned, half of the Dorgont PUG families had migrated to Bayangol *sum* from Uvs *aimag* within the past two decades[14]. While this means they lacked direct 60-year experience of local environmental history, their statements likely drew on conversations with long-established residents, as well as broader social exchanges. Such claims, therefore, point not only to individual observation but also to forms of shared environmental knowledge constructed collectively over time. These "migrant" herders were also the people with whom I had the most frequent interactions. This was largely because, during the most labour-intense activities – such as collecting *hörzön*, shearing sheep, or castrating animals – it was primarily among these migrant families that mutual support and labour exchange occurred. Few people originally from Bayangol *sum* participated in these collaborative efforts. While one explanation could be the higher concentration of migrant families in the PUG's subdivision where I conducted my fieldwork, the same pattern extended to everyday interactions: the daily visits herders paid to one another; long summer nights spent playing card games; and shared participation in public events like the Naadam festival in Baruunharaa, the *sum* centre. Although promoting cooperation among members is an important aspect of the PUG model, most of the help and the interaction I observed unfolded along kinship, friendship, and neighbourhood lines, often independent of, or parallel to, the formal structure of the PUG.

Secondly, among all my interlocutors, only Yadamjav – the father of my host family – explicitly linked the intense rainfall that caused the flooding to broader changes in the climate, though he still used the term for weather (*tsag agaar*). When I asked others, "Why has there been so much rain?" the most common answer I received, in slightly varying forms, was: "The Russians shot the clouds to bring water for the crop fields"[15]. This referred to cloud seeding, a technique of artificially inducing rain for agricultural purposes. It typically involves dispersing a seeding agent – usually silver iodide – into clouds using aircraft or ground-based generators to encourage the formation of ice crystals, which then grow larger and fall as snow or melt into rain.

What stood out to me in this explanation was the notable absence of any blame directed at those responsible – allegedly "the Russians." Nor did I encounter the kind of moral objection that Murphy describes in his ethnography, where herders considered shooting at the sky to induce rain spiritually unclean and offensive (Murphy, 2011). This may be because

13 A *ger* (also known as a yurt) is a Mongolian round, mobile house made of a wooden lattice structure covered with felt and canvas. While it has long served as the primary dwelling of nomadic herders, it is also commonly found on the outskirts of Mongolian cities, where many urban residents continue to live.

14 The first family arrived from Uvs *aimag* in 2002, and the most recent one toward the end of the summer of 2023. The main motivations for migration that people shared with me included proximity to roads, the railroad and cities; better prices for their products as a result; and improved educational opportunities for their children. The head of the last family to arrive was the only one to mention the poor quality of pastures in Uvs in recent years as a reason for relocating.

15 *Oros hümüüs üül buudsan, gazar tarian talbai us garahaar* (Otgon, 22/07/2023).

herders are becoming more familiar with the technology, which is increasingly used in Mongolian agriculture. Moreover, despite the considerable disruption caused by the flooding and the challenges associated with hastily relocating the encampments, none of my interlocutors expressed complaints about the rain itself. Batnyam, a wealthy *myangat malchin* – a person with more than 1,000 heads of livestock – was almost amused by the framing of the intense rain as an issue in my questions, remarking that nobody should complain about rain in summer since, in his opinion, it is always beneficial for the pastures.

Debt, helplessness and revolution

On separate occasions, two herders brought up cloud seeding as an explanation for the intense rainfall and promptly asked for my thoughts on the matter. They explained that this was something they had heard from others in the area and seen circulating on Facebook, adding – almost apologetically – that as "herders from the countryside" they "do not know many things" and had not had the opportunity to pursue higher education. One of them, Otgon, had mentioned the warming of *tsag agaar* (weather) as the reason why the Russians had shot the clouds, saying that their fields were not receiving enough rain due to high temperatures[16].

I replied that I also believe temperatures are rising and that, as far as I know, in a warmer world more water evaporates from the seas, making extreme rainfall events more likely. Perhaps prompted by my mention of "the world," his following response took on a more "global" perspective: he said that "the natural world needs to be interacted with in the correct way" and that "Mongolians are not alone, everybody in the world needs to do this"[17]. While this could be read as a call for shared planetary responsibility, I understood it as a reflection of his awareness of the broader global ecological and economic dynamics underpinning the climate crisis–an indirect way of saying that the true responsibility for rising temperatures lies elsewhere. Indeed, he later noted that most of the polluting factories are located in "developed countries" (*högjingüi uls*), and that there is very little that they – the Mongolians, but especially the herders – can do in their situation.

This sentiment came up frequently in conversations about herders' roles in pasture rehabilitation and biodiversity conservation projects – such as the one they are involved in through MNFPUG – and what these initiatives mean for winter preparations and, more broadly, for the changing weather conditions. While my questions were initially framed around environmental concerns, my interlocutors often responded by focussing on economic pressures. Rather than diverting the conversation, these responses revealed the extent to which climate-related challenges are deeply entangled with structural economic hardship and the retreat of the state in the post-socialist context. The high costs of winter fodder, children's tuition fees, and occasional medical expenses all shape herders' capacity to adapt and prepare, embedding the effects of climate change within the daily struggle to sustain livelihoods. These conditions have created a widespread reliance on bank loans, which most herders take out each year using their livestock as collateral.

> Y: Preparing livestock for winter, buying grain and hay costs 5 million MNT[18]. [. . .] All herders are in debt.

> E: We say that we are herding the bank's livestock. In the past the animals belonged to the state. Then they become private. Now they belong to the banks. (Yadamjav and Enh-Oyuun, 25/10/23)[19]

They repay their debts by selling butchered animals (*idesh*) in late autumn to urban families, and especially by selling cashmere in the spring – a situation closely resembling what Murphy describes in his paper on the so-called "cashmere-debt cycle" (Murphy, 2018). This creates a situation of deadlock, in which herders feel abandoned by institutions and perceive alternative courses of action as not only unfeasible, but almost unimaginable:

> E: Just a few people are "eating" Mongolia's wealth. So we herders are left out in the middle of it all. We are the ones who have been abandoned. There's no one discussing or making decisions about us. We're just getting by on our own. [. . .] This means that we've truly been left behind. [. . .] We don't know what to do in the future. Who can we complain to about it? We live with it quietly, without much opportunity to raise our concerns, because we chose this livelihood, so we just endure it in silence. (Enh-Oyuun, 25/10/23)[20]

16 A thoughtful comment by one of the anonymous reviewers made me realise that the state of necessity motivating the cloud shooting might help explain the absence of blame directed at those responsible.

17 *Baigal' delhiitei zöv har'tsah heregtei. Gants Mongol ch bish delhii niiteeree hiih heregtei* (Otgon, 22/07/2023).

18 The exchange rate during the period of my fieldwork was around 3,500 Mongolian tögrög (MNT) for 1 USD.

19 Y: *Mal övöljiltiin beltgel, budaa övs avahaar 5 saya tögrög boldog [. . .] Büh malchid zeeltei.* E: *Bid nar bankny mal mallaj baina gej yar'dag. Bür ömnö n' ulsyn mal baisan. Tegeed huviin mal bolson. Odoo bankny mal bolson*.

20 Hedhen hümüüs l mongolyn höröngiig idej baina l daa. Tegeed dund n' malchid bid nar hayagdaad l. Bid nar bol hayagdsan hümüüs shüü dee. Bid naryn talaar avya heleltsej baigaa hen ch baihgüi. Bid öör öörsdiigöö l bolgoj baina. [. . .] Tegeheer bid nar hayagdsan baigaa baihgüi yuu. [. . .] Tsaashid yahyg medehgüi. Hend gomdohov dee. Gomdoh erhgüi l am'darch baina daa. Bidnii songoson am'dral geed chimeegüi l baidag.

Even when the urgency of shifting course to address the climate crisis was acknowledged by my interlocutors, the possibility for such change was often situated in the future – distant from a present dominated by socioeconomic precarity and a pervasive feeling of helplessness. While climate change was physically experienced in their daily lives, it was perceived as something they had little power to influence, and thus became a lesser priority compared to the immediate demands of sustaining livelihoods. As a result, meaningful action was not seen as possible in the current conditions, but rather as something that might emerge with the younger generation, viewed as more educated and more attuned to dominant international narratives. For some, this pointed to the need for a radical transformation – both in the structural conditions shaping herders' lives and in prevailing mindsets. Otgon, the herder who remarked that "Mongolians are not alone" and that "everybody in the world needs to act," framed this challenge in terms of revolution, saying: "A revolution in mindset is greatly needed"[21].

Getting ready for winter, with *hörzön* and coal

I want to conclude this paper by showing how the dynamics discussed above reverberate in herders' cooperative practices surrounding a key aspect of winter preparations – the accumulation of fuel used for cooking and heating the *ger* – and the resulting implications for understanding the everyday realities and limitations of projects such as the one the Dorgont PUG is involved in.

In this part of Mongolia, as in many other regions, trees are scarce, making wood an uncommon fuel source. Instead, the primary material used for this purpose is *hörzön* – compressed and dried animal dung. Unlike the other seasons, during winter nights sheep and goats are kept in pens where their waste accumulates. Constant trampling compacts it into a dense mass, which is then harvested in the spring, typically around late April. Using spades, herders cut the compacted dung into blocks, which are carried outside and stacked in mounds aligned north to south to maximise exposure to sunlight for drying throughout the summer. Once fully dried, the *hörzön* is used as fuel during the following winter. The collection process is physically demanding and labour-intensive, usually carried out with the help of neighbouring male herders. This assistance is not compensated with money; rather, those who help are served a meal – prepared by the women of the host household. The labour is then reciprocated by helping them with their *hörzön* later, sustaining a system of mutual support among herding families.

The preparation and collection of *hörzön* was the first instance in which I observed this reciprocal labour exchange, which I initially perceived as a practice introduced or revitalised by CBRMs such as the PUGs – particularly those engaged in biodiversity and conservation projects, like the Dorgont PUG. From both part of the literature and my conversations with members of MNFPUG, I understood that PUGs emerged in the context of the atomisation of Mongolian pastoralism following the dissolution of the *negdel*s (herders' collectives), when herding families tended to live and work independently, often only alongside a few relatives. According to the narrative adopted by such organisations, it was just after experiencing several *zud*s that herders realised the importance of coming together – leading to the formation of PUGs – to manage shared grazing areas and support one another in labour-intensive tasks, particularly those related to winter preparations. This framing, however, is biased by the highly localised focus of PUGs, which overlooks the broader networks in which herders participate (Ichinkhorloo and Yeh, 2016), as well as the longstanding dynamics of labour collaboration and reciprocity that predate the formation of such institutions. The instances of cooperation I participated in signalled that such reciprocal labour was not solely a product of the PUGs, but rather part of deeper, enduring social practices – often taking forms and expressions not accommodated by the narrative of institutions such as the MNFPUG.

I witnessed something that initially appeared to me as a shift in the opposite direction one afternoon of late October. That day, I accompanied Yadamjav to buy a full truckload of coal for 350,000 MNT near the station in Erhet, a small hamlet situated along the railroad that crosses Mongolia from north to south, a short drive from our camp. Upon returning, he told me to pile it next to the mounds of *hörzön* we had collected in spring. The irony of breaking my back heaping this infamous polluting fossil fuel par excellence while doing the fieldwork for a PhD funded by the Italian Ministry of University and Research with a scholarship dedicated to "green" research projects was not lost on me. Even though the specific place where I was instructed to stack it – on a mound parallel to the piles of *hörzön* – made a lot of practical sense, it nonetheless created a strong dissonance in my mind. This moment made me reflect on the gap between what compensation projects envision and the complex realities of life in the Mongolian countryside, where herding families continue to depend on diverse sources of fuel and must address immediate needs and practical constraints.

Beyond considerations of the differing environmental sustainability of the two fuels (Endicott, 2012; Yembuu, 2016), my initial impression was that the act of buying coal symbolised a movement in the opposite direction from the mutual help dynamics at the heart of PUGs – toward greater individualisation. However, I began to re-evaluate this initial, somewhat naïve framing by reflecting on the moments of reciprocal labour I had observed – specifically, who participated and, more broadly, the actual scope of the social relations my interlocutors enacted. As mentioned earlier, most of the herders involved in those communal works represented only a subset of the Dorgont PUG membership, nearly all of whom had migrated from Uvs *aimag*. They were part of what Sneath (1993) describes as a "network of social relations of obligation," which, in this context, exists alongside rather than within the formal PUG structure.

21 Oyuun uhaany huv'sgal ih heregtei.

Moreover, in certain seasonal tasks that families undertook simultaneously – such as goat combing – assistance often came not from fellow PUG members, but from non-herding relatives and friends residing in urban areas. These were, in some cases, the same individuals who purchased meat for the winter (*idesh*) from my host family, sent their sons to spend the summer in the countryside to help tend the herds, or hosted the children in their city apartments. This dynamic resonates with Ichinkhorloo and Yeh's (2016) critique of CBNRM programmes, which they characterise as fostering "ephemeral" communities. They are ephemeral in part because such initiatives attempt to construct "community" within fixed localities, while overlooking pre-existing social networks that extend well beyond them and connect the countryside with urban areas.

At the same time, the act of buying coal proved far less individualistic than I had initially assumed. While I was shovelling coal, Yadamjav went back to purchase more and delivered it to an elderly woman living alone in a nearby encampment. The following day, we went together to help a couple living in Erhet store their coal – people who had assisted us with haymaking a few weeks prior. When I asked Yadamjav why he had bought coal, considering that we already had *hörzön*, he gave me two reasons. First, a new family of relatives from Uvs *aimag* had arrived at their camp that summer, along with their large new *ger*, which would be difficult to heat using *hörzön* alone. Second, there was a widespread expectation among herders in the area of an especially harsh winter – which in fact did occur.

Discussion and conclusion

In this paper I have examined how the herders I lived with in Bayangol *sum* experience, interpret, and navigate environmental change within a broader landscape of socio-economic uncertainty and evolving kinship and community ties. By foregrounding local discourses about weather, rainfall, and cloud seeding, I have sought to shift the analytical lens from abstract notions of "climate change" to lived experiences grounded in social and ecological entanglements.

I suggest that my interlocutors' tendency to speak about *weather* – referring to immediate[22] atmospheric conditions in a particular place – rather than invoking the more distant, detached and abstract notion of *climate*, and especially the way they express such observations through changes in the floral composition of the pasture and in specific weather patterns, reflects not only their experiential engagement with the constantly shifting landscape they inhabit (Ingold, 2000) in an entanglement of more-than-human social relations (Tsing, 2015), but also resonates strongly with some of Timothy Morton's critiques of the term "climate change" (Morton, 2013). Understanding "climate change" as an *hyperobject*–an entity so vast in temporal and spatial scale that exceeds conventional human understanding and demands new ways of thinking and talking – rather than treating it as a clear-cut explanatory principle, as it is often the case in institutional policies and donor projects – helps avoid the risks of oversimplifying the issue and obscuring its local manifestations. These tendencies contribute to a sense of disconnection that can hinders effective action. As reminded by Tim Ingold, in order to address the threat and to secure a world suitable for human and non-human life, it is of paramount importance "to close the gap that currently exists between the experienced environment of our everyday lives – that is, the world around us – and the projected "environment" of science and policy discourse." An environment, the latter, that we can only know through data-sets drawn from detached observations, "apprehended as the globe with its atmosphere rather than a manifold of earth and sky, as a catalogue of biodiversity rather than the entangled lifeways of animals and plants, as susceptible to climatic change rather than the vicissitudes of weather" (Ingold, 2014).

My findings highlight how environmental interpretation among Dorgont PUG herders is not strictly rooted in scientific reasoning nor in long-term ecological monitoring, but rather in an assemblage of lived experience, circulating explanations, and historical imaginaries. The fact that none of the herders I spoke with had personally witnessed 60 years of weather patterns in the area – and yet spoke confidently of an unprecedented rainfall – suggests a form of collective environmental memory, shaped through conversation and possibly social media narratives.

Similarly, the recurring explanation that "the Russians shot the clouds" reflects a socially shared causal narrative that blends circulating explanations with past geopolitical memory and observable weather anomalies. Rather than dismissing such statements as misinformed, they should be understood as culturally embedded ways of interpreting and making sense of extreme weather events, especially in contexts where official climate discourse fails to engage with herders' lived realities, priorities and everyday concerns.

Yadamjav's attribution of the flooding to climate change – albeit framed in terms of *tsag agaar* (weather) – and Otgon's connection between a warming weather and cloud seeding, hint at the selective incorporation of global environmental discourses into local narratives. These examples

22 I thank Professor Elisabetta Ragagnin (personal communication) for pointing out that the first word of the compound *tsag agaar*, meaning "time," when added to *agaar*, "air," gives a temporal dimension to this expression of weather. Nevertheless, I maintain that – at least in the way my interlocutors used it – the term conveys a perception that is both spatially and temporally situated, grounded in lived experience rather than in an abstract or detached notion of climate. Beyond their choice of terminology, I believe my interpretation is supported by the ways herders spoke about these changes, articulating them through phenomenologically experienced weather and observed shifts in pasture quality and composition.

highlight not only an awareness of broader climatic shifts, but also the ways in which scientific terms and concepts are refracted through locally meaningful frameworks. Rather than viewing scientific language and local perceptions as binary or oppositional, it is more productive to see them as overlapping, and at time contradictory, interpretative frameworks through which people make sense of a rapidly shifting environment.

Far from representing passive victims, the herders I worked with articulate situated critiques and engage in pragmatic adaptations that often go unrecognized by institutional frameworks. Their actions – ranging from reciprocal labour exchanges within extended networks to the integration of fossil fuels like coal alongside the "traditional" *hörzön* – reveal both the fragility and resilience of social life under pressure.

The fact that many herders responded by focussing on economic pressures when asked about their roles in pasture rehabilitation and biodiversity conservation projects – and what these mean for winter preparations and, more broadly, the changing weather conditions – highlights how deeply these themes are intertwined with their economic situation, their sense of abandonment by institutions, and the resulting challenges in envisioning alternative courses of action.

I suggest that Enh-Oyuun's remark – the mother of my host family – can be productively interpreted through the lens of what Arjun Appadurai terms "the capacity to aspire," a form of navigational capacity that is "unequally distributed among wealthier and poorer communities, that allows people to make their way from more proximate needs to more distant aspirational worlds" (Appadurai, 2013, p. 213). As Appadurai notes, it is not the case that the poor – and, by extension, the excluded, the disadvantaged, and the marginal groups – cannot wish, want, need, plan or aspire, but rather that the diminishing of the circumstances in which these practices can occur is a hallmark of their marginality. And since – like every other cultural capacity – it requires "practice, repetition, exploration, conjecture and refutation," the capacity to aspire remains less developed where the opportunity to enact these practices in regard to the future are limited. Consequently, those at the margins are left with a more fragile horizon of aspiration precisely because they lack opportunities to develop and exercise this navigational capacity (pp. 188–189).

Rather than suggesting an outright inability to imagine alternative courses of action in response to the climate crisis, I propose that economic and institutional constraints limit the space for articulating and pursuing such alternatives in the everyday lives of my interlocutors, and underlie Otgon's framing of the challenge in terms of revolution.

In this context, Lars Højer's discussion of the two temporal orientations he identified in his Mongolian material – apathy and revolution – is especially relevant (Højer, 2018). Højer states that "revolution" develops from "apathy," which he characterises as a feeling of being entrapped in a tragic present devoid of subjecthood – understood here as "the ability to act in ways that make a genuine difference" (p. 78). Revolution is thus something that is sought as a yearning for rupture, to bring about drastic change by creating discontinuities between the "here" of the present and "then" of the future, but that share with "apathy" the same point of departure: an intensely felt inability to act. I contend that my interlocutors' reflections resonate with this formulation of apathy – extended, in some cases, even to the possibility of blaming someone for their condition. Otgon's call for a "revolution of the mindset," then, can be read not as a concrete demand for action, but as an expression of what Højer describes as "felt impossibility for making a smooth change in one's own life and in relation to Mongolia's future as a whole" (p. 86).

These lived realities challenge policy models of community-based resource management, which often assume fixed, locality-bound notions of "community." In practice, herding life is shaped by mobile, kin-based networks, migration histories, and rural-urban ties that extend well beyond the formal structures of PUGs. While PUGs were introduced to restore governance capacity, they failed to address the deeper disruption caused by the dismantling of the dual control system – once an integrated framework balancing state oversight and customary pastoral coordination.

Its collapse fractured the alignment of land, labour, and livestock management, leaving herders to navigate increasingly uncertain socio-environmental conditions with diminished institutional support. As a result, policy expectations for local participation and responsibility often clash with herders' constrained ability to act.

The perception of changes in weather patterns and ecological conditions is real and widespread, yet herders' responses are often deferred, articulated as the responsibility of younger, more educated generations. This deferral reflects not disengagement but structural limitations, economic precarity, and a loss of coordinated governance. Otgon's voiced need for a "revolution in mindset" signals both the necessity of systemic change and recognition of present constraints. In his words, resignation and hope coexist, shaped by lived experience rather than technocratic policy logics. For climate interventions to be effective, they must account for these complex temporal, social, economic, and political textures. Without this, the vision of sustainable community-based management risks remaining disconnected from the realities it seeks to transform.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Written informed consent was not obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article because Verbal consent was obtained, as common for ethnographic research.

Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The doctoral scholarship was co-funded with resources from the "Programma Operativo Nazionale Ricerca e Innovazione" 2014–2020 (CCI2014IT16M2OP005), FSE REACT-EU resources, Action IV.5 "Dottorati su tematiche Green."

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. Generative AI was used to check the manuscript for grammatical accuracy.

References

Ahearn, A. (2019). "Surviving Extreme weather: mongolian indigenous knowledge, local institutions and governance innovations for adaptation," in *Indigenous peoples and climate change: emerging research on traditional knowledge and livelihoods*. Editors A. Ahearn, M. Oelz, and R. K. Dhir (Geneva: ILO), 9–19.

Ahearn, A., and Hahn, A. (2017). *Pastoralist livelihoods in Asian drylands: environment, governance and risk*. Winwick, Cambridgeshire: The White Horse Press.

Allegretti, A. M., Laituri, M., Batjav, B., and Baival, B. (2015). "'Participatory Mapping and Herders' local knowledge on mongolia's landscapes and socio-ecological boundaries," in *Proceedings of the trans-disciplinary research conference: building resilience of Mongolian rangelands, ulaanbaatar*. Editors M. Fernández-Giménez, B. Baival, S. R. Fassnacht, and D. Wilson (Fort Colllins, CO: Colorado State University, Libraries).

Appadurai, A. (2013). *The future as cultural fact: essays on the global condition*. London; New York: Verso.

Borsy, P., Bussac, C., and Bandi, O. (2021). "Final evaluation of the Project: green gold and animal health in Mongolia," in *Freiburg: UNIQUE forestry and land use GmbH*.

Brosius, J. P., Tsing, A. L., and Zerner, C. (2005). *Communities and conservation: histories and politics of community-based natural resource management* (Lanham, MA: AltaMira Press).

Byrnes, R. C., Eastburn, D. J., Tate, K. W., and Roche, L. M. (2018). A global meta-analysis of grazing impacts on soil health indicators. *J. Environ. Qual.* 47 (4), 758–765. doi:10.2134/jeq2017.08.0313

Dashbal, B., Bestelmeyer, B. T., Densambuu, B., Ulambayar, B., Sainnemekh, S., Van Zee, J., et al. (2023). Implementing a resilience-based management system in Mongolia's rangelands. *Ecosphere* 14 (10), e4665. doi:10.1002/ecs2.4665

Deng, L., Shangguan, Z., Bell, S. M., Soromotin, A. V., Peng, C., An, S., et al. (2023). Carbon in Chinese grasslands: Meta-analysis and theory of grazing effects. *Carbon Res.* 2 (1), 19. doi:10.1007/s44246-023-00051-7

Endicott, E. (2012). *A history of land use in Mongolia*. New York: Palgrave Macmillan US. doi:10.1057/9781137269669

Ericksen, A. (2014). Depend on each other and don't just sit: the socialist legacy, responsibility, and Winter risk among Mongolian herders. *Hum. Organ.* 73 (1), 38–49. doi:10.17730/humo.73.1.e218g65507n665u0

Fernández-Giménez, M. E. (2001). The effects of livestock privatisation on pastoral land use and land tenure in post-socialist Mongolia. *Nomadic Peoples* 5 (2), 49–66. doi:10.3167/082279401782310862

Fernandez-Gimenez, M. E., and Batbuyan, B. (2004). Law and disorder: local implementation of Mongolia's land law. *Dev. Change* 35 (1), 141–166. doi:10.1111/j.1467-7660.2004.00346.x

Fujita, N., Amartuvshin, N., Yamada, Y., Matsui, K., Sakai, S., and Yamamura, N. (2009). Positive and negative effects of livestock grazing on plant diversity of Mongolian nomadic pasturelands along a slope with soil moisture gradient. *Grassl. Sci.* 55 (3), 126–134. doi:10.1111/j.1744-697X.2009.00147.x

Goldstein, M. C., and Beall, C. M. (1994). *The changing world of Mongolia's nomads*. Berkeley: Univ. of California Press.

Griffin, K. (1995). *Poverty and the transition to a market economy in Mongolia* (London: Palgrave Macmillan UK). doi:10.1007/978-1-349-23960-3

Hardin, G. (1968). The tragedy of the commons. *Science* 162 (3859), 1243–1248. doi:10.1126/science.162.3859.1243

Herrero-Jáuregui, C., and Oesterheld, M. (2018). Effects of grazing intensity on plant richness and diversity: A meta-analysis. *Oikos* 127 (6), 757–766. doi:10.1111/oik.04893

Højer, L. (2018). "Apathy and revolution: temporal sensibilities in Contemporary Mongolia," in *Recovering the human subject: freedom, creativity and decision*. Editors J. Laidlaw, B. Bodenhorn, and M. Holbraad (Cambridge: Cambridge University Press), 74–94. doi:10.1017/9781108605007

Humphrey, C., and Sneath, D. (1999). *The end of nomadism? Society, state, and the environment in Inner Asia*. Durham, NC: Duke University Press.

Ichinkhorloo, B., and Yeh, E. T. (2016). Ephemeral "communities": Spatiality and politics in rangeland interventions in Mongolia. *J. Peasant Stud.* 43 (5), 1010–1034. doi:10.1080/03066150.2016.1168812

Ichinkhorloo, B. (2017). "Environment as commodity and shield: reshaping herders' collective identity in Mongolia," in *Pastoralist livelihoods in Asian drylands: environment, governance and risk* (Winwick, Cambridgeshire: The White Horse Press).

Ingold, T. (2000). *The perception of the environment. Essays on livelihood, dwelling & skill*. London; New York: Routledge.

Ingold, T. (2014). "Designing environments fo life," in *Anthropology and nature*. Editor K. Hastrup (New York: Routledge), 233–246.

Irvine, R. D. G., Bodenhorn, B., Lee, E., and Amarbayasgalan, D. (2019). Learning to see climate change: children's perceptions of environmental transformation in Mongolia, Mexico, Arctic Alaska, and the United Kingdom. *Curr. Anthropol.* 60 (6), 723–740. doi:10.1086/706606

Janes, C. R., and Chuluundorj, O. (2015). *Making disasters: climate change, neoliberal governance, and livelihood insecurity on the Mongolian steppe*. Santa Fe, New Mexico: School for Advanced Research Press.

Janes, C. R., Chuluundorj, O., Hilliard, C. E., Rak, K., and Janchiv, K. (2006). Poor medicine for poor people? Assessing the impact of neoliberal reform on health care equity in a post-socialist context. *Glob. Public Health* 1 (1), 5–30. doi:10.1080/17441690500321418

Kang, S., Jang, K., and Lkhamsuren, B. (2015). "Satellite-based assessments on regional summer and Winter conditions triggering massive livestock loss (Dzud) in Mongolia," in *Building resilience in Mongolian rangelands*. Editor M. Fernández-Giménez 60–64.

Liang, Y., Han, G., Zhou, H., Zhao, M., Snyman, H. A., Shan, D., et al. (2009). Grazing intensity on vegetation dynamics of a typical steppe in Northeast Inner Mongolia. *Rangel. Ecol. and Manag.* 62 (4), 328–336. doi:10.2111/08-167.1

Marin, A. (2012). Between cash cows and golden calves: adaptations of Mongolian pastoralism in the "Age of the Market". *Nomadic Peoples* 12 (2), 75–101. doi:10.3167/np.2008.120206

Mearns, R. (2004). Sustaining livelihoods on Mongolia's Pastoral commons: insights from a participatory poverty assessment. *Dev. Change* 35 (1), 107–139. doi:10.1111/j.1467-7660.2004.00345.x

Morton, T. (2013). *Hyperobjects: philosophy and ecology after the end of the world*. Minneapolis, MN: University of Minnesota press.

Murphy, D. J. (2011). *Going on Otor: Disaster, Mobility, and the Political Ecology of Vulnerability in Uguumur, Mongolia. University of Kentucky Doctoral Dissertations Paper 168*. Lexington, Kentucky: University of Kentucky. Available online at: https://uknowledge.uky.edu/gradschool_diss/168.

Murphy, D. J. (2018). "We're living from loan-to-loan: pastoral vulnerability and the cashmere-debt cycle in Mongolia," in *Research In Economic Anthropology*. Editor D. C. Wood (Leeds, United kingdom: Emerald Publishing Limited), 7–30. doi:10.1108/S0190-128120180000038002

Okayasu, T., Okuro, T., Jamsran, U., and Takeuchi, K. (2011). Threshold distinctions between equilibrium and nonequilibrium pastoral systems along a continuous climatic gradient. *Rangel. Ecol. and Manag.* 64 (1), 10–17. doi:10.2111/REM-D-09-00133.1

Ostrom, E. (1990). *Governing the commons: the evolution of institutions for collective action*. Cambridge: Cambridge University Press. doi:10.1017/CBO9780511807763

Reid-Shaw, I., Jargalsaihan, A., Reid, R. S., Jamsranjav, C., and Fernández-Giménez, M. E. (2021). Social-Ecological change on the Mongolian steppe: herder perceptions of causes, impacts, and adaptive strategies. *Hum. Ecol.* 49 (5), 631–648. doi:10.1007/s10745-021-00256-7

Rossabi, M. (2005). *Modern Mongolia: from khans to commissars to capitalists*. Berkeley: University of California Press.

Sasaki, T., Okayasu, T., Jamsran, U., and Takeuchi, K. (2008). Threshold changes in vegetation along a grazing gradient in Mongolian rangelands. *J. Ecol.* 96 (1), 145–154. doi:10.1111/j.1365-2745.2007.01315.x

Sneath, D. (1993). Social relations, networks and social organisation in post-socialist rural Mongolia. *Nomadic Peoples* 33, 193–207.

Sneath, D. (2002). "Mongolia in the "Age of the market": pastoral land-use and the development discourse," in *Markets and moralities: ethnographies of postsocialism*. Editors R. E. Mandel and C. Humphrey (Oxford, UK: Berg), 191–210.

Sneath, D. (2003). Land use, the environment and development in post-socialist Mongolia. *Oxf. Dev. Stud.* 31 (4), 441–459. doi:10.1080/1360081032000146627

Sneath, D. (2018). *Mongolia remade: Post-socialist national culture, political economy, and cosmopolitics*. Amsterdam: Amsterdam University Press. doi:10.5117/9789462989566

Soma, T., and Schlecht, E. (2018). The relevance of herders' local ecological knowledge on coping with livestock losses during harsh winters in western Mongolia. *Pastoralism* 8 (1), 3. doi:10.1186/s13570-017-0108-y

Tsing, A. L. (2015). *The mushroom at the end of the world: on the possibility of life in capitalist ruins*. Princeton; Oxford: Princeton University Press.

Tumur, E., Heijman, W. J. M., Heerink, N., and Agipar, B. (2020). Critical factors enabling sustainable rangeland management in Mongolia. *China Econ. Rev.* 60, 101237. doi:10.1016/j.chieco.2018.10.004

Undargaa, S. (2016). *Pastoralism and common pool resources*. London: Routledge. doi:10.4324/9781315726779

Undargaa, S. (2023). Legal ambiguity and land dispossession: multi-scale conflicting views on territorial authority at the herlen bayan-ulaan State reserve pasture area, Mongolia. *Nomadic Peoples* 27 (2), 265–291. doi:10.3197/np.2023.270206

Undargaa, S., and McCarthy, J. F. (2016). Beyond property: Co-management and pastoral resource access in Mongolia. *World Dev.* 77, 367–379. doi:10.1016/j.worlddev.2015.08.012

Viveiros De Castro, E. (2004). Perspectival anthropology and the method of controlled equivocation. *Tipití J. Soc. Anthropol. Lowl. S. Am.* 2 (1). doi:10.70845/2572-3626.1010

Viveiros De Castro, E. (2019). On models and examples: engineers and bricoleurs in the anthropocene. *Curr. Anthropol.* 60 (S20), S296–S308. doi:10.1086/702787

Yembuu, B. (2016). "Mongolian nomads: effects of globalization and social change," in *Everyday knowledge, education and sustainable futures*. Editors M. Robertson and P. K. E. Tsang (Singapore: Springer Singapore), 89–105. doi:10.1007/978-981-10-0216-8_7

Yoshihara, Y., Chimeddorj, B., and Buuveibaatar, B. (2009). Heavy grazing constraints on foraging behavior of Mongolian livestock. *Grassl. Sci.* 55 (1), 29–35. doi:10.1111/j.1744-697X.2009.00134.x

Zemmrich, A., Manthey, M., Zerbe, S., and Oyunchimeg, D. (2010). Driving environmental factors and the role of grazing in grassland communities: a comparative study along an altitudinal gradient in Western Mongolia. *J. Arid Environ.* 74 (10), 1271–1280. doi:10.1016/j.jaridenv.2010.05.014

Pastoralism
Research, Policy
and Practice

TYPE Original Research
PUBLISHED 20 October 2025
DOI 10.3389/past.2025.15238

OPEN ACCESS

EDITED BY
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RECEIVED 08 July 2025
ACCEPTED 09 October 2025
PUBLISHED 20 October 2025

CITATION
Mwilawa AJ, Gurmu EB, Weisbjerg MR, Laswai GH, Poole J and Arndt C (2025) Animal performance and methane emissions in feedlot vs, traditional pastoral systems with concentrate supplementation for Tanzanian Short Horn Zebu and Boran cattle. *Pastoralism* 15:15238.
doi: 10.3389/past.2025.15238

Animal performance and methane emissions in feedlot vs, traditional pastoral systems with concentrate supplementation for Tanzanian Short Horn Zebu and Boran cattle

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The current study examined the effect of concentrate supplementation on beef cattle performance and methane (CH_4) emissions in traditional pastoral systems in Tanzania. The study used summarized data (least square means, SEM, n) from a previous experimental study conducted in Tanzania in 2007-08, as the raw data are not available. The experiment involved 60 Boran and 60 Tanzanian Shorthorn Zebu (TSHZ) cattle, assigned to five dietary treatments for 100 days: grazing alone (GrazC00), grazing with 50% concentrate (GrazC50), and *ad libitum* hay with 60%, 80%, and 100% concentrate supplementation (HayC60, HayC80, and HayC100, respectively). The concentrate levels (50%, 60%, 80%, and 100%) were determined relative to the ad-libitum concentrate intake established before the experiment. The experiment measured dry matter intake (DMI) and live weights throughout the experimental periods. The current study calculated average daily weight gain (ADG) and daily CH_4 production (DMP) following the 2019 Refinement to the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines. The estimated CH_4 emissions were then used to calculate emission intensity (EI) relative to weight gain ($EI_{WG,}$ g CH_4/kg WG). Statistical analysis used the lme4 package in R and the lm function to fit ANOVA with breed and treatment main effects and their interaction, with significance set at $p < 0.05$. Results showed that concentrate supplementation increased ADG by 6%–33% and decreased DMP by 3%–35%, regardless of breed. Among treatments, HayC100 had the lowest DMP, indicating greater efficiency at higher concentrate levels. In both breeds, EI decreased as concentrate levels increased from 0% to 100%, with the lowest EI_{WG} observed in the HayC100 treatment (from 396 at GrazC00 to 87 g CH_4/kg WG at HayC100). The reduction in EI_{WG} was consistent across both breeds, showing that the supplementation effect was similar regardless of breed differences. Overall, concentrate supplementation improved cattle performance and reduced DMP, due to decreased CH_4 conversion factor (Ym), and lower EIs. These findings suggest that concentrate supplementation could be an effective strategy for enhancing beef production efficiency and reducing environmental impact in Tanzania.

KEYWORDS

concentrate supplementation, enteric methane, emission intensity, Boran, Tanzanian Shorthorn Zebu

Introduction

Cattle production plays a crucial role in Tanzania's agricultural sector, contributing to poverty reduction and food security (Suleiman, 2018). It is an integral component of mixed-crop livestock farming systems, directly or indirectly enhancing household income and food security (Mdoe et al., 2021). However, the growing domestic demand for beef poses a challenge due to rapid population growth and increased incomes, which have led to higher *per capita* consumption (Desiere et al., 2018; Kibona et al., 2022).

Traditional pastoral livestock production systems dominate the sector, accounting for 94% of beef cattle production. However, productivity is suboptimal due to high mortality rates, disease prevalence, poor reproductive performance, and forage scarcity (MLFD, 2015; Michael et al., 2018). The productivity losses attributed to forage scarcity can be significant. Lyatuu et al. (2023) indicated that limited access to forage, both in quantity and quality, can reduce cattle weight gain by up to 30%, aggravating the challenges faced by farmers. Moreover, forage scarcity during the dry season exacerbates these challenges, leading to cyclic weight fluctuations and increasing both feed resource requirements and the time to reach slaughter weight (Kanuya et al., 2006). The primary beef cattle breeds in Tanzania include the Tanzania Shorthorn Zebu (TSHZ), with a mature body weight ranging from 200 to 350 kg, and the Boran breed, with a larger body weight of 500–800 kg (MLF, 2018). Despite their adaptability to local conditions, these breeds exhibit slower growth rates compared to exotic breeds when raised under traditional grazing systems (Msalya et al., 2017). To address these challenges, strategies such as improved nutrition are being explored.

One promising approach to enhance cattle meat production is concentrate supplementation (Selemani et al., 2015). Concentrates commonly used in Tanzanian systems are formulated from locally available ingredients such as maize bran, cottonseed cake, sunflower seed cake, and fish meal. These provide energy and protein diversity to complement low-quality forages, thereby improving the nutritional value of grazing cattle diets and promoting growth (Steinfeld et al., 2006; Mwangi et al., 2019). The average daily gain of feedlot-finished animals in Tanzania was nearly threefold higher than that of grazed ones (Mushi, 2020). However, while feedlot systems are known to improve growth, the optimal levels of concentrate supplementation within feedlot conditions, and in comparison with grazing, have not been established (Selemani et al., 2015; Asimwe et al., 2016; Mushi, 2020). Enteric CH_4 emissions from livestock contribute significantly to agricultural greenhouse gas (GHG) emissions in Tanzania. In 2014, enteric CH_4 accounted for 39.7% of agricultural emissions in the country (Mushi et al., 2015; Seif and Kipkirui, 2024). Mitigating enteric CH_4 emissions offers an opportunity for near-term impact reduction, potentially aiding efforts to limit global temperature rise to 1.5 °C (Collins et al., 2018).

Concentrate supplementation also holds the potential for mitigating enteric CH_4 emissions by improving the feed conversion ratio (FCR) and reducing emission intensities (EI = emissions per unit of product) (White et al., 2014). Mitigation strategies implemented in other parts of Africa have shown potential in increasing diet digestibility and reducing enteric CH_4 emissions (Korir et al., 2022). Berhanu et al. (2019) demonstrated that integrating improved forage varieties (*Leucaena leucocephala*, *Moringa stenopetala*, *Sesbania sesban*, *Cajanus cajan*, *Crotalaria juncea*, and *Lablab purpureus*) can reduce enteric CH_4 emissions by up to 25% while simultaneously enhancing livestock productivity. However, there is little data regarding animal productivity improvement and enteric CH_4 mitigation in pastoral cattle systems in Tanzania, particularly through concentrate supplementation.

Therefore, the objective of this study was to investigate whether feedlot and grazing systems, with and without concentrate supplementation, will result in improved animal performance and lower enteric CH_4 emissions per product compared to traditional pastoral systems. By exploring this potential among Tanzanian Short Horn and Boran cattle, this research seeks to contribute to the development of sustainable cattle production systems in Tanzania, while acknowledging that the sustainability of concentrate-based interventions depends on the availability and cost of local feed resources.

Materials and methods

For the estimation of enteric CH_4 emissions and other parameters, we used summarized data (least square means, SEM, n) from a previous experimental study conducted in Tanzania in 2007-08 to calculate derived parameters, maintaining the distribution properties of the original data, as

TABLE 1 Growth performance and diet composition (Boran vs. TSHZ steers, Kongwa Ranch, 2007–2008).

Parameter	Breed	n	Initial LW (kg)	Final LW (kg)	DMI (kg/d)	CP (g/kg DM)	NDF (g/kg DM)	ADF (g/kg DM)	GE (MJ/kg DM)	DE (%)
GrazC00	Boran	12	168 ± 3.1	237 ± 5.0	8.3 ± 0.05	83	578	341	17.5	59.3
	TSHZ	12	98 ± 3.1	154 ± 5.0	7.7 ± 0.05	83	578	341	17.5	59.3
GrazC50	Boran	12	168 ± 3.1	248 ± 5.0	7.7 ± 0.05	97	480	263	18.0	65.8
	TSHZ	12	100 ± 3.1	163 ± 5.0	7.2 ± 0.05	95	491	271	17.9	65.1
HayC60	Boran	12	167 ± 3.1	224 ± 5.0	6.6 ± 0.05	107	397	187	18.8	70.3
	TSHZ	12	95 ± 3.1	149 ± 5.0	5.1 ± 0.05	102	430	212	18.7	68.0
HayC80	Boran	12	168 ± 3.1	245 ± 5.0	6.9 ± 0.05	111	369	167	18.8	72.3
	TSHZ	12	104 ± 3.1	162 ± 5.0	5.6 ± 0.05	114	353	154	18.9	73.4
HayC100	Boran	12	169 ± 3.1	255 ± 5.0	7.5 ± 0.05	118	326	134	18.9	75.4
	TSHZ	12	99 ± 3.1	180 ± 5.0	6.3 ± 0.05	117	331	138	18.9	75.0

GrazC00 = grazing alone as control; GrazC50 grazing + 50% *ad libitum* concentrate intake; HayC60, HayC80, and HayC100 = (*ad libitum* hay + 60, 80, and 100% of the ad-libitum concentrate intake, respectively). TSHZ, tanzanian short horn zebu; DMI, dry matter intake; FCR, feed conversion ratio; CP, crude protein; NDF, neutral detergent fibre; ADF, acid detergent fibre; GE , gross energy; DE, digestible energy. There were no SE, values for feed parameters since the analysis was conducted on pooled feed samples.

shown in Table 1. Using the least square mean, standard error of mean (SEM), and number of animals, we back-calculated the lower and upper 95% confidence limits (CL) to provide three values for each variable: the mean, lower and upper 95% CL for initial live weight (ILW), final live weight (FLW), and dry matter intake (DMI), assuming the residuals for the original raw data analysis were normally distributed. The minimum, mean, and maximum values were then utilized to derive or compute average daily weight gain (ADG, kg/day), feed conversion ratio (FCR, kg DMI/kg ADG), daily CH_4 production (DMP, g CH_4/day), CH_4e yield (MY, g CH_4/kg DMI), and emission intensity of weight gain (EI_{WG}, g CH_4/kg WG). The analysis results indicate the range of values between breeds, treatments, or their interactions. If the *p*-value shows significance, it was stated that breed, treatments, or their interaction had significant differences in the range of parameters estimated.

The details of the experiment conducted at Kongwa Ranch in Tanzania (S 6° 03.810′ and E 36° 27.296′ at an altitude of 1,067 m) from mid-November 2007 to March 2008, during the wet season, are described in sections *Animals experimental design, Treatment diets, Feed intake and animal performance measures* as follows.

Animals experimental design

The experiment involved 60 Boran steers purchased from Kongwa Ranch, aged between 1 and 2 years, with an initial average weight of (mean ± SE) 168 ± 1.4 kg. Additionally, 60 Tanzania Short-Horn Zebu (TSHZ) steers were acquired from local auction markets, aged between 1.5 and 2.5 years, with an initial average live weight (LW) of 99 ± 1.4 kg. The age of the TSHZ steers was estimated based on their dentition, while the age of Boran steers was obtained from ranch records. The animals were blocked by breed and assigned to treatments considering their initial average weight. A preliminary 7-day adaptation period involved mixing all steers and providing common feeding and management. During the last 3 days of this preliminary period, the animals were weighed simultaneously for three consecutive days to determine their average initial LW for allocation to dietary treatments. Before each weighing session, animals were deprived of water for a day, then provided water and weighed individually using a digital scale while walking on a platform. Withdrawing water before weighing helped minimize variation in gut fill and provided more accurate body weight measurements. Four steers with similar initial LW and the same breed were grouped in one pen. Each pen served as an experimental unit for feed intake and feed conversion efficiency, whereas an individual animal was considered as an experimental unit for weight change.

The study used a feedlot structure at Kongwa Ranch, comprising 24 pens measuring 4 × 5 m each. The structure featured partial roofing with iron sheets for shade, feeding and watering troughs, and a small shed (palm-thatched) at the rear end to keep shade during sunny hours.

Treatment diets

The dietary treatments included: grazing with no concentrate as a control (GrazC00); grazing plus 50% *ad libitum* concentrate

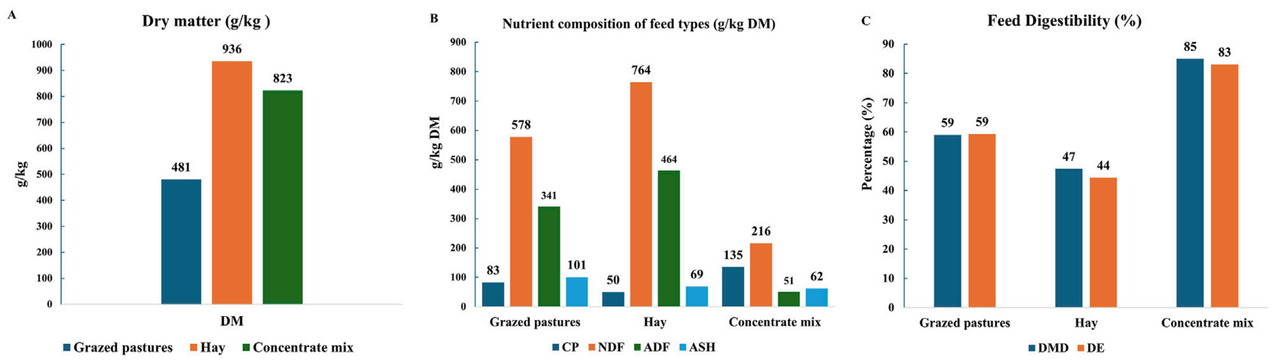

FIGURE 1
Chemical composition of forage, hay, and concentrate mixture fed during the experiment: Dry matter content **(A)**; Nutrient composition of the forages **(B)**; and the difestibility of grazed pastures, hay and concentrate mix **(C)**.

intake (GrazC50); 60% *ad libitum* concentrate intake plus *ad libitum* hay (HayC60); 80% *ad libitum* concentrate intake plus *ad libitum* hay (HayC80); and *ad libitum* concentrate intake plus *ad libitum* hay (HayC100). The *ad libitum* feeding allowed for approximately 10%–15% refusal. The 50%, 60% and 80% ad-libitum concentrate intake were expressed relative to the 100% *ad libitum* concentrate intake. The concentrate dietary levels were designed to identify the point at which additional concentrate no longer resulted in proportional performance gains, thereby balancing productivity with feed cost. Grazing alone was included as a reference treatment representing normal farming practice.

Animals on GrazC50 to HayC100 diets were housed in three pens per diet, with four animals per pen. Steers in GrazC00 were kept outside in a wire-fenced kraal at night, while those in GrazC50 were confined in pens at night for concentrate supplementation. Steers in GrazC50, HayC60, HayC80, and HayC100 diets were kept in separate pens throughout the experimental period.

Following the allocation of animals to their treatments and pens, a 19-day adaptation period was provided for the animals to adjust to the feeds, pens, and experimental procedures. During this period, animals in GrazC00 grazed, those in GrazC50 grazed and received evening concentrate supplementation in their pens, and animals in HayC60, HayC80, and HayC100 diets were provided hay *ad libitum*, with proportional concentrate supplementation given to the GrazC50, HayC60, and HayC80 groups until reaching the HayC100 *ad libitum* intake levels.

Grazing took place on natural grassland allocated for GrazC00 and GrazC50 treatments, with *ad libitum* access during the day. The grazed pastures consisted predominantly of perennial grasses (Aristida adscensionis 15.7%, *Dictyostelium* Aegyptus 12.8%, Cenchrus ciliaris 11.8%) and legumes (Macrotyloma uniflorum 11.4%), with other species contributing smaller proportions (<10%). Overall, grass accounted for ~70% of the botanical composition, with legumes and herbs comprising the remainder.

The concentrate feed was formulated using local ingredients purchased from various suppliers. The recipe included maize meal (380 g/kg DM), cotton-seed cake (130 g/kg DM), molasses (470 g/kg DM), mineral mix (10 g/kg DM), salt (5 g/kg DM), and urea (5 g/kg DM). This combination aimed to achieve a final composition of 125 g of crude-protein (CP) per kg DM. The formulation targeted an average daily gain (ADG) of 1 kg per steer. Once the ingredient quantities were calculated, the dry ingredients were weighed and thoroughly mixed to achieve the desired protein level. All concentrate ingredients were provided in dry form, except molasses, which was mixed with dry ingredients at feeding.

Feed intake and animal performance measures

Feed offered and feed refusals for each pen were measured daily, and the difference was taken as the total amount of feed taken by the four animals in each pen. Feed intake was determined per pen, and the value obtained was divided by the number of animals in the pen to obtain an average intake per animal. Animals were weighed on the 30th day and thereafter every 2 weeks until the end of the fattening trial. Animals were weighed in the morning for three consecutive days before the date of slaughter, and the average weight was taken as the final live weight (FLW). The FLW was used together with ILW to calculate ADG.

Sample preparation

Feed samples were first dried at 50 °C for 2 days in a forced-air oven to prevent nutrient losses and allow storage. The dried samples were ground to pass through a 1-mm mesh screen of a hammer mill (MF 10 basic, IKA, Werke GmbH and CO. KG, Staufen, Germany). For dry matter determination, subsamples were further dried at 105 °C overnight following the AOAC International (2006) procedures. Neutral detergent fibre (NDF) and acid detergent fibre (ADF) were analyzed according to Van Soest et al. (1991) using an Ankom200 Fibre Analyzer (Ankom Technology Corp., Fairport, NY). Total nitrogen (N) was determined by combustion using a CHN analyzer (Elementar Vario MAX cube, Elementar, Langenselbold, Germany) following the Dumas method of AOAC International (2006), and crude protein (CP) was calculated as 6.25 *N.

Estimation of feed digestibility

The ADF and N were used to estimate dry matter digestibility (DMD) utilizing the Equation 1 from Oddy et al. (1983).

$$DMD\% = 83.58 - (0.824 \times ADF\%) + (2.626 \times N\%) \quad (1)$$

where, DMD% is dry matter digestibility, % DM; ADF% is acid detergent fibre % DM; N% is nitrogen content in the feed, % DM.

The digestible energy as a proportion of gross energy (DE%) was derived from the estimated DMD using Equation 2, derived from CSIRO (2007).

$$DE\% = \frac{DMD\,(\%)^{*}\,0.172 - 1.707}{0.81^{*}GE\left(\frac{MJ}{kg}DM\right)}{}^{*}100 \quad (2)$$

where DE% is digestible energy as a percentage of gross energy intake; DMD is the dry matter digestibility in % estimated in Equation 2; GE is the gross energy content of the diets in MJ per kg DM.

Enteric methane emission

We estimated the daily enteric CH_4 production (DMP) based on the DMI measured during the experiment (Equation 3).

$$DMP\left(kg\frac{CH4}{day}\right) = \left(DMI\left(\frac{kg}{day}\right) \times GE\left(\frac{MJ}{kg\,DM}\right) \times \left(\frac{Ym,\%}{100}\right)\right) \times \Big/ 55.65 \quad (3)$$

where DMP represents the daily enteric CH_4 emissions (kg CH_4/day) estimated from measured dry matter intake; DMI is dry matter intake (kg/d) measured during the experimental period. GE is the gross energy content of the diets (MJ/kg DM). Ym is the CH_4 conversion factor, which is the extent to which feed energy is converted to CH_4 (IPCC, 2019). Ym values were estimated using equations interpolated from IPCC (2019) Table 10.12, which relates Ym to feed digestibility and energy content (Figure 2). The factor 55.65 (MJ/kg CH_4) is the energy content of CH_4.

The DMP for each treatment was used to calculate total enteric CH_4 for the duration of the experiment (CH_4 kg/head/experiment) and EI (kg CH_4 per kg WG, EI_{WG}).

Statistical analysis

We used the lme4 package in R and the lm function to fit an ANOVA with Breed and Treatment main effects and their interaction for LW, ADG, DMI, FCR, DMP, EI, and MY. The emmeans function was used to estimate least square means and standard errors and to conduct comparisons between different treatments, adjusted for multiple comparisons using Tukey. The $p < 0.05$ was considered a significant difference in the range of parameters estimated. ANCOVA was conducted to check if the ILW of the two breeds influences ADG.

Results

Chemical composition of feeds and diets

Among the feeds, digestibility followed the order: concentrate > pasture > hay, consistent with CP and fibre content differences (Figure 1). This gradient provided a broad range of diet quality for evaluating CH_4 emissions. Increasing the proportion of concentrate in diets raised CP from ~80 to ~120 g/kg DM and DE from ~59% to ~75%, while fibre content declined markedly (Table 1). This wide nutrient gradient supports testing CH_4 responses to dietary quality shifts.

Animal performance

There were differences in ADG between breeds and among treatments (Table 2). Analysis of covariance (ANCOVA), using initial live weight as a covariate, indicated that ILW was negatively associated with ADG. After adjusting for ILW, breed, and treatment effects, ADG remained significant. The FCR improved with higher concentrate levels, lowest in HayC100 (≈8.4 kg DMI/kg ADG).

Enteric methane emissions

4. The DMP decreased progressively with concentrate inclusion, falling by 64% in Boran and 67% in TSHZ from GrazC00 to HayC100 (Table 2). Methane conversion factors (Ym) also declined (≈60% reduction) as shown in Figure 2. The EI_{WG} followed similar trends, with the lowest in HayC100

TABLE 2 Least square means for the effects of breed and treatment diets on animal performance and enteric methane emissions in indigenous cattle in Tanzania over the 100-day experimental period.

Parameter	N/breed/ treatment	Breed	Treatments					Mean	p and SEM		
			GrazC00	GrazC50	HayC60	HayC80	HayC100		B	T	B*T
ADG, g/day	9	Boran	690	800	570	770	860	738	<0.05	<0.05	Ns
		TSHZ	560	630	540	580	810	624	16.8	26.6	37.6
		Mean	625^{bc}	715^{b}	555^{c}	675^{b}	835^{a}				
FCR*, kg DMI/kg ADG	27	Boran	-	-	12.0^{p}	9.1^{qrs}	8.9^{qrst}	10.0	<0.05	<0.05	<0.05
		TSHZ	-	-	9.8^{qr}	10.0^{q}	7.9st	9.3	0.196	0.24	0.34
		Mean	-	-	10.9^{a}	9.6^{b}	8.4^{c}				
DMP (g CH_4/day)	3	Boran	213^{p}	151^{r}	102^{s}	93^{t}	76^{u}	127	<0.05	<0.05	<0.05
		TSHZ	198^{q}	146^{r}	92^{t}	69^{v}	66^{v}	114	0.46	0.73	1.04
		Mean	206^{a}	148^{b}	97^{c}	81^{d}	71^{e}				
EI_{WG} (g CH_4/kg WG)	27	Boran	401	250	187	123.0	90	205	Ns	<0.05	Ns
		TSHZ	391	265	177	122.9	84	208	3.7	5.9	8.3
		Mean	396^{a}	257^{b}	182^{c}	123^{d}	87^{e}				

LS, Means with different superscripts differ ($p < 0.05$); a-e for treatment effect; p-u for B*T effect; *p*-value: the probability of values; SEM: standard error of the mean; GrazC00: grazing alone as control; GrazC50: grazing +50% *ad libitum* concentrate intake; HayC60, HayC80, and HayC100: *ad libitum* hay+60,80% and 100% of the *ad libitum* concentrate intake, respectively; Average daily live weight gains in grams; DMI: dry matter intake; FCR: feed conversion ratio. DMP: daily methane production: EI_{wg} emission intensity per weight gain. * FCR was not analyzed for pasture treatments as intake was indirectly derived from weight gain.

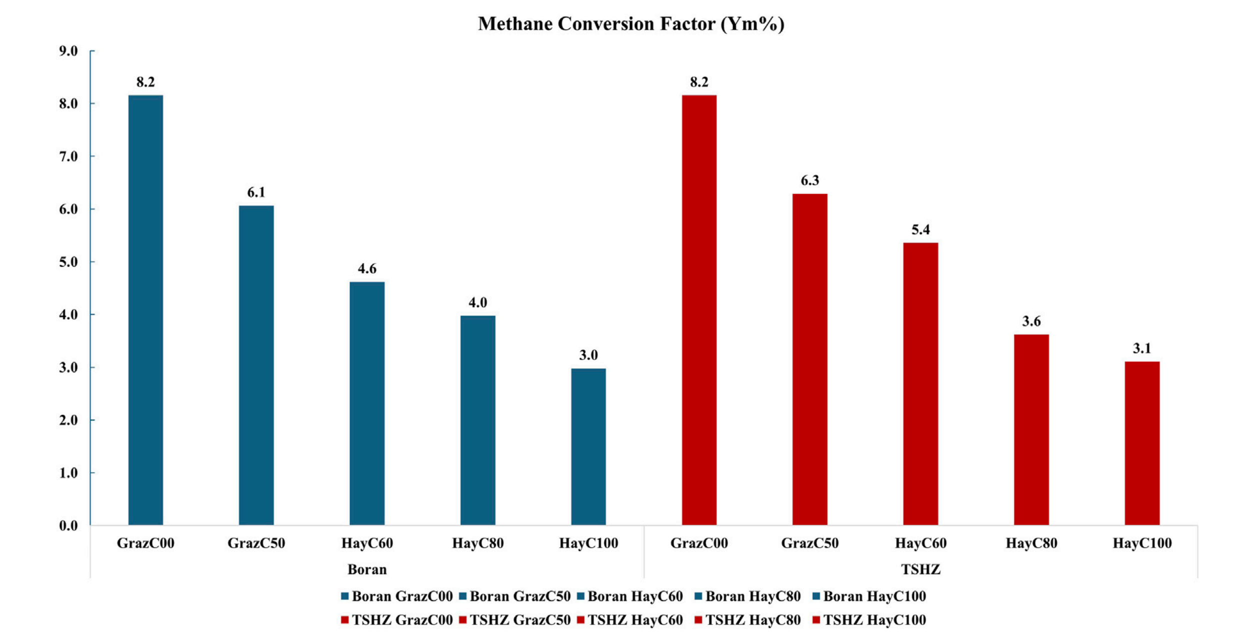

FIGURE 2
Enteric methane conversion factors (Ym, %) of the treatment diets estimated based on diet quality.

(~87–90 g CH_4/kg WG). Breed effects were minor and generally non-significant.

Discussion

Animal feed and performance

Among the diets, the concentrate mix contained the highest CP levels, primarily due to the inclusion of cottonseed cake and urea, both rich in CP. Increasing the proportion of this concentrate mix in the hay- or pasture-based diets improved overall nutrient density, as reflected in the HayC100 treatment, which provided 117–118 g CP/kg DM. These values align with the recommended CP range for fattening bulls (105–145 g CP/kg DM), reported by Menezes et al. (2019) and Costa-Roura et al. (2020). The HayC80 HayC60 diets for Boran cattle also met this range, supporting their intermediate growth performance relative to HayC100.

The highest performance observed for bulls on the HayC100 diet, or ad-libitum concentrate intake, is consistent with findings of Makarechian et al. (1995), who reported that ad-libitum concentrate showed higher ADG (1.8 kg/day) compared to those on restricted concentrate diets (1.3 kg/day) in weaned bulls in a study in Canada. The current study also demonstrated that DMI increased as the concentrate level in a hay diet was increased. Similarly, the current study demonstrated that DMI increased as the concentrate level in hay diets increased, consistent with Moletta et al. (2014), who reported a 14% increase in DMI when the concentrate level increased from 0.8% to 1.4% of live weight.

Although the HayC60 diet contained more concentrate than the GrazC50 diet, animal performance (WG and ADG) was higher in the GrazC50 diet. Although HayC60 had a higher dietary digestibility (DE) than GrazC50, animal performance was higher in GrazC50, suggesting factors beyond DE, such as voluntary intake or differences in nutrient availability from grazed forage, may have influenced weight gains. This is consistent with the findings of Davis et al. (2014), who reported that digestibility accounts for only 35% of the variation in WG.

Comparisons between breeds revealed that Boran cattle exhibited higher ADG across treatments. However, when accounting for ILW as a covariate, part of these differences can be explained by body size, as Boran cattle started the trial heavier than TSHZ. Importantly, a significant breed effect persisted even after this adjustment, suggesting that Boran cattle possess intrinsic growth or feed efficiency advantages beyond differences in starting weight. This nuance helps reconcile our findings with Retallick et al. (2017), who reported breed differences in feed efficiency indices, indicating both efficiency and size contribute to performance differences. Similarly, Salum et al. (2024) observed higher growth rates in Boran cattle than TSHZ, supporting our conclusion that diet composition (energy/protein density and digestibility) interacts with breed-specific growth potential to drive performance outcomes.

Enteric methane emissions

The present study found that DMP was highest in cattle on GrazC00, whereas concentrate supplementation resulted in reduced enteric CH_4 emissions. This difference is likely driven by the lower Ym and feed digestibility associated with concentrate supplementation. Pedreira et al. (2013) likewise reported a 33% reduction in Ym with increased grain supplementation, corroborating the trends observed in the present finding.

In the current study, Y_m values were obtained using IPCC equations rather than being directly measured. While increasing the concentrate ratio led to higher feed intake, it did not increase DMP, contrary to the findings of Jiao et al. (2014) and van Wyngaard et al. (2018). This highlights the critical role of Y_m values in influencing enteric CH_4 emissions, as emphasized by Beauchemin and McGinn (2006). The current study supports their conclusion that variations in Y_m have a greater impact on enteric CH_4 emissions than feed intake alone. It is important to note that Y_m values were not measured but derived using IPCC equations.

Furthermore, considering factors beyond the forage-to-concentrate ratio, such as feed digestibility and supplement type, is crucial (Jonker et al., 2015). Beauchemin and McGinn (2006) demonstrated that corn-based supplements produced lower CH_4 emissions compared to barley-based supplements. However, applying this approach in Tanzania may be challenging, as cattle are supplemented with the same concentrate mix, making it more relevant to focus on optimizing the forage-to-concentrate ratio rather than altering concentrate composition.

The magnitude of enteric CH_4 reduction in this study was substantially higher than that reported by Huhtanen and Huuskonen (2020), who reported only a 4% reduction in EI between diets with 70% and 30% concentrate supplementation. This difference likely stems from baseline diet quality. The Huhtanen and Huuskonen (2020) study involved diets already optimized for lower emissions, hence the additional reduction from increasing concentrate levels would be smaller (Muetzel et al., 2024). Their control diet (grass silage) had higher digestibility than the grazed pasture in this study, narrowing the forage–concentrate gap. By contrast, the present study's forage-only diet (GrazC00) had low digestibility, magnifying the impact of concentrate supplementation on enteric CH_4 mitigation. These findings underscore the originality of this work, conducted under extensive Tanzanian conditions that differ markedly from the temperate systems in most published literature.

Breed differences in DMP were also observed, with Boran cattle producing more enteric CH_4 than TSHZ. This is consistent with their higher DMI, linked to larger body size (Stakelum and Connolly, 1987; Walker et al., 2015). Importantly, Y_m value was diet-based and not adjusted for breed, so potential enteric CH_4 yield differences attributable to breed physiology may have been underestimated. Despite Boran cattle being younger (1–2 years old) than TSHZ cattle (1.5–2.5 years), their greater frame size resulted in higher intake and emissions (MLF, 2018).

A limitation of this study is that, while higher concentrate levels effectively improved animal performance and reduced emission intensity, we did not assess the economic feasibility of different supplementation levels. Future work should include cost–benefit analyses to determine the most practical supplementation strategies for producers.

Conclusion

Finishing cattle on pasture with concentrate supplementation proved to be a viable strategy when high-quality pasture is available.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal study was approved by Tanzania Livestock Research Institute. The study was conducted in accordance with the local legislation and institutional requirements.

Author contributions

AW: Data collection, Data cleaning, Formal Analysis, Writing – original draft. EG: Methodology, Formal Analysis, Writing – original draft. MW: Conceptualization, Methodology, Fund acquisition, writing – review and editing. GL: Conceptualization. JP: Formal Analysis. CA: Methodology, visualization, writing – review and editing. All authors contributed to the article and approved the submitted version.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The Tanzanian experiment was jointly funded by the Tanzania National Ranching Company (NARCO) and the DANIDA-ENRECA IGMAFU Project (51-08-LIFE). Additional support for this study was provided by the CGIAR Initiatives Mitigate+: Research for Low Emissions Food Systems, Livestock and Climate, and the CGIAR Science Programs on Sustainable Animal and Aquatic Foods, Climate Action, and Multifunctional Landscapes, all supported by contributors to the CGIAR Trust Fund. Further support was provided by the European Union through the EU-DeSIRA ESSA project (Earth Observation and Environmental Sensing for Climate-Smart Sustainable Agropastoralism Ecosystem Transformation in East Africa). The content of this article is the sole responsibility of the authors and does not necessarily reflect the views of the European Union. The project also received funding from the New Zealand Government in support of the Livestock Research Group of the Global Research Alliance on Agricultural Greenhouse Gases.

Acknowledgments

The authors are grateful to the Tanzania National Ranching Company (NARCO), and DANIDA-ENRECA IGMAFU Project.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. During the preparation of this work, the authors used ChatGPT to improve the language and readability of the manuscript. After using this ChatGPT, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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References

AOAC International (2006). *Official methods of analysis*. 18th ed. Arlington, VA, USA: AOAC International.

Asimwe, L., Kimambo, A., Laswai, G., Mtenga, L., Weisbjerg, M. R., and Madsen, J. (2016). Economics of finishing Tanzania shorthorn zebu cattle in feedlot and optimum finishing period. *Livest. Res. Rural. Dev.* 28, 1–11.

Beauchemin, K. A., and McGinn, S. M. (2006). Enteric methane emissions from growing beef cattle as affected by diet and level of intake. *Can. J. Anim. Sci.* 86, 401–408. doi:10.4141/a06-021

Berhanu, Y., Olav, L., Nurfeta, A., Angassa, A., and Aune, J. B. (2019). Methane emissions from ruminant livestock in Ethiopia: promising forage species to reduce CH4 emissions. *Agriculture* 9, 130. doi:10.3390/agriculture9060130

Collins, W. J., Webber, C. P., Cox, P. M., Huntingford, C., Lowe, J., Sitch, S., et al. (2018). Increased importance of methane reduction for a 1.5 degree target. *Environ. Res. Lett.* 13, 054003. doi:10.1088/1748-9326/aab89c

Costa-Roura, S., Balcells, J., de La Fuente, G., Mora-Gil, J., Llanes, N., and Villalba, D. (2020). Effects of protein restriction on performance, ruminal fermentation and microbial community in holstein bulls fed high-concentrate diets. *Animal Feed Sci. Technol.* 264, 114479. doi:10.1016/j.anifeedsci.2020.114479

CSIRO (2007). *Nutrient requirements of domesticated ruminants*. Collingwood, VIC, Australia: CSIRO Publishing.

Davis, M., Freetly, H., Kuehn, L., and Wells, J. (2014). Influence of dry matter intake, dry matter digestibility, and feeding behavior on body weight gain of beef steers. *J. Animal Sci.* 92, 3018–3025. doi:10.2527/jas.2013-6518

Desiere, S., Hung, Y., Verbeke, W., and D'Haese, M. (2018). Assessing current and future meat and fish consumption in sub-sahara Africa: learnings from FAO food balance sheets and LSMS household survey data. *Glob. Food Secur.* 16, 116–126. doi:10.1016/j.gfs.2017.12.004

Huhtanen, P., and Huuskonen, A. (2020). Modelling effects of carcass weight, dietary concentrate and protein levels on the CH4 emission, N and P excretion of dairy bulls. *Livestock Sci.* 232, 103896. doi:10.1016/j.livsci.2019.103896

IPCC (2019). "Emissions from livestock and manure managemen," in *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories, volume 4: agriculture, forestry and other land use*. Editors Buendia, E. C., Tanabe, K., Kranjc, A., Jamsranjav, B., Fukuda, M., and Ngarize, S. (Geneva, Switzerland: IPCC).

Jiao, H., Dale, A., Carson, A., Murray, S., Gordon, A., and Ferris, C. (2014). Effect of concentrate feed level on methane emissions from grazing dairy cows. *J. Dairy Sci.* 97, 7043–7053. doi:10.3168/jds.2014-7979

Jonker, A., Muetzel, S., Molano, G., and Pacheco, D. (2016). Effect of fresh pasture forage quality, feeding level and supplementation on methane emissions from growing beef cattle. *Anim. Prod. Sci.* 56, 1714–1721. doi:10.1071/an15022

Kanuya, N., Matiko, M., Nkya, R., Bittegeko, S., Mgasa, M., Reksen, O., et al. (2006). Seasonal changes in nutritional status and reproductive performance of zebu cows kept under a traditional agro-pastoral system in Tanzania. *Trop. Anim. Health Prod.* 38, 511–519. doi:10.1007/s11250-006-4419-z

Kibona, C. A., Yuejie, Z., and Tian, L. (2022). Factors that influence beef meat production in Tanzania. A cobb-douglas production function estimation approach. *PLoS One* 17, e0272812. doi:10.1371/journal.pone.0272812

Korir, D., Eckard, R., Goopy, J., Arndt, C., Merbold, L., and Marquardt, S. (2022). Effects of replacing brachiaria hay with either Desmodium intortum or dairy concentrate on animal performance and enteric methane emissions of low-yielding dairy cows. *Front. Animal Sci.* 3, 963323. doi:10.3389/fanim.2022.963323

Lyatuu, E. T., Komwihangilo, D., Msuta, G., Kelya, N., Okeyo, M., Ojango, J., et al. (2023). Unlocking total factor productivity of smallholder dairy farmers in Tanzania. *Tanzan. J. Agric. Sci.* 22, 338–345.

Makarechian, M., Arthur, P., Liu, M., and Okine, E. (1995). The effect of level of concentrate in feedlot diets on growth, health and carcass characteristics of bulls. *J. Appl. Animal Res.* 7, 49–62. doi:10.1080/09712119.1995.9706050

Mdoe, N. S. Y., Mlay, G. I., Boniface, G., Isinika, A. C., and Magomba, C. (2021). Livestock, crop commercialisation and poverty reduction among rural households in the Singida region, Tanzania. *APRA, Work. Pap. 65, Brighton Future Agric. Consort.* doi:10.19088/APRA.2021.024

Menezes, A. C. B., Valadares Filho, S. C., Pacheco, M. V., Pucetti, P., Silva, B. C., Zanetti, D., et al. (2019). Oscillating and static dietary crude protein supply. I. Impacts on intake, digestibility, performance, and nitrogen balance in young nellore bulls. *Transl. Animal Sci.* 3, 1205–1215. doi:10.1093/tas/txz138

Michael, S., Mbwambo, N., Mruttu, H., Dotto, M., Ndomba, C., da Silva, M., et al. (2018). *Tanzania livestock master plan*. Nairobi, Kenya: International Livestock Research Institute ILRI.

MLF (2018). *Tanzania livestock master plan*. Ministry of Livestock and Fisheries. Available online at: https://www.mifugouvuvi.go.tz.

MLFD (2015). Tanzania livestock modernization initiative (TLMI). *Ministry Livestock Fish. Dev*. Available online at: https://livestocklivelihoodsandhealth.org.

Moletta, J. L., Torrecilhas, J. A., Ornaghi, M. G., Passetti, R. A. C., Eiras, C. E., and Prado, I. N. d. (2014). Feedlot performance of bulls and steers fed on three levels of concentrate in the diets. *Acta Sci. Anim. Sci.* 36, 323–328.

Msalya, G., Kim, E.-S., Laisser, E. L., Kipanyula, M. J., Karimuribo, E. D., Kusiluka, L. J., et al. (2017). Determination of genetic structure and signatures of selection in three strains of Tanzania shorthorn zebu, boran and Friesian cattle by genome-wide SNP analyses. *PLoS One* 12, e0171088. doi:10.1371/journal.pone.0171088

Muetzel, S., Hannaford, R., and Jonker, A. (2024). Effect of animal and diet parameters on methane emissions for pasture-fed cattle. *Animal Prod. Sci.* 64. doi:10.1071/an23049

Mushi, D. E. (2020). Feedlot performance of Tanzanian shorthorn zebu finished on local feed resources. *Trop. Anim. Health Prod.* 52, 3207–3216. doi:10.1007/s11250-020-02346-y

Mushi, D. E., Eik, L. O., Bernués, A., Ripoll-Bosch, R., Sundstøl, F., and Mo, M. (2015). "Reducing GHG emissions from traditional livestock systems to mitigate changing climate and biodiversity," in *Sustainable intensification to advance food security and enhance climate resilience in Africa*. Editors L. Rattan, R. S. Bal, L. M. Dismas, K. David, O. H. David, and O. Lars (Switzerland: Springer International Publishing), 343–365.

Mwangi, F. W., Charmley, E., Gardiner, C. P., Malau-Aduli, B. S., Kinobe, R. T., and Malau-Aduli, A. E. (2019). Diet and genetics influence beef cattle performance and meat quality characteristics. *Foods* 8, 648. doi:10.3390/foods8120648

Oddy, V., Robards, G., and Low, S. (1983). "Prediction of *in vivo* dry matter digestibility from the fibre and nitrogen content of a feed," in *Feed information and animal production. Commonwealth agricultural bureaux*. Editors G. E. Robards and R. G. Packham (Farnham Royal, UK), 395–398.

Pedreira, M. d.S., Oliveira, S. G. d., Primavesi, O., Lima, M. A. d., Frighetto, R. T. S., and Berchielli, T. T. (2013). Methane emissions and estimates of ruminal fermentation parameters in beef cattle fed different dietary concentrate levels. *Rev. Bras. Zootec.* 42, 592–598. doi:10.1590/s1516-35982013000800009

Retallick, K., Bormann, J., Weaber, R., MacNeil, M., Bradford, H., Freetly, H., et al. (2017). Genetic variance and covariance and breed differences for feed intake and average daily gain to improve feed efficiency in growing cattle. *J. Animal Sci.* 95, 1444–1450. doi:10.2527/jas.2016.1260

Salum, K. A., Laswai, G. H., and Mushi, D. E. (2024). Performance of boran and two strains of Tanzania short horn zebu cattle fed on three different diets. *Int. J. Animal Sci. Technol.* 8, 21–30. doi:10.11648/j.ijast.20240802.12

Seif, S. K., and Kipkirui, E. (2024). Harnessing Tanzania's rangelands to mitigate methane emissions from livestock enteric fermentation. *Eur. J. Theor. Appl. Sci.* 2, 514–517. doi:10.59324/ejtas.2024.2(2).44

Selemani, I. S., Eik, L. O., Holand, Ø., Ådnøy, T., Mtengeti, E. J., Mushi, D. E., et al. (2015). "Feeding strategies for improved beef productivity and reduced GHG emission in Tanzania: Effect of type of finish-feeding on carcass yield and meat quality of zebu steers," in *Sustainable intensification to advance food security and enhance climate resilience in Africa*. Editors R. Lal, B. R. Singh, D. L. Mwaseba, D. Kraybill, D. O. Hansen, and L. O. Eik (Switzerland: Springer), 367–382.

Stakelum, G., and Connolly, J. (1987). Effect of body size and milk yield on intake of fresh herbage by lactating dairy cows indoors. *Ir. J. Agric. Res.* 26, 9–22.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., Rosales, M., et al. (2006). *Livestock's long shadow: environmental issues and options*. Food and Agriculture Org.

Suleiman, R. (2018). "Local and regional variations in conditions for agriculture and food security in Tanzania," in *AgriFoSe2030 report*.

Van Soest, P. J., Robertson, J. B., and Lewis, B. A. (1991). Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. *J. Dairy Sci.* 74, 3583–3597. doi:10.3168/jds.s0022-0302(91)78551-2

van Wyngaard, J. D., Meeske, R., and Erasmus, L. J. (2018). Effect of concentrate level on enteric methane emissions, production performance, and rumen fermentation of Jersey cows grazing kikuyu-dominant pasture during summer. *J. Dairy Sci.* 101, 9954–9966. doi:10.3168/jds.2017-14327

Walker, R., Martin, R., Gentry, G., and Gentry, L. (2015). Impact of cow size on dry matter intake, residual feed intake, metabolic response, and cow performance. *J. Animal Sci.* 93, 672–684. doi:10.2527/jas.2014-7702

White, R. R., Brady, M., Capper, J. L., and Johnson, K. A. (2014). Optimizing diet and pasture management to improve sustainability of US beef production. *Agric. Syst.* 130, 1–12. doi:10.1016/j.agsy.2014.06.004

Odessa centre | Pastoralism Research, Policy and Practice

TYPE Review
PUBLISHED 03 December 2025
DOI 10.3389/past.2025.15362

Check for updates

OPEN ACCESS

EDITED BY
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RECEIVED 01 August 2025
REVISED 19 October 2025
ACCEPTED 23 October 2025
PUBLISHED 03 December 2025

CITATION
Franca A, Arca P, Altana GM, Assouma MH, Manzano P, Vagnoni E, Vayssières J, Vigne M, Zeren G and Scoones I (2025) Are impact assessment approaches effective for addressing researches on GHG emissions from pastoral systems?
Pastoralism 15:15362.
doi: 10.3389/past.2025.15362

Are impact assessment approaches effective for addressing researches on GHG emissions from pastoral systems?

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The environmental impacts of livestock systems have been often under discussion in relation to their negative impacts to climate change. For several years, conventional assessments of such impacts have been preferably adapted and implemented on industrialized livestock systems. On the contrary, when applied to extensive systems such as pastoral ones, they have created distortions in the attribution of the related climate impacts. In the context of the in-depth studies on the topic conducted by the ERC research project PASTRES, several case studies of contextualized research on GHG emissions of three different pastoral systems in Africa, Asia and Europe were analyzed. Different assessment methodologies were compared, without or with the use of the Life Cycle Assessment (LCA) approach. Some limitations emerged from the analysis that concerned: 1) the analysis of emissions in a broader context/ecosystem-based approach 2) the definition of Functional Units 3) the provision of ecosystem services, with particular attention to biodiversity and the inclusion of C sequestration within the LCA calculation. These limitations penalize a complete and adequate estimate of environmental impacts and, consequently, a correct evaluation of implementation scenarios that aim to create conditions of greater sustainability of pastoral systems. The analysis suggests that the assessment of the impacts of pastoral systems, strongly characterized by land occupation, use of environmental resources, seasonal climate and social relations, requires a systemic approach that adapts and extends the

LCA methodology, through the harmonization of alternative metrics based on both conventional LCA and the assessment of the social and nutritional implications of pastoral farming.

KEYWORDS

pastoral systems, GHG emissions, life cycle assessment, ecosystem services, environmental impacts

Introduction

Extensive livestock systems, including pastoralism, involve many millions of people across rangelands covering over half the world's land surface. These systems play numerous roles, shaping marginalized areas with their multifunctionality, ensuring livelihoods for local communities and contributing to economic development through employment opportunities and value creation (Ragkos and Nori, 2016). The multifunctionality of pastoral systems is revealed in the form of a whole range of environmental, social and economic functions of the primary sector, since, in addition to marketable goods (food and fibre), agriculture produces a range of non-market products (OECD, 2001).

The environmental impacts of extensive livestock systems are currently under discussion among media campaigns, researches and variegate narratives in relation to their presumed cause-effect relationship with regard to climate change. A report edited by Houzer and Scoones (2021) in the framework of the ERC funded project PASTRES (pastres.org), highlighted how a better understanding of extensive livestock impacts on greenhouse gas emissions (GHG) is essential. Environmental assessment approaches such as Life Cycle Assessment (LCA) are widely used to estimate the GHG emission intensity of livestock systems (Goglio et al., 2023). LCAs allow the identification of environmental hotspots and effective mitigation solutions and are considered essential tools to guide environmental strategies within the ecological transition of production systems (Hellweg et al., 2023). The vast majority of LCA analyses on livestock systems examine standardized industrial systems, mostly from Europe and North America, in which a limited set of inputs and outputs are analyzed (Houzer and Scoones, 2021). On the other hand, data from important pastoral regions are insufficiently represented in numerous global studies, leading to potentially misleading estimates (Scoones, 2023). Clark and Tilman (2017) showed that only about 13% of assessments of GHG emissions from livestock systems comes from Asia, Latin America and Africa, where extensive livestock systems and pastoralism are widely diffused (Figure 1).

Using such simplistic and uniform criteria to evaluate the environmental impacts of such multifunctional, complex, dynamic and diversified systems, such as pastoral ones, would seem reductive (Houzer and Scoones, 2021). The consequence is that conventional assessments may cause potential flaws in the examination of such multifunctional extensive pastoral systems and rarely reflect pastoral contexts, creating distortions and misunderstandings in debates about the climate impacts (Scoones, 2023). Only a few studies performed comprehensive assessment of the pastoral production process, adequately reflecting its multifunctionality, including other relevant impact categories rather than global warming, such as land use, water consumption, biodiversity, carbon sequestration (Aguilera et al., 2021; Atzori et al., 2017a) and other related ecosystem services

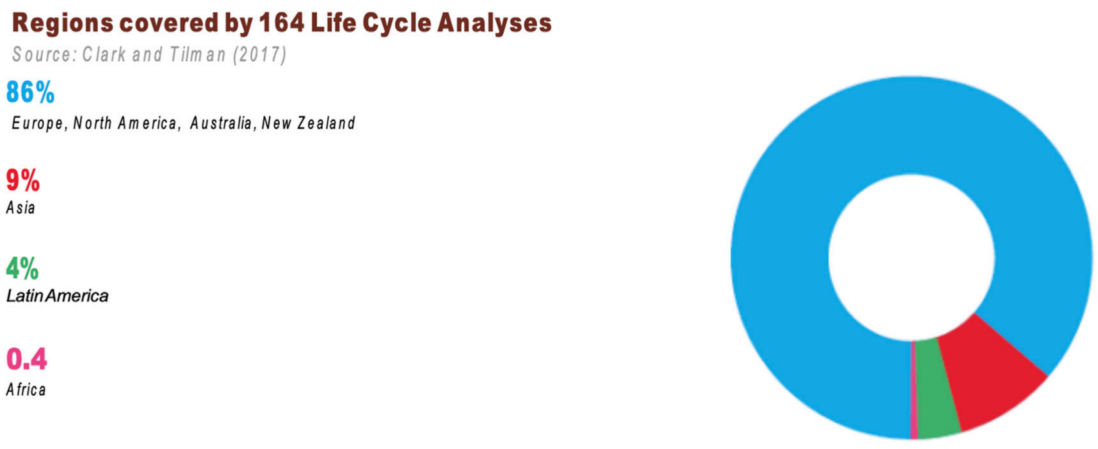

FIGURE 1
Regions covered by 164 Life Cycle Analyses (From Houzer and Scoones, 2021, source: Clark and Tilman, 2017).

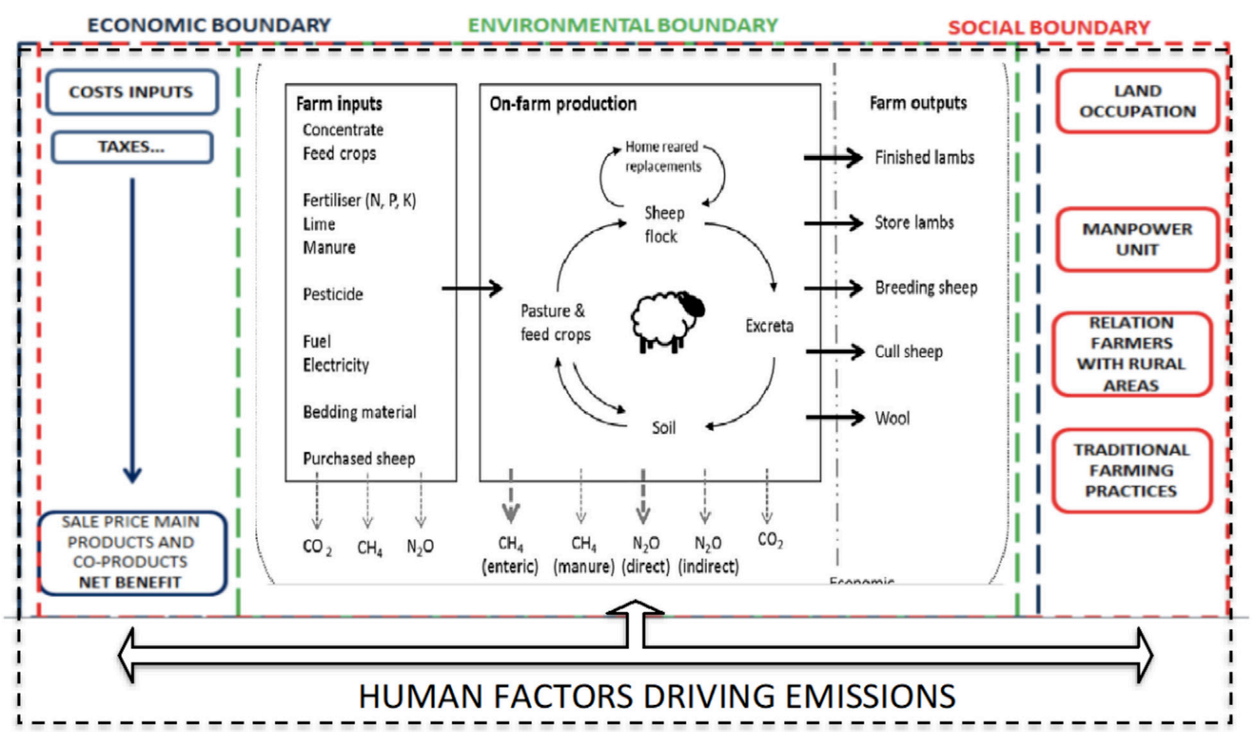

FIGURE 2
Environmental system boundaries inclusive of economic and social aspects for sheep farming systems (Adapted from Jones et al., 2014 and Batalla et al., 2014). Elaborated by LIFE SheeptoShip, deliverable A.2.1 Scientific and technical state of the art (Atzori, 2017b).

provided by livestock systems (Tsonkova et al., 2014). Ecosystem services (ES) are defined by the Millennium Ecosystem Assessment (2005) as "benefits people obtain from ecosystems". They are divided into provisioning ES (i.e. production of food and other materials) and non-provisioning ES (regulating, cultural, and supporting). Multifunctionality and ecosystem services have often been considered as two very different approaches, the first one being farm-centered versus the second one more service-oriented, with limited interactions between scientific communities using those approaches (Huang et al., 2015).

Some recent studies have highlighted how the study of GHG emissions related to extensive livestock farming systems cannot avoid developing analysis methodologies that take into account the variables that characterize these multifunctional systems. Vayssières et al. (2024) have pointed out that when studying pastoral systems, in which transhumance and mobility are the main traits and inputs are very low, C balance assessment at ecosystem scale seems more appropriate to investigate GHG balance, applying a systemic view and making strong efforts in the system boundary definition, to better consider all important sources of GHG emissions and C storage. Very recently, Vagnoni et al. (2024) revealed that the environmental performances of extensive sheep farming systems varied significantly depending on the Functional Unit (FU) used. FU is a standardized reference measure representing the function or service provided by a product, process, or system. It quantifies and normalizes all input (resources, energy) and output (emissions, waste) flows of the study, making the results comparable across different alternative systems. For instance, the Carbon Footprint (CF) calculated per kg of milk (fat and protein corrected milk) highlighted the dominant role of enteric methane emissions, while the area-based FU offered insights into the resource use per hectare, revealing how land management practices influence overall sustainability (Aguilera et al., 2021; Batalla et al., 2015). Therefore, there is still considerable uncertainty today about how to implement an analysis of GHG emissions from pastoral systems and how to correctly interpret the multifunctionality of these systems. The above mentioned PASTRES Report moved also in such context and indicated that a refined analytical approach, starting from a context-based data campaign, is needed to focus on the challenges and potentials of extensive livestock systems in a climate change mitigation scenario. The PASTRES Report took as reference of a more holistic, integrated systems level analysis, three contextualized research on GHG emissions of pastoral systems, coming from West Africa (Senegal), Asia (Qinghai-Tibetan, China) and Europe (Sardinia, Italy).

Following an inductive approach and aiming to contribute to the heated debate on the actual environmental role of extensive livestock systems, this article goes to the heart of the matter, starting from an in-depth comparison of the methodologies utilized for GHG emission estimation in the three PASTRES case-studies (Section *Description of case studies*) and referring to the analysis of the results obtained with the application of these three different methodological approaches (Section *Estimation of GHG emissions in the three case studies: methodologies used and main results obtained*). Then, the article critically analyses the limitations that emerged in the three case studies (Section *Issues emerged from the three case studies*) and, finally, provides insights (Section *Insights and suggestions for an adequate study of GHG emissions from extensive livestock farming systems*), aimed at proposing a critical perspective on the methodological challenges to make the assessment of GHG emissions from pastoral farms more reliable and appropriate. Finally, a specific focus on LCA approach is presented (Section *Further remarks from LCA research for extensive livestock farming*), aimed at proposing a reference LCA model. The paper aims to contribute to a deeper understanding of the positioning and role of these systems in the broader context of the ecological transition of agri-food systems.

Description of case studies

The PASTRES Report by Houzer and Scoones (2021) focuses on three cases – from West Africa (Senegal), Asia (Qinghai-Tibetan, China) and Europe (Sardinia, Italy) – that have adopted different and differently sophisticated approaches, adapting them to each local pastoral setting. In Table 1 the main characteristics and some methodologically relevant elements of the three case studies are reported.

In the Chinese and Italian case studies, two different methodological approaches were followed for estimating GHG emissions.

West Africa (Senegal)

A study by Assouma et al. (2019a), Assouma et al. (2019b) was set in the pastoral area of Ferlo, Senegal, with a "landscape" ecosystem approach measuring the overall carbon balance of the Widou Thiengoly service area borehole, a 706 km^2 circular area that hosts 354 pastoral camps with a population of 4,800 inhabitants. The total livestock population of the area is about 25,000 free grazing animals, including cattle (54% of total livestock units), sheep (27%), goats (8%), donkeys (8%) and horses (3%). The area under study was subdivided into different units based on land use, the type of vegetation and soils (Assouma et al., 2017), with grazing lands occupying the greater area (90% of the total area) with sparsely wooded savannas, and the remaining area shared between settlements, forest plantations, natural ponds, boreholes and enclosures, set up for experimental plots. In this area, a formal research project was set up to assess all main sources of GHG emissions and C sinks of the whole pastoral ecosystem, taking into account not only anthropogenic sources.

Asia (China, Qinghai-Tibetan Plateau)

Two territorial-scale LCA-based studies were carried out in Qinghai Province of China on GHG emission of pastoral systems in transition. In the first study (Zhuang and Li, 2017), Chanaihai village and Guinan Grassland Development Limited Company offered the opportunity to compare a traditional pastoral system with a livestock husbandry system, combining extensive and semi-intensive management systems, respectively. The Chanaihai pastoral system is characterized by 431 households practicing transhumant seasonal pastoralism on 18,779 ha of rangelands, where 63,701 sheep and 4,000 yaks are reared. The different seasonal pastures provide for the needs of livestock production throughout the year. The Grassland Development Limited Company operates an intensive livestock husbandry system, with a combination of rangelands, feedlots, artificial grasslands and stations for forage and fertilizer processing. This demonstration area is characterized by 15,800 ha of rangelands and 2000 ha of artificial grassland supporting 80,000 sheep. The rangeland is utilized for grazing, similarly to the extensive system. Feedlots are only used for rams feeding, while the rest sheep are still grazing on the rangeland. The study assessed and compared the GHG emissions under these two production management systems, and explored the major causes for the differences, comparing GHG emissions from a pastoral system with a more industrialized intensive system, involving feedlots, seeded pastures and imported feed (Zhuang and Li, 2017).

On the other side, in Sichuan Province of China, GHG emissions under two rangeland management systems were estimated in the two villages Axi and Xiareer (Zhuang et al., 2019). The two villages have similar socio-economic and ecological environments but different forms of rangeland management systems. Axi village allocated its rangelands to individual households, with all-year continuous grazing under the individual use of rangeland with fences demarcating boundaries. In the Axi territory, 20,000 ha of grassland provide pastures to 16,000 sheep and 15,000 yaks, reared by 203 households with around 1,000 herders. Xiareer village has a community-based system for the common use of the whole rangeland. Xiareer village has 12,000 ha of grassland grazed by 20,180 sheep and 6,000 yaks, reared by 140 households with 802 herders. This study compared the Axi household-based system under continuous grazing in fenced, individualised plots with the Xiareer more traditional community-based system, involving movement across four seasonal pastures.

Europe (Sardinia, Italy)

The Sardinian case study is based on the analysis of a transition from a semi-intensive to a semi – extensive dairy sheep farming system (Vagnoni and Franca, 2018; Arca et al., 2021). A farm located in North Sardinia, Italy (Osilo municipality), shifted from an intensive feeding system based on grain-cereal crops, annual forage crops and irrigated crops, with cheese industry-oriented production (milk sold to the cheese

TABLE 1 Main characteristics and some methodologically relevant elements of the three case studies.

Country	Region	Reference	Approach	Case study scale	Extension (ha)	Farming system	Livestock	Functional unit	LCI	Output
Senegal	Widou Thiengoly	Assouma et al. (2019a)	Ecosystem C balance	Landscape scale	63,542 (Widou Thiengoly Service Area)	Extensive on common rangelands	33,095 LU: Cattle (54%), Sheep (27%), Goat (8%), Donkey (3%), Horses (8%)	not considered	no	Measurement and estimation of all GHG fluxes
China 1	Guinan county	Zhuang and Li (2017)	LCA from cradle to gate*	Territorial scale	18,779 (Chanaihai Village)	Extensive on common rangelands	63,701 Sheep, 4,000 Yaks	1 ha of total area 1 kg carcass weight	no	GHG emission inventory
					17,800 (Guinan GDLC)	Semi-intensive animal husbandry			no	
China 2	Ruoergai county	Zhuang et al. (2019)	LCA from cradle to gate	Territorial scale	20,000 (Axi Village)	Extensive on household rangelands	16,000 Sheep 15,000 Yaks	1 kg carcass weight	no	GHG emissions inventory
					12,000 (Xiareer Village)	Extensive on common rangelands	20,180 Sheep 6,000 Yaks			
Italy 1	Sardinia	Vagnoni and Franca (2018)	LCA from cradle to gate	Farm scale	85 (Pulinas farm, Osilo)	Semi-extensive on sedentary farms	340 dairy sheep	1 kg of FPCM	yes	Carbon footprint (IPCC) + other 17 impact categories (ReCiPe endpoint)
Italy 2	Sardinia	Arca et al. (2021)	LCA from cradle to gate	Farm scale	85 (Pulinas farm, Osilo)	Semi-extensive on sedentary farms	340 dairy sheep	1 kg of FPCM 1 ha of UAA	yes	Carbon footprint (IPCC) + other 17 impact categories (ReCiPe endpoint)

industry), towards a semi-extensive system switched to valorisation of natural feed resources. Extensification of the production system was part of a wider new farm management strategy oriented to a direct on-farm cheese manufacturing, and to reducing production costs. Extensification slightly reduced flock size (from 340 to 320 sheep) and animal diet switched from hay/silage consumption from temporary grasslands to the grazing of legume-rich permanent grasslands that increased from 10% to 90% of 70 ha farm agricultural area, with a strong reduction of concentrates, fertilizers and irrigation use. This diversification process has certainly increased the complexity of the work on the farm, requiring know-how on cheese making and marketing, but valorising the role of young family members employed into the renewed farming system (Dumont et al., 2022).

Estimation of GHG emissions in the three case studies: methodologies used and main results obtained

The three different methodological approaches utilized for estimating the GHG emissions are described. Here we report exclusively the main methodological options proposed by the three studies. For details and further information, we refer the reader to the individual papers indicated in the text and in Table 2.

West Africa (Senegal)

The conceptual model based on an ecosystem approach was aimed at estimating the main C and N stocks and flows at Sahelian pastoral ecosystem level. In detail, GHG emissions to the atmosphere (CO_2, CH_4, N_2O), were analysed accounting for enteric fermentation (CH_4) emitted by both livestock and termites, anaerobic degradation (CH_4) in standing water of ponds closed to the boreholes, organic matter decomposition (N_2O and CH_4), combustion (CO_2) and bush fires from grasses and trees (N_2O and CH_4). On the other hand, C sinks are represented by woody plants, deposited excreta and bodies of the animals. In the study, Assouma et al. (2019a) have found that the emission estimated by IPCC Tier I protocol for Africa (25 g dry matter/kg live weight) is probably too high for the pastoral landscape they observed. The authors proposed a new standard of either 18 g dry matter/kg live weight for cattle and 34 g/kg live weight for small ruminants, or 73 g/kg metabolic weight for all ruminants, as a result of this ecosystem approach, revealing a level of dry matter intake/kg live weight for cattle and for small ruminants lower than that estimated by the current standard of IPCC used in emissions calculations. This approach application permitted finding a negative C balance, which clashes with the negative image of African livestock consolidated by previous sectorial and LCA studies (Gerber et al., 2013), based only on anthropogenic sources of GHG.

Asia (China, Qinghai-Tibetan Plateau)

Two studies were carried out, both applying an LCA approach. In the first one (China 1), the study was based on the GHG emission inventory and a calculation method applied to two different livestock production systems (traditional pastoral vs. combined extensive/intensive). The GHG emission inventory included enteric CH_4 emission, direct and indirect N_2O emission from manure, CH_4 soil emission, N_2O and carbon emission/uptake, and emission from manure combustion. In addition, carbon emission/uptake from artificial grassland, and feedlot, and other external inputs (seed, diesel, electricity, organic fertilizer, etc.) were accounted for in the estimation of GHG emission in the combined extensive/intensive system. GHG emissions were higher in the intensive system, both per ha of area and per kg of carcass weight. The intensive system had a slightly lower production of methane, but with a reduction of methane emissions significantly lower than is suggested by the literature. The reduction of methane emissions in combined extensive/intensive system was significantly lower than often suggested by the literature, at 6.95% rather than between 22% and 62%. Moreover, the higher emissions in the traditional pastoral system were offset by lower emissions from external inputs and higher levels of C sequestration. Overall, the intensive system had 40% higher emissions per carcass weight.

In the second study (China 2) two livestock production systems (household-based under continuous grazing vs. traditional community-based system) were compared. LCA was used to evaluate the GHG emissions intensity of both systems. Enteric emissions and manure CH_4, and N_2O emissions were calculated using the S-GAF model (Zhuang and Li, 2017). The soil CH_4 and N_2O emission data were measured on-site by using the static chamber method. On the other hand, soil organic carbon was measured by sampling the topsoil (0–30 cm) in 2011 and 2014 on-site. As a result, on-farm emission patterns of the two systems were broadly similar (around 9 kg CO_2-eq per kg of meat), but when the C sequestration levels were added, the contrasts were striking. The traditional community-based system showed a positive C balance (0.62 kg CO_2-eq per kg meat), while the household-based system had a relatively high net emission level (10.51 kg CO_2-eq per kg meat). This huge difference is explained by the authors through differences in soil C sequestration, due to the predominance of perennials, incorporation of litter and the spreading and trampling of manure in the traditional system (Chen et al., 2015). Overall, the study reported that light grazing contributes to soil C and N sequestration, while enclosed areas have compacted soil, less mineralization, lower root biomass and reduced quality of forage biomass from artificial grassland.

Europe (Sardinia, Italy)

The LCA was conducted using two different impact assessment methods: Carbon Footprint-IPCC (2013) and ReCiPe endpoint (H) V1.12. From an environmental point of view, extensification of this dairy sheep system increased

TABLE 2 GHG estimations and related references for the analysed case studies.

Country	Approach	GHG emissions estimates	Reference for formulae	Direct measurements
Senegal	Ecosystem C balance	Enteric fermentation	Archimède et al. (2011)	
		GHG fluxes from soil and water	Assouma et al. (2017)	
		Other GHG emissions (termites, fuel consumption)	Traoré et al. (2008), Jamali et al. (2011)	
		Livestock C accumulation		Estimates measuring changes in the livestock population
		Plant C accumulation (trees and shrubs)		Direct measurements and estimates
		Soil C accumulation (stocks)		Variations in C monthly stored in the soil (C inputs – C output)
		Soil C accumulation (C inputs)		Organic matter deposited as livestock excreta, litter from trees, shrubs and herbaceous plants (root turnover) and rhizodeposition
		Soil C accumulation (C outputs)		Static chamber
China 1	LCA from cradle to gate	CH_4 from enteric emissions	Zhuang and Li (2017)	
		CH_4 from manure	Zhu (2014)	
		Manure direct N_2O emission	Zhu (2014)	
		Manure indirect N_2O emission	Zhu (2014)	
		Rangeland soil C change	Yang et al. (2010)	
		Rangeland soil CH_4 change	Zhang et al. (2010), Hu (2010), Jin et al. (2015), Yu et al. (2013), Zhang et al. (2014)	
		Rangeland soil N_2O emission	Zhang et al. (2010), Hu (2010), Zhang et al. (2014)	
		Artificial grassland soil C change	Animal husbandry bureau in Guinan (2007), experiment (2014)	
		Artificial grassland soil CH_4 change	Jin et al. (2015)	
		Artificial grassland soil N_2O direct emission	Jin et al. (2015)	
		Artificial grassland soil N_2O indirect emission	Jin et al. (2015)	
		Feedlot manure CH_4 emission	Xu et al. (2014)	
		Feedlot manure N_2O emission	Xu et al. (2014)	
		Manure combustion (CO_2 + NO_2)	Tian et al. (2011)	
		Diesel	Ma (2002)	
		Electricity	Hou et al. (2012)	

(Continued on following page)

TABLE 2 (*Continued*) GHG estimations and related references for the analysed case studies.

Country	Approach	GHG emissions estimates	Reference for formulae	Direct measurements
China 2	LCA from cradle to gate	CH_4 from enteric emissions	Zhuang and Li (2017)	
		CH_4 from manure	Zhuang and Li (2017)	
		Manure direct N_2O emission	Zhuang and Li (2017)	
		Manure indirect N_2O emission	Zhuang and Li (2017)	
		Rangeland soil C change	Li (2013)	
		Rangeland soil CH_4 change	X. Zheng, pers. comm, direct data by static chamber	
		Rangeland soil N_2O emission	X. Zheng, pers. comm, direct data by static chamber	
		Manure Combustion CO_2	Zhuang and Li (2017)	
Italy 1	LCA from cradle to gate	CH_4 from enteric emissions	Vermorel et al. (2008)	
		GHG from pesticides and fertilizers	IPCC (2006)	
		NO_2 emitted through animal excreta	IPCC (2006)	
Italy 2	LCA from cradle to gate	CH_4 from enteric emissions	Vermorel et al. (2008)	
		C Seq from crops and natural grassland	Petersen et al. (2013)	
		GHG from pesticides and fertilizers	Nemecek and Kägi (2007)	
		N_2O direct and indirect and CO_2 emissions to air	Tier 1 - IPCC method (IPCC, 2019)	
		NH_3 emissions to air	Tier 2 IPCC method (IPCC, 2019), ISPRA (2011)	
		N_2O emitted through animal excreta	IPCC (2019)	
		Daily N excretion of animal categories	Decandia et al. (2011)	

grassland biodiversity (+53% of surface covered by natural grasslands), provided a reduction of environmental impact assessed through a land use-based FU, with −43% kg CO_2-eq per ha of utilized agricultural area-UAA (Vagnoni and Franca, 2018) and a further environmental benefit in terms of soil C sequestration (+63% of sequestered C in the soil) (Arca et al., 2021). On the other hand, carbon footprint assessed using a mass-based FU was similar in both systems at farm level, being respectively 2.99 CO_2-eq and 3.25 CO_2-eq per kg of normalized milk. In both systems, enteric methane resulted in around half of all GHG emissions. Similar results have been found in other Mediterranean systems, including in northern Spain (Batalla et al., 2015), as well as elsewhere in Sardinia (Atzori et al., 2017b). Two methodological issues arise from this study:

1) When emission intensity was expressed per ha of UAA, semi-extensive dairy sheep farming led to better environmental performance even without C sequestration accounting. On the other hand, semi-intensive systems resulted in lower impacts when GHG emission intensity was referred to 1 kg of normalized milk.
2) The semi-extensive system had a strong potential for offsetting GHG emissions through sequestration in permanent grasslands. When soil C sequestration was included, the study showed slightly lower GHG emissions per kg of milk in the semi-intensive production system (from 3.37 CO_2-eq to 3.12 CO_2-eq per kg), but the reduction was higher in the semi-extensive system (from 3.54 kg to 2.90 kg CO_2-eq per kg).

Issues emerged from the three case studies

From the three case studies analysed, some limitations emerge that penalize a complete and adequate estimate of GHG emissions and, consequently, a correct assessment of implementation scenarios that aim to create conditions of greater sustainability for pastoral systems.

West Africa (Senegal)

This case study estimated the main C and N stocks and flows and GHG fluxes between the pastoral system and the atmosphere, measuring the overall emissions balance at landscape scale. For doing this, Assouma et al. (2019b) suggested an *ecosystem approach*, considering all the ecosystem components (livestock, soil and plants) and the interactions between themselves and with the atmosphere. Indeed, this ecosystem angle revealed some key points that should be taken into account when allocating impacts between livestock and natural processes: firstly, seasonal patterns of rainfall may drive the entire variability of gas flows, which should be taken into consideration when approaching studies on the environmental performance of systems with a strong territorial and ecosystemic vocation such as extensive pastoral ones. Thus, wet and dry seasons can completely change the outcomes of the environmental assessment of these systems. Focusing on specific emissions for each season could enable addressing seasonally hotspots in emission and designing more relevant mitigation options. Another source of variation was referred by the authors to emissions from manure in pastoral systems with such a wide territorial basis. In fact, in such conditions manure cannot be assumed to be distributed uniformly, as pointed out in most environmental assessments (Houzer and Scoones, 2021). Thus, direct field-level data and not constant livestock excretion rates should be established and used in the emission analysis. Moreover, further uncertainties arise in relation to the proportion of the manure that is managed and the emission factors for nitrogen used may not reflect the context of most extensive livestock production systems (Rufino et al., 2014). In general terms, when only anthropogenic sources of GHG are taken into account, instead of considering the whole ecosystem angle, studies about the environmental impact of pastoral products might be a source of uncorrected interpretation of GHG flows. Starting from this assumption, Assouma et al. (2019a) suggested that, in the case of transhumant livestock that grazes seasonally in different ecosystems during a year, estimating C balances for diverse ecosystems along agro-climatic gradients might better integrate mobile livestock impacts in studies on the environmental impacts of pastoral products, with a focus on the dynamic relationship between pastoral practices and land use. By recognizing the importance of landscape variability and seasonal pasture availability, pastoralists can develop land use strategies that support sustainable pastoral systems, enhance biodiversity, and improve the resilience of both pastoralists and ecosystems in the face of climate change.

Asia (China, Qinghai-Tibetan Plateau)

Both Chinese case studies investigated GHG emissions of pastoral systems at territorial scale, by using an LCA "from cradle to gate" approach. The two studies underlined some recommendations for better address the studies on GHG emissions from pastoral systems, albeit with different nuances. The Case Study China 1 Zhuang and Li (2017), revealed that enteric CH_4 emissions calculations based on a model rather than field observations could affect the accuracy of results to some extent. Indeed, direct measurements and estimations of emissions allow a context-based analysis, bounding the system not just by focusing on animals and feed, but using a wider system approach. More precisely, the *context-based approach* should include observations on the vegetation (e.g., plant biodiversity) and grazing managements, in order to have direct and more detailed data regarding, for example, the effect of vegetation and grazing patterns on C sequestration. It means that the approach to be used for estimating GHG emission should not exclude a complex framework of data collection, with direct measurements on plant biodiversity at territorial scale.

In the China 2 case study, recommendations by authors Zhuang et al. (2019) mainly concerned issues relating to the accounting for soil C sequestration, in the case in which different grazing techniques and regimes are taken into consideration, frequent when pastoral systems are linked to the grazing of large portions of territories with mobile and transhumant animals. Land use practices directly influence soil carbon sequestration potential. As highlighted in this case study, understanding the dynamics of soil C sequestration requires accurate assessments of land use changes and grazing management. Zhuang et al. (2019) suggested how an accurate study on soil C sequestration dynamics should be included in the LCA analysis, when it is addressed to define the environmental impact of a changing scenario in terms of a transition from mobile seasonal to sedentarized continuous grazing. Also, more direct field data is needed to better describe this transition. For example, exactly as in the China 2 case study, they suggested that enteric CH_4 emissions should be based on field observations for having more accurate results to some extent. Finally, when grazing management affects vegetation, Zhuang et al. (2019) suggested the collecting of more detailed vegetation measurements, which might help in making observation on the indirect effect of changing vegetation on, for instance, soil C sequestration potential of the changed plant environment.

In both Chinese case studies, the interplay between land use and pastoral sustainability is clear. By adopting practices that enhance soil health, biodiversity and resource management, pastoralists can create systems that are not only productive but also resilient to environmental changes (Teague and Wright, 2018; Díaz et al., 2018). Understanding and integrating land use considerations into GHG emissions assessments and lifecycle analyses will be essential for developing sustainable pastoral systems in the Qinghai-Tibetan Plateau and beyond.

Europe (Sardinia, Italy)

When estimating GHG emissions from a Sardinian dairy sheep farm, after a land use change due to a transition scenario of extensification, a clear environmental benefit was revealed, accounting for soil C sequestration in emission intensity estimation, whatever the FU considered, product-based or area-based. It suggests that LCA of pastoral products, systems and scenarios should be based on a more complete and wider estimation of the environmental performances, reclaiming the use of different FUs in order to allow a more comprehensible and suitable assessment of the environmental impacts. Moreover, in a land use change scenario towards pasture-based systems, soil C sequestration is favoured by the presence of large grazing areas covered by permanent grasslands, whether natural (natural pastures) or semi-natural (artificial pastures). The improvement of soil organic C stock associated with permanent grasslands would contribute effectively to mitigating GHG emissions in Mediterranean dairy sheep farms, highlighting the positive role of ecosystem services provided by extensive farming systems.

Insights and suggestions for an adequate study of GHG emissions from extensive livestock farming systems

From the analysis of the methodological issues that emerged from the analyzed case studies, useful indications arise for redefining the assessment approaches for GHG emissions from pastoral systems, with the aim of trying to understand if a reference LCA model is possible to better address the environmental impacts and carbon footprint of extensive animal farming systems. More precisely, the needs that emerged were to consider: 1) analysis of emissions with a broader context/ecosystem-based approach; 2) definition of the FUs; 3) the provision of ecosystem services, with special focus on biodiversity and the inclusion of C sequestration within the LCA calculation.

Context/ecosystem based approach

Considering the data scarcity on pastoral systems, and high time, energy and economic costs to complete them, the majority of LCA studies in literature make use of data from high-income countries and industrial systems. These global and standardized assessments do not permit catching the complexity and variability of pastoral systems and therefore risk being highly partial and poorly adequate (Houzer and Scoones, 2021). Some authors (Glatzle, 2014; Manzano et al., 2023a; Vagnoni et al., 2024), highlighted that it a new front of investigation and research is urgent, aimed at deepening the assessments relating to the environmental impacts of extensive livestock systems, particularly in relation to the emissions of climate-altering gases, in such a way as to establish, more and more accurately, the effective impact of pastoral farming on climate change. This would allow studies of extensive systems to be freed from standard parameters relating to industrial, intensive and product-oriented farming systems. Direct data and surveys at territorial and ecosystem level are necessary for better describing the complexity of emissions from pastoral systems, and it is even more necessary as these systems are characterized by mobility, nomadism and the use of large portions of grazing lands. The use of default emissions factors (Tier 1), can induce the risk of not reflecting the variability inherent in the extensive production conditions, which is the very basis of production in a non-equilibrium system, especially in pastoral settings (Krätli, 2015). Also in semi-extensive systems, with flock partial sedentarization and where pasture utilization is the principal feed resource, direct data collection is needed to better express the variability of quali-quantitative pasture traits. Models that continue to assume stability and uniformity in livestock systems, ignoring the pivotal importance of this variability, cannot be applied in region-specific contexts where ecosystem and livestock differences emerge. New models, and LCA approaches, should be able to capture this contextual variability which translates into a range of operational options, in particular mobility, as a crucial tool for the adaptive capacity and resilience of pastoralists (Krätli et al., 2023).

The mobility of livestock on large portions of grazing territories and their use characterizes pastoral systems in all their forms (Rugani et al., 2019; Gac et al., 2020). Considering impacts from pastoral systems simply as an aggregate assessment of impacts could miss important patterns of spatial heterogeneity and temporal variability (Houzer and Scoones, 2021). Particularly, GHG emissions are highly variable over space and time in extensive systems, being potentially positive and negative in the same area at different times, requiring much more focused mitigation measures compatible with livestock-keepers' practices (Charteris et al., 2021). This spatial and temporal heterogeneity should be reflected when analysing GHG emissions from pastoral systems. As an example, permanent grasslands in extensive systems are the most important, and in many pastoral settings the unique, source of feed for livestock. Numerous studies have established that in permanent grasslands the relationship between soil organic carbon, nitrogen, and site factors varies according to the land use types, vegetation types, environment, and soil types (Busman et al., 2023). But, on the contrary, when LCA analysis is performed on productive basis, pasture-based diets, that valorise the availability of permanent grasslands, are often associated with higher GHG emissions due to higher methane emissions from low-quality diets and to the low production efficiency of extensive livestock (Steinfeld et al., 2006; Gerber et al., 2013). Efficiency is often measured in terms of emissions per unit of output (milk or meat), but this does not take account of the multi-functional use of livestock and land into pastoral systems. This standardised measure of efficiency reveals an anthropogenic perspective, for which this mass-based FU results in an indicator aimed at minimizing the input use and the impacts per unit of marketable product (Molle et al., 2017). The utilization of these units derives from the challenge of increasing productivity and production efficiency, typical of industrialised sectors. Extensive systems are considered the least efficient, although they actually make productive use of areas that have limited alternative uses and allow the production of valuable proteins for food use starting from herbaceous biomasses of low nutritional value (Houzer and Scoones, 2021).

Land use is defined as "total arrangements, activities, and inputs undertaken in a certain land cover type (a set of human actions)" and it refers to the social and economic purposes for which land is managed (Verones et al., 2017). Variability of land use and land use changes may affect not only productivity and resilience of land and rural territories and related communities, but also the wider ecosystem benefits provided by their pastoral use (Davies et al., 2012). In many marginal areas of the world, where livestock have long played an important role in maintaining silvopastoral ecosystems, land abandonment and intensification of agricultural production systems via land use intensification is affecting farmland biodiversity (Houzer and Scoones, 2021). The positive impacts of extensively grazing livestock for reducing GHG emissions in open forest-mosaic and savanna landscapes is clear, when compared with land abandonment scenarios, moreover when practices of sustainable grazing are applied (Manzano and White, 2019). Land abandonment leads to woody vegetation encroachment, and related increased fire risk. Pastoral land use can greatly reduce the potential fuel load for forest fires and vegetation structure can be maintained in a way that promotes greater species diversity (Franca et al., 2016; Bernués et al., 2011). On the other hand, environmental benefits of grazing activity may be hindered by inadequate grazing management, and can be obtained only if the pastures are managed in a rational and sustainable way. In practice, avoiding phenomena of overgrazing and undergrazing, which *vice versa* can create environmental damage, such as soil compaction and loss of biodiversity (Schrama et al., 2023). For these reasons, the proper characterization of Land Use and Land Use Changes (LULUC) within extensive small ruminant systems is of special concern and it's a matter of yet greater complexity, as no consistent methodology exists for calculating and characterizing the impacts of LULUC over time. Regarding the inclusion of LULUC impacts within LCA of livestock systems, several organizations have given guidelines for their incorporation. In case of an attributional LCA of a small ruminant supply chain, for instance, different standards may be helpful for considering the inclusion of LULUC, including recommendations from the International Life Cycle Data System (ILCD) Handbook (ILCD, 2010; ILCD, 2011) and Product Environmental Footprint (PEF) guidelines (PEF, 2013), the International Dairy Federation (IDF) (IDF, 2010), and FAO-LEAP guidelines (FAO, 2016a; FAO, 2016b). In the framework of SheepToShip LIFE project (www.sheeptoship.eu), recommendations of the EU-PEF, IDF, and LEAP guidelines were followed, utilizing the Ecoinvent database as a source of secondary data, as the LULUC modelling tool utilized by this database considers the PAS 2050 calculation scenarios, and is therefore already compliant with both PEF and FAO LEAP guidelines (Reinhard et al., 2017).

When considering LULUC, great attention needs to be taken on the baseline scenarios. Extensive livestock systems, making use of permanent grasslands (often as patches within wooded ecosystems), can be considered as replications of 'natural' or 'wild' systems. This makes assessing baselines crucial, as livestock may not add to 'natural' emissions (as assumed in standard LCA measures and climate scenarios). As a result, the complete abandonment of livestock production in certain extensive contexts could therefore have negative impacts on landscape-level emissions (Manzano and White, 2019). LCAs current practice used to derive emission estimates usually do not consider such baseline conditions, whether shifts following advocated removal of livestock resulting in a return to 'wild' ecosystems or shifts to intensified agriculture. IPCC (2010) uses managed land as a proxy for anthropogenic emissions and removals, thereby not considering such baseline emissions either. This results in large distortions in the interpretation of results, with major implications for policy (Manzano and White, 2019). A new perspective in accounting GHG emissions from extensive livestock systems requires the accounting of natural baseline emissions, the fluxes from a livestock abandoned scenario, where the increase of wild herbivores and fires certainly does not paint an "emissions-zero" scenario (Pardo et al., 2024).

Choice of the functional units

The LCA food scientific community has been wondering for some time about the criteria to be used to identify the most appropriate FU to express the environmental impacts of livestock systems. In fact, the effects of intensification on emission intensity can significantly depend on the FU adopted; some authors have observed that intensification does not produce variations in emission intensity per kg of normalized milk (mass-based FU), while higher values of emission intensity per ha (area-based FU) have been observed in more intensive systems (Salou et al., 2017). Furthermore, the choice of FU can produce controversial results in terms of environmental output, depending on whether the systems are intensive or extensive (Baldini et al., 2017). The use of the FU based on area and the inclusion of the soil Cseq in the estimation of emission intensity are considered by Escribano et al. (2020) as more appropriate for the assessment of environmental impacts of extensive agricultural systems based on permanent grasslands. This conclusion was confirmed by an LCA study on a semi-extensive Sardinian dairy sheep farm, conducted by Arca et al. (2021). In addition, FU based on area avoids large debate about mode of allocation between products (Kyttä et al., 2022). Finally, the attribution of emissions that have a fossil origin vs. a biogenic origin, and the distinction in the latter between their natural and anthropogenic character, can also be very relevant to measure impacts (Manzano et al., 2025).

Inclusion of ecosystem services

Pastoral systems can contribute to ES in a broader and more complex way and the extent of this contribution can vary widely. Indeed, they are mainly based on land use and in particular on pastures, often of low productivity, and with extensive use of grasslands, associated not only with the ES mentioned above, but also with a wider series, including, for example, biodiversity conservation (which contributes, for example, to pollination), fire prevention and many others (Vagnoni et al., 2015; Bengtsson et al., 2019; Zhao et al., 2020; Arca et al., 2021; Von Greyerz et al., 2023).

Given the complexity and multifunctionality of pastoral systems and the wide variability of climatic and economic conditions that they have to face, a large scale assessment of all ecosystem services for all general land use types would be necessary for the application in LCA. Yet, as underlined by Barnaud and Couix (2020), ecosystem services as a concept appear as a legitimate analytical tool to investigate multifunctionality. In this perspective, in order to assess the impacts on ecosystem services, a set of indicators would be necessary (van Oudenhoven et al., 2012). Several authors include suggestions for indicators of ecosystem services for land management, both capacity indicators (representing the potential to provide services, e.g., carbon storage) and flow indicators (representing the actual provision of a service experienced by people, e.g., erosion prevention) (Tsonkova et al., 2014). Some ecosystem services can instead be measured directly, mainly provisioning services: e.g., crops, wood or fibre, number of animals and freshwater withdrawal (Kandziora et al., 2013). Cultural services depend on human values and can only be estimated indirectly, e.g., from the number of visitors or facilities, preference surveys and the number of protected species or habitats (Kandziora et al., 2013; de Groot et al., 2010). Regulatory and supporting services are the most difficult to measure, because they often arise from complex interactions of ecosystem properties or occur at spatial scales other than the observed landscape scale (e.g., climate regulation or gene pool protection) (Zhang et al., 2022).

Having pastoralists a functional role for the use and preservation of permanent grasslands, their traditional pasture practices and grazing management help in providing various ecosystem services. But, in general, the multiple functions of pastoral systems, are not considered in LCA calculations. LCAs, for example, do not weigh production against any upper limit on demand, thus distorting the results in favour of industrial systems. Failing to distinguish between different types of "proteins" and specific dietary requirements, these biases are further reinforced (García-Dory et al., 2022; Moughan, 2021). Conversely, an adequate LCA study should be able to highlight whether the negative impact of the low production efficiency of extensive grazing systems can be offset by the positive effect of the ES they provide to the territories in which they operate (Vagnoni et al., 2018; Manzano et al., 2023b). LCA for ruminant systems commonly include only beef and milk as valuable outputs, and no other ES potentially provided (Baldini et al., 2017; Clune et al., 2017). The risk is to overlook the positive contributions to ES, other than direct food provisioning, and this can be misleading when making decisions about future livestock systems, such as promoting the idea that meat produced in intensive systems generally has lower climate impacts than meat from extensive systems (Von Greyerz et al., 2023). The risk is even greater in the case of traditional, mobile pastoralism (Manzano et al., 2023b).

So, including non-provisioning ES in LCA studies might represent a new strategy for more adequately accounting for environmental impacts of multifunctional pastoral productions. However, while food products can be valued using market prices, attributing value to other ES is less straightforward. Some authors (Ripoll-Bosch et al., 2013; Kiefer et al., 2015; Bragaglio et al., 2020) have attempted to include foods and other ES into the LCA study, using economic allocation, where the environmental impact is distributed proportionally to outputs (foods and other ES) based on their economic value. In order to allocate emissions to ecosystem services, Ripoll-Bosch et al. (2013) proposed for grazing systems an approach that uses agri-environmental payments from CAP (EU Common Agricultural Policy). This method is a viable solution to consider for future LCA application to Mediterranean sheep farming system. Of course, this method might be taken into consideration only in European Union countries where these payments are applied, where they are interpreted as subsidies supporting farmers because of recognizing the environmental role of their sustainable productive activities into marginal and rural territories (Tchakerian, 2008). In these countries, agri-environmental payments are directly associated with support for both organic farms and farms in areas of "natural constraints," where agricultural production is more difficult due to unfavourable natural conditions. There are also a range of payment schemes more directly connected to livestock, including support for biodiversity conservation in semi-natural pastures or preservation of local livestock breeds. It can therefore be difficult to decide which payment scheme/s to include when using these as a base for economic allocation in LCA to account for non-provisioning ES, especially as payments are sometimes only vaguely reflecting the ES provided (Simoncini et al., 2019), which can give variable results.

More recently, von Greyerz et al. (2023) studied the environmental impacts of varying cattle production systems in Sweden, with different levels of extensification, and attributed the climate impact not only to beef and milk, but also to a set of provided ES, applying economic allocation. Results were influenced by the differences between farms in coupling the payment schemes. Particularly, when payments were directly related to livestock rearing (e.g., as mentioned before, related with biodiversity conservation or preservation of local breeds) the differences in the climate impact were still large between farm types, while the difference decreased considerably when all environmental schemes were included. Including ES in the LCA analysis, does not reduce or cancel the emissions, but gives a more realistic and adequate estimate of the environmental impact of a livestock system, moreover when it is related with a large pasture utilization and land occupation, like pastoral systems are. While emissions do not disappear, ES-corrected climate impact can potentially be useful as part of consumer communication or in decision-making, reducing the risk of overlooking ES provided by ruminant production in a simpler way than using separate indicators. Otherwise, including ecosystem services in LCA shall lead to a more complete comparison among the environmental profile of extensive livestock systems. Vagnoni et al. (2018) consider this method as a viable solution to consider for future LCA application to Mediterranean sheep farming systems, mainly if further CAP measures will more strictly recognize the environmental role of Mediterranean pastoralism. In the long term, Atzori et al. (2022) highlighted that considering the LCA method from a systemic perspective, which may enable a transition in the small ruminant sector toward a more sustainable bio-economy based society, prioritizing rural development and capacity building for sustainable production of dairy sheep sector is likely to stimulate both productivity and ecosystem services maintenance.

The majority of LCA studies prioritize the assessment of a limited number of environmental indicators, i.e. GHG emissions and land use, reflecting the limited data available for other factors such as biodiversity and ecotoxicity (Clark and Tilman, 2017; Sahlin et al., 2020). LCAs therefore often fail to integrate the diverse interactions (both positive and negative) between livestock and the ecosystems they encounter into their analyses, and they often do not account for the various ecosystem services that well-managed livestock can offer in a pastoral context (Houzer and Scoones, 2021). Besides its primary function of producing milk and meat (and wool), most extensive farming systems provide other functions to society. Some examples of ecosystem services attributed to pastoral grazing include: maintaining both the vitality and the traditions of rural communities (specially, in marginal areas), as well as preventing environmental issues (i.e., soil erosion and desertification, wildfire, biodiversity depletion, etc.); conserving cultural landscapes; maintaining rangeland (which maintains sequestration potential in soils and vegetation), nutrient and water cycle regulation and soil health (Schils et al., 2022). The actual contribution of pastoral systems to such services has rarely been quantified (Glimskär et al., 2023).

In Europe, farming systems such as pasture-based systems - evolved towards complex socio-ecological systems in situations of natural resource scarcity, where production is integrated with biodiversity conservation and the delivery of ecosystem services to society - are considered farming systems with High Nature Value (HNV) that require quantifying and paying ecosystem services as a tool for developing strategies to simultaneously meet future food security and sustainable agriculture (Pinto-Correia et al., 2018; Pinto-Correia et al., 2022). However, this approach constitutes a formidable challenge and a requires continuous renewal of policy mechanisms to compensate management models that ensure the delivery of societally desired public goods, gaining new practices and business models that allow for the preservation or even regeneration of natural resources, biodiversity and landscapes (Bouma, 2021; Schröder et al., 2020). After performing as literature review about the inclusion of ecosystem services into LCA analyses on food production systems, Vanderwilde and Newell (2021) clustered the LCA-ES literature in the main categories of "biodiversity and ES clusters," "land use cluster" and "dynamic modelling," highlighting how reconsidering LCA with an ecosystem services extension can provide a complementary evaluation both of beneficial contribution of ecosystem services to wellbeing and, also, their detrimental impacts. Nevertheless, despite the recent progress in explicit consideration of ES in LCA (Zhang et al., 2010), today there is still a general lack of a methodological consensus on how to comprehensively integrate ES accounting in LCA and the first steps are being taken to unite the theory and practice of accounting for ecosystem services in LCA, albeit with difficulties linked to a methodological and procedural consensus (McLaren et al., 2021). More recently, Damiani et al. (2023) stated that biodiversity loss can be assessed in different ways into LCA environment but will presumably include a broader set of information regarding, for example, taxonomic coverage and other ecosystem services.

Biodiversity

Currently, a relevant discussion is still ongoing on how to fit biodiversity conservation with LCA studies on products' and services' value chains. Crenna et al. (2020) reviewed approaches for the impact assessment of biodiversity in LCA, highlighting that the "*existing metrics of biodiversity impact assessment in LCA are poor at capturing the complexities of biodiversity,*" and pointing out that LCA framework was not yet sufficient to support decision-making based on available biodiversity indicators. Into this *in progress* context, FAO (2021) assessed that several crucial issues determine the impact of agriculture on biodiversity at farm level. Among them, issues related with land use (namely geographical location, intensification and fragmentation of agricultural lands), composition of the modified native vegetation and the on-farm measures for biodiversity conservation. When specifically related to livestock systems, UNEP Life Cycle Initiative (FAO, 2021) assessed that the development of sophisticated research methods for considering biodiversity in studying LCA of livestock systems and products should account for land-use intensity and habitat fragmentation, but also global extinction probabilities, and indicators of biodiversity loss, referring to research outcomes from many authors (Kuipers et al., 2021; Larrey-Lassalle et al., 2018; Chaudhary and Brooks, 2018). When using an ecosystem approach for assessing the environmental footprint of a pastoral system/product, FAO (2021) suggests that the effect of extensive grazing on landscape biodiversity might be evaluated through observing and measuring the impact on seed dissemination, species conservation, plant species control and habitat's regeneration and preservation. García-Dory et al. (2022) observed that many long-standing debates that show how such production systems, including pastoralism, may increase biodiversity and help in preserving landscapes and ecosystems, that are seriously affected when pastoral mobility is restricted, or grazing activity is forbidden (Behnke and Mortimore, 2016). In Mediterranean environment, for example, extensive grazing has a significantly positive effect on biodiversity indicators, such as Shannon and species richness indices (Landsberg et al., 2002; Brooks et al., 2006; Franca et al., 2018) and has been considered as a tool for maintaining the genetic diversity within plant populations, particularly in silvopastoral conditions, where plant diversity may ensure a higher tolerance of pastures under shading conditions (Perevolotsky, 2005). Extensive grazing may also provide human and animal food and moreover cultural services, through cultural identity, traditional knowledge, and tourism (Plieninger et al., 2006; Assouma et al., 2018a; Paul et al., 2020; Russell et al., 2018). All add up to substantial environmental and conservation benefits of particular types of livestock production that should be taken into account. As discussed further below, an ecosystems approach more effectively integrates these factors into any analysis, addressing the landscape as a whole, and is thus more suitable for assessing complex, variable, extensive systems. In general, all these functions are not considered in LCA calculations of extensive farming. Assessments that stop at the boundary of the farm can miss the wider contributions of extensive livestock production to biodiversity, and also to overall environmental and landscape improvements. Otherwise, including ecosystem services in LCA shall lead, for example, to a more complete comparison among the environmental profiles of extensive and intensive livestock farming systems.

C sequestration

Soil C has historically been excluded from LCA studies for a variety of reasons, including the lack of soil C sequestration data to provide conservative GHG estimates and an assumption that soils, without additional carbon inputs, are in long-term equilibrium (Rotz et al., 2019). Under this assumption, livestock would add additional emissions to an otherwise balanced carbon cycle. As a result, most assessments do not include C sequestration in their analyses (Rowntree et al., 2020). Moreover, many LCA assessments assume that the grazing abandonment might be beneficial for the re-wilding/re-naturalization of the land, allowing more effective soil C sequestration (Houzer and Scoones, 2021). This assumption is fed by LCA studies focused on high-income countries, in which experts prioritized GHG emissions and land use (Paul et al., 2020; McClelland et al., 2018), while other environmental indicators are comparatively neglected (Nordhagen et al., 2020; Sahlin et al., 2020), with only a patchy focus on potential environmental benefits of livestock production, including sequestration and biodiversity maintenance.

On the other hand, the exclusion of C sequestration from LCA analyses is challenged by some studies relating to permanent grasslands, attesting that pastoral practices have been tested and proven successful fitting to the aim of maintaining or improving pasture-based systems, ideally increasing the capacity of grasslands to store carbon (Blanfort et al., 2010; Calado et al., 2018; Arca et al., 2021) and then, consequently, showing how C sequestration can be significant in extensive systems. Such systems may be in balance or seasonally negative, meaning that livestock here may not be net contributors to emissions. However, support towards more research on carbon and nitrogen flows, context-specific emissions and C sequestration in extensive livestock systems, including in pastoral areas across the world, is needed. Such research should be based on analyses that must encompass differences across times and spaces, reflecting the complex dynamics of carbon and nitrogen cycles in such systems (Houzer and Scoones, 2021). Again, a systems approach would acknowledge movement across rangelands and account for the benefits to potential C sequestration and, more in general, to ecosystem services.

Pastoral systems, particularly in the Mediterranean regions, are characterized by contrasting livestock systems with different extensification level (Caballero et al., 2009; Porqueddu et al., 2017). Even in the context of semi-extensive systems, where temporary grasslands (i.e., annual forage crops) are combined with permanent grasslands, correct agronomic practices of managed grasslands may affect the increase of soil C sequestration, how shown by Arca et al. (2021) in Mediterranean dairy sheep farms. In any cases, permanent grasslands improve soil C stock with respect to forage crops, partly explained by a greater supply of C from crop residues left in the soil, due to their extensive root systems, and partly by the increased residence time of C, due to the absence of soil tillage (Jones, 2010; Seid et al., 2016). In contrast, grassland degradation leads to the release of carbon into the atmosphere (Van den Pol-van Dasselaar, 2017). The management of grazing can improve soil C sequestration on grasslands, decreasing or increasing the grazing pressure on overgrazed and slightly grazed lands, respectively. The management of N fertilization can affect N_2O emission and soil C input from biomass residues.

Thus, including soil C sequestration in LCA analyses aimed at pastoral systems, in presence of large areas covered by permanent grasslands and destined to the grazing, can be suggested (Gutierrez-Pena et al., 2019; Batalla et al., 2015; Arca et al., 2021). The improvement of soil organic C stock associated to the permanent grasslands would contribute effectively to mitigate GHG emissions in pastoral territories, highlighting the positive role of ecosystem services provided by extensive farming systems. Data can sometimes be available in the literature. However, they can widely differ according to different parameters as local ecosystems, pastoral systems management including grazing pressure, climate conditions of the assessed year. In Mongolia for instance, references on C flows in the literature show large differences in annual C balance for different rangeland types, ranging from – 160–187 g C $m^{-2}yr^{-1}$ (Morton et al., 2024). In addition, the estimation of soil C sequestration is often influenced by the models used to estimate grazed biomass. In this sense, direct field measurements related to ecosystems, production systems and practices under study are advisable in order to improve estimation accuracy, data quality and results reliability.

Finally, it can be highlighted the need to improve LCA methodology to capture agricultural systems characteristics. In particular, key aspects include soil CO_2 emissions, soil C sequestration, soil N_2O emissions, circular economy solutions, biodiversity, nutrient flows (Goglio et al., 2024). A key tool in this sense may be a harmonized multiscale approach for LCA methodological developments, with special consideration to soil resources and their contribution. The systematic inclusion of soil in LCA would allow enhancement agroecosystems sustainability and give soil resources their rightful place in the quest to tackle sustainable development goals and combat climate change. Therefore, we propose to insert the soil C storage rate as CO_2 soil uptake from atmosphere lowering the environmental impacts of agroecosystem management (De Feudis et al., 2022).

Further remarks from LCA research for extensive livestock farming

Harmonizing LCA methods to improve its accuracy and robustness in addressing sustainability across livestock systems and products, Goglio et al. (2023) identified several key topics based on structured workshops and survey between LCA experts: biodiversity had the highest priority among respondents followed by social aspects, soil C sequestration and food-feed production. Social aspects therefore play a significant role in the general definition of the sustainability of a production cycle or a production system. Particularly, as in the case of extensive livestock farming, when the system under examination has strong implications for large portions of territory and for the populations that live and produce in it. But even if analysing LCA at single farm level (Figure 2), the general boundaries of a livestock farm might be extended to variables that approaches social (manpower units, relationships with rural areas, tourism and traditional cultural aspects, etc.) and economic boundaries (cost and revenues, taxes and national subventions, local economic advantages of added values, general willingness to pay for environmental goods and ecosystem services). Social impacts of a product's life cycle might be assessed trough of the practice of Social Life Cycle Assessment (S-LCA) (UNEP et al., 2020). S-LCA measures the impact of a product or process on society along the full life cycle (Dyson, 2024). S-LCA is one of three methodologies (together with Environmental LCA and Life Cycle Costs) that have been developed to assess the sustainability of organizations, products and services and considers many types of impacts directly to people, and the impacts can be positive and negative (Finkbeiner et al., 2010; UNEP, 2009).

The direct dimension of these impacts requires a major as possible collection of primary data and information at local level with a site-specific approach. Potentially, S-LCA could be helpful in completing an impact analysis of pastoral products, enlarging the system boundaries in LCA studies also to social aspects, and representing a solid and more coherent option for trying to include variability and multifunctionality into studies on environmental impacts of extensive production systems (Flysjö et al., 2012; Ripoll-Bosch et al., 2013; Batalla et al., 2014). But at present, such an approach can only be used prospectively, as there are only a few S-LCA papers based on agri-food supply chains in the scientific literature (Møller et al., 2024). This limitation is mainly due to the fact that onsite data collection is funds- and time-consuming, and that field investigation may be made difficult by the wide distribution of the locations where a pastoral value chain can occur, when mobility and land use variability remain the more characterizing factors of such extensive livestock systems (UNEP et al., 2020). In addition, impact pathways which relates primary data to social indicators are still few (Sureau et al., 2020).

Another way of facing the difficulty of defining the complexity and dynamicity of pastoral systems into CO_2eq-based simplistic quantitative criteria, is to consider the nutritional value and socio-geographic context of food provided by extensive livestock, accounting for the function of that food in providing human sustenance and supporting health (Manzano et al., 2023c; McAuliffe et al., 2020). Nutritional LCA (nLCA) has been developed in the past decade to achieve this nuance (Saarinen et al., 2017; Sonesson et al., 2017; Sonesson et al., 2019), starting from the consideration that extensive livestock generates not only food, but also nutritional coproducts, valorizing unproductive marginal land. Nutritional LCA, being useful in valorizing the interconnection between food production and the environment in which food is produced, can represent an important contribution to express how and how much the pastoral product reflects and incorporates the complexity and variability of the socio-geographical context in which it is produced.

The three case studies suggest that when assessing climate change impact of pastoral systems, strongly characterized by land occupation, use of environmental resources, seasonal climate and social relations, an approach that adapts and extends the LCA methodology is needed. Variability and uncertainty of socio-economic and environmental/climate conditions that shepherds face requires an approach capable of differentiating between contrasting contexts. Only with such a shift in approach will we get beyond the sometimes simplistic and misleading policy messages emerging from much research on the livestock–environment nexus. This paper confirms that LCA must be approached in a holistic manner, and advances the following methodological measures on how to set up and formulate an LCA method suitable for pastoral systems: first of all, accurately define the objectives, the boundaries of the context in which one operates and the quality of the inventory data. If the interest is limited to knowing the environmental impacts of a single pastoral product, LCA is confirmed as the most appropriate method. If instead the aim is to assess the entire pastoral system, considering its characteristics of variability and uncertainty, further analysis methods can integrate the conventional LCA and achieve a satisfactory evolution of the LCA methods, including the Social LCA, for the socio-economic implications, and the Nutritional LCA, for those more related to the food and subsistence function of pastoral products. Research in this field is active and it would be important to improve the knowledge regarding the choice of impact categories and FUs most suitable for estimating impacts at the territorial level, integrating information and databases deriving from other methodological approaches, such as remote sensing and precision farming techniques applied to extensive contexts. Finally, it is desirable to produce site-specific LCI databases for pastoral systems in regions of the world where pastoralism remains a fundamental food resource.

Conclusion

The multifunctionality of extensive livestock systems justifies the use of alternative metrics that assess the environmental performance of such systems in a more complete and adequate way. LCA is a scientific method and for this reason it must be approached in an objective way, without falling into the temptation of advocacy positions towards a sector, that of pastoral production, in difficulty at a global level, despite being in line with the evolutions of the Farm to fork context and the goals of sustainable development. LCA researchers should work for the harmonization of alternative metrics based on Conventional, Social and Nutritional LCA, contributing to a deeper understanding of the positioning and role of global extensive livestock systems in the broader context of the ecological transition of agri-food systems.

Author contributions

AF and IS conceptualized the study and drafted the manuscript. PA, EV, and GA handled data collection and analysis, offered insights and feedback and drafted the manuscript. HA, GZ, JV, and MV contributed to case studies' design and reviewed the manuscript, PM offered insights and feedback and reviewed the manuscript. All authors contributed to the article and approved the submitted version.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This paper was facilitated by an Advanced Grant from the European Research Council, which supports the PASTRES programme (pastres.org; Grant Number:740342). The insights emerging from this work are currently being implemented within the framework of the research projects INSTINCT (PRIN 2022, Grant Number: 2022NF3FR9) and SUREPASTOR (PRIMA 2024, https://surepastor.unifi.it/).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Aguilera, E., Reyes-Palomo, C., Díaz-Gaona, C., Sanz-Cobena, A., Smith, P., García-Laureano, R., et al. (2021). Greenhouse gas emissions from mediterranean agriculture: evidence of unbalanced research efforts and knowledge gaps. *Glob. Environ. Change* 69, 102319. doi:10.1016/j.gloenvcha.2021.102319

Arca, P., Vagnoni, E., Duce, P., and Franca, A. (2021). How does soil carbon sequestration affect GHG emissions from a sheep farming system? Results of an LCA case study. *Italian J. Agron.* 16, 1789. doi:10.4081/ija.2021.1789

Archimède, H., Eugène, M., Marie Magdeleine, C., Boval, M., Martin, C., Morgavi, D. P., et al. (2011). Comparison of methane production between C3 and C4 grasses and legumes. *Animal Feed Sci. Technol.* 166–167, 59–64. doi:10.1016/j.anifeedsci.2011.04.003

Assouma, M. H., Serça, D., Guérin, F., Blanfort, V., Lecomte, P., Touré, I., et al. (2017). Livestock induces strong spatial heterogeneity of soil CO2, N2O, CH4 emissions within a semi-arid sylvo-pastoral landscape in West Africa. *J. Arid. Land* 9, 210–221. doi:10.1007/s40333-017-0009-y

Assouma, M. H., Lecomte, P., Hiernaux, P., Ickowicz, A., Corniaux, C., Decruyenaere, V., et al. (2018a). How to better account for livestock diversity and fodder seasonality in assessing the fodder intake of livestock grazing semi-arid Sub-Saharan Africa rangelands. *Livest. Sci.* 216, 16–23. doi:10.1016/j.livsci.2018.07.002

Assouma, M. H., Hiernaux, P., Lecomte, P., Ickowicz, A., Bernoux, M., and Vayssières, J. (2019a). Contrasted seasonal balances in a Sahelian pastoral ecosystem result in a neutral annual carbon balance. *J. Arid Environ.* 162, 62–73. doi:10.1016/j.jaridenv.2018.11.013

Assouma, M. H., Lecomte, P., Corniaux, C., Hiernaux, P., Ickowicz, A., and Vayssières, J. (2019b). Pastoral landscapes in the Sahel: a carbon balance with unexpected potential for climate change mitigation. *Perspective* 52, 1–4. doi:10.19182/agritrop/00083

Atzori, A. S., Vagnoni, E., Molle, G., Franca, A., Decandia, M., Porqueddu, C., et al. (2017a). Facing carbon emission mitigation of dairy sheep supply chain: Estimation of a baseline trend. *Italian J. Animal Sci.* 16, 180. doi:10.1080/1828051X.2016.1277806

Atzori, A. S., Vagnoni, E., Sanna, L., Arca, P., Molle, G., Franca, A., et al. (2017b). Deliverable A.2.1 project LIFE SHEEPTOSHIP, review on LCA approaches and GHG mitigation actions in sheep supply chain. Available online at: http://www.sheeptoship.eu/images/Report/A.2.1_Review_LCA_studies.pdf.

Atzori, A. S., Bayer, L., Molle, G., Arca, P., Franca, A., Vannini, M., et al. (2022). Sustainability in the Sardinian sheep sector: a systems perspective, from good practices to policy. *Integr. Environ. Assess. Manag.* 18, 1187–1198. doi:10.1002/ieam.4593

Baldini, C., Bava, L., Zucali, M., and Guarino, M. (2018). Milk production life cycle assessment: a comparison between estimated and measured emission inventory for manure handling. *Sci. Total Environ.* 625, 209–219. doi:10.1016/j.scitotenv.2017.12.261

Barnaud, C., and Couix, N. (2020). The multifunctionality of Mountain farming: social constructions and local negotiations behind an apparent consensus. *J. Rural Stud.* 73 (2020), 34–45. doi:10.1016/j.jrurstud.2019.11.012

Batalla, I., Pinto, M., Unamunzaga, O., Besga, G., and Del Hierro, O. (2014). "Integrating social and economic criteria in the carbon footprint analysis in sheep dairyfarms," in Proceedings of the 9th international conference on life CycleAssessment in the agri-food sector, *8–10 October* (San Francisco, USA).

Batalla, I., Knudsen, M. T., Mogensen, L., Hierro, Ó. d., Pinto, M., and Hermansen, J. E. (2015). Carbon footprint of milk from sheep farming systems in northern Spain including soil carbon sequestration in grasslands. *J. Clean. Prod.* 104, 121–129. doi:10.1016/j.jclepro.2015.05.043

Behnke, R., and Mortimore, M. (2016). "Introduction: the end of desertification?," in *The end of desertification? Disputing environmental change in the drylands*. Editors R. Behnke and M. Mortimore (Berlin: Springer).

Bengtsson, J. J., Bullock, M., Egoh, B., Everson, C., Everson, T., O'Connor, T., et al. (2019). Grasslands—More important for ecosystem services than you might think. *Ecosphere* 10 (2), e02582. doi:10.1002/ecs2.2582

Bernués, A., Ruiz, R., Olaizola, A., Villalba, D., and Casasús, I. (2011). Sustainability of pasture-based livestock farming systems in the european Mediterranean context: synergies and trade-offs. *Livest. Sci.* 139, 44–57. doi:10.1016/j.livsci.2011.03.018

Blanfort, V., Fontaine, S., Picon Cochard, C., Klumpp, K., Huguenin, J., and Soussana, J. F. (2010). Evaluation of carbon sequestration in tropical grassland, ecological processes and farm practices in Amazonian cattle systems. *Adv. Animal Biosci.* 1 (2), 493–494. doi:10.1017/s2040470010001111

Bouma, J. (2021). How to realize multifunctional land use as a contribution to sustainable development. *Front. Environ. Sci.* 9, 620285–12. doi:10.3389/fenvs.2021.620285

Bragaglio, A., Braghieri, A., Pacelli, C., and Napolitano, F. (2020). Environmental impacts of beef as corrected for the provision of ecosystem services. *Sustainability* 12, 3828. doi:10.3390/su12093828

Brooks, T. M., Mittermeier, R. A., da Fonseca, G. A., Gerlach, J., Hoffmann, M., Lamoreux, J. F., et al. (2006). Global biodiversity conservation priorities. *Science* 313 (5783), 58–61. doi:10.1126/science.1127609

Busman, N. A., Melling, L., Goh, K. J., Imran, Y., Sangok, F. E., and Watanabe, A. (2023). Soil CO2 and CH4 fluxes from different forest types in tropical peat swamp forest. *Sci. Total Environ.* 858, 159973. doi:10.1016/j.scitotenv.2022.159973

Caballero, R., Fernàndez-Gonzàlez, F., Perez Badia, R., Molle, G., Roggero, P. P., Bagella, S., et al. (2009). Grazing systems and biodiversity in mediterranean areas: spain, Italy and Greece. *Pastos* 39 (1), 9–53. Available online at: https://www.secs-g.es/pastos/PDFS/Articulos/2009_39_1_09.pdf

Calado, N., Ventura, A., and Picos, J. (2018). *Minipaper 2: implementing adaptation strategies through economic incentives*. European Commission, 13.

Charteris, A. F., Harris, P., Marsden, K. A., Harris, I. M., Guo, Z., Beaumont, D. A., et al. (2021). Within-field spatial variability of greenhouse gas fluxes from an extensive and intensive sheep-grazed pasture. *Agric. Ecosyst. s and Environ.* 312 (2021), 107355. doi:10.1016/j.agee.2021.107355

Chaudhary, A., and Brooks, T. M. (2018). Land use intensity-specific global characterization factors to assess product biodiversity footprints. *Environ. Sci. and Technol.* 52 (9), 5094–5104. doi:10.1021/acs.est.7b05570

Chen, W. Q., Huang, D., Liu, N., Zhang, Y. J., Badgery, W. B., Wang, X. Y., et al. (2015). Improved grazing management may increase soil carbon sequestration in temperate steppe. *Sci. Rep.* 5, 10892. doi:10.1038/srep10892

Clark, M., and Tilman, D. (2017). Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. *Environ. Res. Lett.* 12 (6), 064016–11. doi:10.1088/1748-9326/aa6cd5

Clune, S., Crossin, E., and Verghese, K. (2017). Systematic review of greenhouse gas emissions for different fresh food categories. *J. Clean. Prod.* 140, 766–783. doi:10.1016/j.jclepro.2016.04.082

Crenna, E., Marques, A., La, N. A., and Sala, S. (2020). Biodiversity assessment of value chains: state of the art and emerging challenges. *Environ. Sci. and Technol.* 40. doi:10.1021/acs.est.9b05153

Damiani, M., Sinkko, T., Caldeira, C., Tosches, D., Robuchon, M., and Sala, S. (2023). Critical review of methods and models for biodiversity impact assessment and their applicability in the LCA context. *Environ. Impact Assess. Rev.* 101 (2023), 107134. doi:10.1016/j.eiar.2023.107134

Davies, J., Poulsen, L., Schulte-Herbrüggen, B., Mackinnon, K., Crawhall, N., Henwood, W. D., et al. (2012). *Conserving Dryland biodiversity*. xii +84p

De Feudis, M., Selmi, C., Falsone, G., Missere, D., Di Bonito, M., and Vittori Antisari, L. (2022). The importance of incorporating soil in the life cycle assessment procedure to improve the sustainability of agricultural management. *CATENA* 218, 106563–11. doi:10.1016/j.catena.2022.106563

de Groot, R. S., Alkemade, R., Braat, L., Hein, L., and Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecol. Complex.* 7 (3, 2010), 260–272. doi:10.1016/j.ecocom.2009.10.006

Decandia, M., Atzori, A. S., Acciaro, M., Cabiddu, A., Giovanetti, V., Molina Alcaide, E., et al. (2011). "Nutritional and animal factors affecting nitrogen excretion in sheep and goats,". *Challenging strategies to pro-mote the sheep and goat sector in the current global context. Options méditerranéennes: Série A. Séminaires Méditerranéens*. Editors M. J. Ranilla, M. D. Carro, H. Ben Salem, and P. Moran d-Fehr (Zaragoza, Spain: CIHEAM/CSIC/Universidad de León/FAO), 99, 201–209.

Díaz, S., Pascual, U., Stenseke, M., Martín-López, B., Watson, R. T., Zsolt, M., et al. (2018). Assessing nature's contributions to people. *Science* 359 (6373), 270–272. doi:10.1126/science.aap8826

Dumont, B., Franca, A., López-i-Gelats, F., Mosnier, C., and Pauler, C. M. (2022). Diversification increases the resilience of European grassland-based systems but is not a one-size-fits-all strategy. *Grass Forage Sci.*, 1–10. doi:10.1111/gfs.12587

Dyson, B. (2024). "Integration of life cycle and life cycle sustainability assessments into decision analytic approaches for sustainable technologies," in *Encyclopedia of sustainable technologies*. Editor A. A. Martin 2nd ed. (Elsevier), 643–655. doi:10.1016/B978-0-323-90386-8.00057-7

Escribano, M., Elghannam, A., and Mesias, F. J. (2020). Dairy sheep farms in semi-arid rangelands: a carbon footprint dilemma between intensification and land-based grazing. *Land Use Policy* 95, 104600. doi:10.1016/j.landusepol.2020.104600

FAO (2016a). "Greenhouse gas emissions and fossil energy use from small ruminant supply chains: guidelines for assessment," in *Livestock environmental assessment and performance partnership*, 105. Rome, Italy: FAO.

FAO (2016b). "Environmental performance of animal feeds supply chains: guidelines for assessment," in *Livestock environmental assessment and performance partnership*, 141. Rome, Italy: FAO.

FAO (2021). "The state of the world's land and water resources for food and agriculture – systems at breaking point," in *Synthesis report 2021*. Rome, 82. doi:10.4060/cb7654en

Finkbeiner, M., Schau, E. M., Lehmann, A., and Traverso, M. (2010). Towards life cycle sustainability assessment. *Sustainability* 2, 3309–3322. doi:10.3390/su2103309

Flysjö, A., Cederberg, C., Henriksson, M., and Ledgard, S. (2012). The interaction between milk and beef production and emissions from land use change – Critical considerations in life cycle assessment and carbon footprint studies of milk. *J. Clean. Prod.* 28 (0), 134–142. doi:10.1016/j.jclepro.2011.11.046

Franca, A., Caredda, S., Sanna, F., Fava, F., and Seddaiu, G. (2016). Early plant community dynamics following overseeding for the rehabilitation of a mediterranean silvopastoral system. *Grassl. Sci.* 62, 81–91. doi:10.1111/grs.12114

Franca, A., Re, G. A., and Sanna, F. (2018). Effects of grazing exclusion and environmental conditions on the soil seed bank of a mediterranean grazed oak wood pasture. *Agroforest Syst.* 92, 909–919. doi:10.1007/s10457-018-0203-0

Gac, A., Tailleur, A., and Dauguet, S. (2020). Allocation des impacts environnementaux à un produit ou à une activité agricole. *Arvalis.* Available online at: https://www.arvalis.fr/sites/default/files/imported_files/___2-152978628971939315.pdf.

García-Dory, F., Houzer, E., and Scoones, I. (2022). Livestock and climate justice: challenging mainstream policy narratives. The institute of development studies and partner organisations. *J. contribution.* doi:10.19088/1968-2022.138

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., et al. (2013). Tackling climate change through livestock - a global assessment of emissions and mitigation opportunities. *Food Agric. Organ. U. N.* doi:10.1016/j.anifeed.sci.2011.04.074

Glatzle, A. F. (2014). Planet at risk from grazing animals? Trop. Grassl. - *Forrajes Trop.* 2 (2), 60–62. doi:10.17138/tgft(2)60-62

Glimskär, A., Hultgren, J., Hiron, M., Westin, R., Bokkers, E. A. M., and Keeling, L. J. (2023). Sustainable grazing by cattle and sheep for semi-natural grasslands in Sweden. *Agronomy* 13, 2469. doi:10.3390/agronomy13102469

Goglio, P., Knudsen, M. T., Van Mierlo, K., Röhrig, N., Fossey, M., Maresca, A., et al. (2023). Defining common criteria for harmonizing life cycle assessments of livestock systems. *Clean. Prod. Lett.* 4, 100035. doi:10.1016/j.clpl.2023.100035

Goglio, P., Smith, L. G., Saget, S., Folegatti Matsuura, M. I. S., and Folegatti, I. S. (2024). Improved life cycle assessment (LCA) methods to account for crop-livestock interactions within agricultural systems. *Agric. Syst.*, 220, 104084, doi:10.1016/j.agsy.2024.104084

Gutierrez-Pena, R., Mena, Y., Batalla, I., and Mancilla-Leyton, J. M. (2019). Carbon footprint of dairy goat production systems: a comparison of three contrasting grazing levels in the Sierra de Grazalema Natural Park (Southern Spain). *J. Environ. Manag.* 232 (2019), 993–998. doi:10.1016/j.jenvman.2018.12.005

Hellweg, S., Benetto, E., Huijbregts, M. A. J., Verones, F., and Wood, R. (2023). Life-cycle assessment to guide solutions for the triple planetary crisis. *Nat. Rev. Earth Environ.* 4, 471–486. doi:10.1038/s43017-023-00449-2

Hou, P., Wang, H. T., Zhang, H., Fan, C. D., and Huang, N. (2012). GreenHouse gas emission factors of Chinese power grids for organization and product carbon footprint. *China Environ. Sci.* 32, 961e967. doi:10.3969/j.issn.1000-6923.2012.05.015

Houzer, E., and Scoones, I. (2021). Are livestock always bad for the planet? Rethinking the protein transition and climate change debate. *Inst. Dev. Stud. Partn. Organ.* doi:10.19088/STEPS.2021.003

Hu, Y. G. (2010). *Studies of effects of climate change and grazing on greenhouse gases flux on the alpine meadow of the qinghai-tibetau Plateau*. Qinghai: Doctoral Dissertation.

Huang, J., Tichit, M., Poulot, M., Darly, S., Li, S., Petit, C., et al. (2015). Comparative review of multifunctionality and ecosystem services in sustainable agriculture. *J. Environ. Manag.* 149, 138–147. doi:10.1016/j.jenvman.2014.10.020

IDF (2010). *IDF guide to life cycle assessment and life cycle management: a common carbon footprint methodology for the global dairy sector*, 63. Brussels: International Dairy Federation. Available online at: https://www.ukidf.org/documents/bulletin445.pdf.

ILCD (2010). *European commission - Joint research centre - Institute for Environment and Sustainability: International reference life cycle data system (ILCD) handbook* - general guide on life cycle assessment - detailed guidance. First edition march 2010. Luxembourg: Publications Office of the European Union, 397. Available online at: https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-General-guide-for-LCA-DETAILED-GUIDANCE-12March2010-ISBN-fin-v1.0-EN.pdf.

ILCD (2011). *European Commission- joint research Centre-. Institute for environment and sustainability: international reference life cycle data system (ILCD) Handbook-* recommendations for life cycle impact assessment in the European context. First edition November 2011. Luxemburg: Publications Office of the European Union, 5–56. Available online at: https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-Recommendations-for-Life-Cycle-Impact-Assessment-in-the-European-context.pdf.

IPCC (2006). *IPCC guidelines for national greenhouse gas inventories: volume 4: agriculture, forestry and other land use*. Paris (France): Intergovernmental Panel on Climate Change.

IPCC (2010). "Revisiting the use of managed land as a proxy for estimating national anthropogenic emissions and removals," in *Meeting report, 5-7 May, 2009, INPE, São José dos campos*. Editors Eggleston, H. S., Srivastava, N., Tanabe, K., and Baasansuren, J. (Brazil: IGES, Japan 2010). Available online at: https://www.ipcc-nggip.iges.or.jp/public/mtdocs/pdfiles/0905_MLP_Report.pdf.

IPCC (2013). *Climate change 2013. The physical science basis*. Working group I contribution to the fifth assessment report of IPCC. Available online at: http://www.climatechange2013.org/ (Accessed November 24, 2024).

IPCC (2019). *Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories* - volume 4: agriculture, forestry and other land use. Available online at: https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html.

ISPRA (2011). "*Greenhouse gas inventory system in Italy*, institute for environmental protection," in *Year 2011, environment department, rome, Italy*. Editors De Lauretis, R. N. R., Romano, D., Vitullo, M., and Arcarese, C.

Jamali, H., Livesley, S. J., Grover, S. P., Dawes, T. Z., Hutley, L. B., Cook, G. D., et al. (2011). The importance of termites to the CH4 balance of a tropical savanna woodland of northern Australia. *Ecosystems* 14, 698–709. doi:10.1007/s10021-011-9439-5

Jin, Z. G., Zhuang, Q. L., He, J. S., Zhu, X., and Song, W. M. (2015). Net exchanges of methane and carbon on the Qinghai-Tibetan Plateau from 1979-2010. *Environ. Res. Lett.* 10. doi:10.1088/1748-9326/10/8/085007

Jones, M. B. (2010). "Potential for carbon sequestration in temperate grassland soils," in *Grassland carbon sequestration: management, policy and economics*. Editors M. Abberton, R. Conant, and C. Batello (Rome: FAO), 1–18.

Jones, A. K., Jones, D. L., and Cross, P. (2014). The carbon footprint of lamb: Sources of variation and opportunities for mitigation. *Agric. Syst.* 123, 97–107. doi:10.1016/j.agsy.2013.09.006

Kandziora, M., Burkhard, B., and Müller, F. (2013). Interactions of ecosystem properties, ecosystem integrity and ecosystem service indicators—A theoretical matrix exercise. *Ecol. Indic.* 28 (2013), 54–78. doi:10.1016/j.ecolind.2012.09.006

Krätli, S., Lottje, C., Mikulcak, F., Foerch, W., and Feldt, T. (2023). *Pastoralism and resilience of food production in the face of climate change*. Bonn: Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH. Technical Paper.

Krätli, S. (2015). *Valuing variability: new perspectives on climate resilient dryland development*. London: IIED.

Kuipers, K. J., May, R., and Verones, F. (2021). Considering habitat conversion and fragmentation in characterisation factors for land-use impacts on vertebrate species richness. *Sci. Total Environ.* 801, 149737. doi:10.1016/j.scitotenv.2021.149737

Kyttä, V., Roitto, M., Astaptsev, A., Saarinen, M., and Tuomisto, H. L. (2022). Review and expert survey of allocation methods used in life cycle assessment of milk and beef. *Int. J. Life Cycle Assess.* 27 (2), 191–204. doi:10.1007/s11367-021-02019-4

Landsberg, J., James, C. D., Maconochie, J., Nicholls, A. O., Stol, J., and Tynan, R. (2002). Scale-related effects of grazing on native plant communities in an arid rangeland region of South Australia. *J. Appl. Ecol.* 39 (3), 427–444. doi:10.1046/j.1365-2664.2002.00719.x

Larrey-Lassalle, P., Loiseau, E., Roux, P., Lopez-Ferber, M., and Rosenbaum, R. K. (2018). Developing characterisation factors for land fragmentation impacts on biodiversity in LCA: Key learnings from a sugarcane case study. *Int. J. Life Cycle Assess.* 23 (11), 2126–2136. doi:10.1007/s11367-018-1449-5

Li, T. (2013). *Research on soil and vegetation carbon storage of grassland under different land use and degree in Aba pastural area, China*. (Sichuan, China: Sichuan Agriculture University), (in Chinese).

Ma, Z. H. (2002). *Comparative study of greenhouse gas emission factors in the main energy of China. Doctoral dissertation*. China: China Institute of Atomic Energy. (in Chinese).

Manzano, P., and White, S. (2019). Intensifying pastoralism may not reduce greenhouse gas emissions: wildlife-dominated landscape scenarios as a baseline in life-cycle analysis. *Clim. Res.* 77, 91–97. doi:10.3354/cr01555

Manzano, P., del Prado, A., and Pardo, G. (2023a). Comparable GHG emissions from animals in wildlife and livestock-dominated savannas. *npj Clim. Atmos. Sci.* 6, 27. doi:10.1038/s41612-023-00349-8

Manzano, P., Azcarate, F. M., Bencherif, S., Burgas, D., Byambaa, B., Cabeza, M., et al. (2023b). Grazing research should consider mobility and governance. *Science* 378 (6622). doi:10.1126/science.abq4062

Manzano, P., Rowntree, J., Thompson, L., del Prado, A., Ederer, P., Windisch, W., et al. (2023c). Challenges for the balanced attribution of livestock's environmental impacts: The art of conveying simple messages around complex realities. *Animal Front. Rev. Mag. animal Agric.* 13 (2), 35–44. doi:10.1093/af/vfac096

Manzano, P., de Aragão Pereira, M., and Windisch, W. (2025). Vast extension but positive outcomes, reduced but negative: Complexity and nuances in evaluating land use by livestock and crops. *Anim. Front.* 15 (1), 43–54. doi:10.1093/af/vfae051

McAuliffe, G. A., Lopez-Aizpun, M., Blackwell, M. S. A., Castellano- Hinojosa, A., Darch, T., Evans, J., et al. (2020). Elucidating three-way interactions between soil, pasture and animals that regulate nitrous oxide emissions from temperate grazing systems. *Agric. Ecosyst. and Environ.* 300, 106978. doi:10.1016/j.agee.2020.106978

McClelland, S. C., Arndt, C., Gordon, D. R., and Thoma, G. (2018). Type and number of environmental impact categories used in livestock life cycle assessment: A systematic review. *Livest. Sci.* 209, 39–45. doi:10.1016/j.livsci.2018.01.008

McLaren, S., Berardy, A., Henderson, A., Holden, N., Huppertz, T., Jolliet, O., et al. (2021). *Integration of environment and nutrition in life cycle assessment of food items: opportunities and challenges*. Rome: FAO.

Millennium Ecosystem Assessment (2005). *Ecosystems and human well-being: opportunities and challenges for business and industry*. Washington, DC: World Resources Institute.

Molle, G., Decandia, M., Sanna, L., Vagnoni, E., Pintus, G., Duce, P., et al. (2017). Report of the characterization of Sardinian dairy sheep production systems. Available online at: http://www.sheeptoship.eu/images/Report/A.1.3_Report%20char.%20Sard.%20pr.%20systems.pdf (Accessed January 24, 2025).

Møller, H., Rydhmer, L., Christensen, T., Krogh Poulsen, L., and Fjerdingby Olsen, H. (2024). Social life cycle assessment in current and future Norwegian livestock production. *Int. J. Life cycle Asses.* 30, 1134–1151. doi:10.1007/s11367-024-02345-3

Morton, J., Kotyza, P., Vigne, M., and Dashbaal, B. (2024). "Cashmere value chain analysis in Mongolia," in *Report for the european union, DG-INTPA value chain analysis for development project (VCA4D CTR 2017/392-417), 122p + annexes*.

Moughan, P. J. (2021). Population protein intakes and food sustainability indices: the metrics matter. *Glob. Food Secur.* 29, 100548. doi:10.1016/j.gfs.2021.100548

Nemecek, T., and Kägi, T. (2007). *Life cycle inventories of Swiss and European agricultural production systems*. Swiss Centre for Life Cycle Inventories, Zurich and Dübendorf, Switzerland. Available online at: www.ecoinvent.ch.

Nordhagen, S., Beal, T., and Haddad, L. (2020). "The role of animal-source foods in healthy," in *Sustainable and equitable food systems*. Switzerland: GAIN Discussion Paper Series 5.

OECD (2001). *Multifunctionality: towards an analytical framework*. Paris: OECD, 157. Available online at: https://www.oecd.org/content/dam/oecd/en/publications/reports/2001/04/multifunctionality_g1gh17be/9789264192171-en.pdf.

Pardo, G., Casas, R., Del Prado, A., and Manzano, P. (2024). Carbon footprint of transhumant sheep farms: Accounting for natural baseline emissions in mediterranean systems. *Int. J. Life Cycle Assess.* 29, 2184–2199. doi:10.1007/s11367-023-02135-3

Paul, B. K., Butterbach-Bahl, K., Notenbaert, A., Nduah Nderi, A., and Ericksen, P. (2020). Sustainable livestock development in low and middle income countries – Shedding light on evidence-based solutions. *Environ. Res. Lett.* 16, 011001. doi:10.1088/1748-9326/abc278

Peal, A., Evans, B., Ahilan, S., Ban, R., Blackett, I., Hawkins, P., et al. (2020). Multi-functional land use is not self-evident for European farmers: a critical review. *Front. Environ. Sci.* 8, 1–10. doi:10.3389/fenvs.2020.00001

PEF (2013). 2013/179/EU: Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. *Official J. Eur. Union*, 9–91. Available online at: http://data.europa.eu/eli/reco/2013/179/oj.

Perevolotsky, A. (2005). Integrating landscape ecology in the conservation of mediterranean ecosystems: the Israeli experience. *Israel J. Plant Sci.* 53, 203–213. doi:10.1560/dql0-q22f-lmd5-97lk

Petersen, B. M., Knudsen, M. T., Hermansen, J. E., and Halberg, N. (2013). An approach to include soil carbon changes in life cycle assessments. *J. Clean. Prod.* 52, 217–224. doi:10.1016/j.jclepro.2013.03.007

Pinto-Correia, T. N., Guiomar, N., Ferraz-de-Oliveira, M. I., Sales-Baptista, E., Rabaça, J., Godinho, C., et al. (2018). Progress in identifying high nature value montados: impacts of grazing on hardwood rangeland biodiversity. *Rangel. Ecol. and Manag.* 71(5):612–625. doi:10.1016/j.rama.2018.01.004

Pinto-Correia, T., Ferraz-de-Oliveira, I., Guimarães, M. H., Sales-Baptista, E., Pinto-Cruz, C., Godinho, C., et al. (2022). Result-based payments as a tool to preserve the high nature value of complex silvo-pastoral systems: Progress toward farm-based indicators. *Ecol. Soc.* 27 (1), 39. doi:10.5751/es-12973-270139

Plieninger, T., Höchtl, F., and Spek, T. (2006). Traditional land-use and nature conservation in European rural landscapes. *Environ. Sci. and Policy* 9, 317–321. doi:10.1016/j.envsci.2006.03.001

Porqueddu, C., Melis, R. A. M., Franca, A., Sanna, F., Hadjigeorgiou, I., and Casasús, I. (2017). The role of grasslands in the less favoured areas of mediterranean Europe. *19th EGF Symposium Grassl. Resour. extensive farming Syst. marginal lands major drivers future scenarios - Grassl. Sci. Eur.* 22, 3–22.

Ragkos, A., and Nori, M. (2016). "The multifunctional pastoral systems in the mediterranean EU and impact on the workforce," in *Ecosystem services and socio-economic benefits of mediterranean grasslands. France, Options méditerranéennes* (Séminaires Méditerranéens), 325–328.

Reinhard, J., Moreno-Ruiz, E., and Gmünder, S. (2017). Consideration of land use change in ecoinvent version 3.3: method, implementation and illustration. *White Paper*, Zürich, Switzerland: Ecoinvent Association.

Resare Sahlin, K., Röös, E., and Gordon, L. J. (2020). "Less but better" meat is a sustainability message in need of clarity. *Nat. Food* 1 (9), 520–522. doi:10.1038/s43016-020-00140-5

Ripoll-Bosch, R., de Boer, I. J. M., Bernues, A., and Vellinga, T. V. (2013). Accounting for multi-functionality of sheep farming in the carbon footprint of lamb: A comparison of three contrasting mediterranean systems. *Agric. Syst.* 116, 60–68. doi:10.1016/j.agsy.2012.11.002

Robert Kiefer, L., Menzel, F., and Bahrs, E. (2015). Integration of ecosystem services into the carbon footprint of milk of South German dairy farms. *J. Environ. Manag.* 152, 11–18. doi:10.1016/j.jenvman.2015.01.017

Rotz, C. A., Asem-Hiablie, S., Place, S., and Thoma, G. (2019). Environmental footprints of beef cattle production in the United States. *Agric. Syst.* 169 (2019), 1–13. doi:10.1016/j.agsy.2018.11.005

Rowntree, J. E., Stanley, P. L., Maciel, I. C. F., Thorbecke, M., Rosenzweig, S. T., Hancock, D. W., et al. (2020). Ecosystem impacts and productive capacity of a multi-species pastured livestock system. *Front. Sustain. Food Syst.*, 4, 544984–2020. doi:10.3389/fsufs.2020.544984

Rufino, M. C., Brandt, P., Herrero, M., and Butterbach-Bahl, K. (2014). Reducing uncertainty in nitrogen budgets for African livestock systems. *Environ. Res. Lett.* 9, 105008. doi:10.1088/1748-9326/9/10/105008

Rugani, B., Maia de Souza, D., Weidema, B. P., Bare, J., Bakshi, B., Grann, B., et al. (2019). Towards integrating the ecosystem services Cascade framework within the life cycle assessment (LCA) cause-effect methodology. *Sci. Total Environ.* 690 (2019), 1284–1298. doi:10.1016/j.scitotenv.2019.07.023

Russell, S., Tyrrell, P., and Western, D. (2018). Seasonal interactions of pastoralists and wildlife in relation to pasture in an African savanna ecosystem. *J. Arid Environ.* 154, 70–81. doi:10.1016/j.jaridenv.2018.03.007

Saarinen, M., Fogelholm, M., Tahvonen, R., and Kurppa, S. (2017). Taking nutrition into account within the life cycle assessment of food products. *J. Clean. Prod.* 149, 828–844. doi:10.1016/j.jclepro.2017.02.062

Salou, T., Le Mouël, C., and van der Werf, H. M. G. (2017). Environmental impacts of dairy system intensification: The functional unit matters. *J. Clean. Prod.* 140 (Part 2), 445–454. doi:10.1016/j.jclepro.2016.05.019

Schils, R. L., Bufe, C., Rhymer, C. M., Francksen, R. M., Klaus, V. H., Abdalla, M., et al. (2022). Permanent grasslands in Europe: land use change and intensification decrease their multifunctionality. *Agric. Ecosyst. and Environ.* 330, 107891. doi:10.1016/j.agee.2022.107891

Schrama, M., Quist, C. W., Arjen de Groot, G., Cieraad, E., Ashworth, D., Laros, I., et al. (2023). Cessation of grazing causes biodiversity loss and homogenization of soil food webs. *Proc. R. Soc. B* 290, 29020231345. doi:10.1098/rspb.2023.1345

Scoones, I. (2023). Livestock, methane, and climate change: the politics of global assessments. *WIREs Clim. Change* 14 (1), e790. doi:10.1002/wcc.790

Seid, M. A., Yoseph, L. W., Befekadu, U. W., Muhammed, A., and Fikre, Z. (2016). Communication for the development of pastoralism. *Revue Sci. Tech. de l'OIE* 35, 639–648. doi:10.20506/rst.35.2.2545

Simoncini, R., Ring, I., Sandström, C., Albert, C., Kasymov, U., and Arlettaz, R. (2019). Constraints and opportunities for mainstreaming biodiversity and ecosystem services in the EU's Common Agricultural Policy: insights from the IPBES assessment for Europe and Central Asia. *Land Use Policy, Elsevier*, 88 (C). doi:10.1016/j.landusepol.2019.104099

Sonesson, U., Davis, J., Flysjö, A., Gustavsson, J., and Witthöft, C. (2017). Protein quality as functional Unit – A methodological framework for inclusion in life cycle assessment of food. *J. Clean. Prod.* 140, 470–478. doi:10.1016/j.jclepro.2016.06.115

Sonesson, U., Davis, J., Hallström, E., and Woodhouse, A. (2019). Dietary-dependent nutrient quality indexes as a complementary functional unit in LCA: A feasible option? *J. Clean. Prod.* 211, 620–627. doi:10.1016/j.jclepro.2018.11.171

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., and de Haan, C. (2006). *Livestock's long shadow: environmental issues and options*. Rome: Food and Agriculture Organization of the United Nations. Available online at: http://www.fao.org/3/a0701e/a0701e00.htm.

Sureau, S., Neugebauer, S., and Achten, W. M. (2020). Different paths in social life cycle impact assessment (S-LCIA)—a classification of type II impact pathway approaches. *Int. J. life cycle Assess.* 25, 382–393. doi:10.1007/s11367-019-01693-9

Tchakerian, E. (coord.). (2008). Pastoralisme méditerranéen : état des lieux et perspectives pour huit régions méditerranéennes. Bilan d'une des composantes du programme européen Pastomed. *Forêt méditerranéenne*, 29 (3), 309–320. Available online at: http://www.foret-mediterraneenne.org/fr/catalogue/id-1119-pastoralisme-mediterraneen-etat-des-lieux-et-perspectives-pour-huit-regions-mediterraneennes.

Teague, W. R., and Wright, A. (2018). The role of grazing in soil health and carbon sequestration. *Agron. J.* 110 (2), 529–537. doi:10.2134/agronj2017.06.0336

Tian, H. Z., Zhao, D., and Wang, Y. (2011). Emission inventories of atmospheric pollutants discharged from biomass burning in China. *Acta Sci. circum.* 31, 349e357. (in Chinese with English Abstract).

Traoré, S., Nygård, R., Guinko, S., and Lepage, M. (2008). Impact of macrotermes termitaria as a source of heterogeneity on tree diversity and structure in a Sudanian Savannah under controlled grazing and annual prescribed fire (burkina faso). *For. Ecol. Manag.* 255, 2337–2346. doi:10.1016/j.foreco.2007.12.045

Tsonkova, P., Quinkenstein, A., Böhm, C., Freese, D., and Schaller, E. (2014). Ecosystem services assessment tool for agroforestry (ESAT-A): an approach to assess selected ecosystem services provided by alley cropping systems. *Ecol. Indic.* 45 (2014), 285–299. doi:10.1016/j.ecolind.2014.04.024

UNEP (2009). Guidelines for social life cycle assessment of products. *Management* 15 (2), 104. Available online at: http://www.unep.fr/shared/publications/pdf/DTIx1164xPA-guidelines_sLCA.pdf.

UNEP (2020). *Guidelines for social life cycle assessment of products and organizations.* Benoît Norris, C., Traverso, M., Neugebauer, S., Ekener, E., Schaubroeck, Mankaa, R., et al. (eds.). United Nations Environment Programme (UNEP).

Vagnoni, E., and Franca, A. (2018). Transition among different production systems in a Sardinian dairy sheep farm: environmental implications. *Small Ruminant Res.* 159, 62–68. doi:10.1016/j.smallrumres.2017.12.002

Vagnoni, E., Franca, A., Breedveld, L., Porqueddu, C., Ferrara, R., and Duce, P. (2015). Environmental performances of Sardinian dairy sheep production systems at different input levels. *Sci. Total Environ.* 502, 354–361. doi:10.1016/j.scitotenv.2014.09.020

Vagnoni, E., Sanna, L., Arca, P., Jones, C., Batta, K., Atzori, A. S., et al. (2018). Guidelines for LCA application on mediterranean dairy sheep supply chains, *LIFEc Sheeptosh. Proj. Rep.* Available online at: http://www.sheeptoship.eu/images/Report/C.1.1_LCA%20guidelines_v3.pdf.

Vagnoni, E., Arca, P., Decandia, M., Molle, G., Serra, G., Sau, P., et al. (2024). Looking for the ecological transition of Mediterranean small ruminant sector. Characterization and main drivers of environmental performance of the Sardinian sheep farming systems. *Clean. Environ. Syst.* 14, 100214. doi:10.1016/j.cesys.2024.100214

Van den Pol-van Dasselaar, A. (2017). EIP-AGRI focus group grazing for carbon. *Start. Pap. EIP-AGRI*, 16.

van Oudenhoven, A. P. E., Petz, K., Alkemade, R., Hein, L., and de Groot, R. S. (2012). Framework for systematic indicator selection to assess effects of land management on ecosystem services. *Ecol. Indic.* 21, 110–122. doi:10.1016/j.ecolind.2012.01.012

VanderWilde, C. P., and Newell, J. P. (2021). Ecosystem services and life cycle assessment: a bibliometric review. *Resour. Conservation Recycl.* 169, 105461. 0921-3449. doi:10.1016/j.resconrec.2021.105461

Vayssières, J., Sasi, D., Assouma, M. H., Vigne, M., and Ickowicz, A. (2024). "Greenhouse gas balance and carbon footprint: Two methodologies for assessing the contribution of extensive *versus* intensive livestock systems to climate change," in *In: the 75th annual meeting of the european association for animal production "global quality: environment, animals, food.* Florence, Italy, September 1st-September 5th 2024.

Vermorel, M., Jouany, J. P., Eugène, M., Sauvant, D., Noblet, J., and Dourmad, J. Y. (2008). *Evaluation quantitative des émissions de méthane entérique par les animaux d'élevage en 2007 en France.* INRA Prod. *Anim.* 21, 403–418.

Verones, F., Bare, J., Bulle, C., Frischknecht, R., Hauschild, M., Hellweg, S., et al. (2017). LCIA framework and cross-cutting issues guidance within the UNEP-SETAC life cycle initiative. *J. Clean. Prod.* 161 (161), 957–967. doi:10.1016/j.jclepro.2017.05.206

von Greyerz, K., Tidåker, P., Karlsson, J. O., and Röös, E. (2023). A large share of climate impacts of beef and dairy can be attributed to ecosystem services other than food production. *J. Environ. Manag.* 325, 116400. doi:10.1016/j.jenvman.2022.116400

Xu, T. W., Hu, L. Y., Ge, S. D., Zou, X. Y., Zhao, N., and Xu, S. X. (2014). Greenhouse gas emissions from Tibetan sheep with supplementary feeding in alpine pasture in Qinghai-Tibet Plateau during cold seasons. *J.* Agro-Environ. Sci. 33, 2071e2076. (in Chinese with English Abstract).

Yang, Y. H., Fang, J. Y., Ma, W. H., Smith, P., Mohammat, A., Wang, S. P., et al. (2010). Soil carbon stock and its changes in northern China's grasslands from 1980s to 2000s. *Glob. Change Biol.* 16, 3036–3047. doi:10.1111/j.1365-2486.2009.02123.x

Yu, L. F., Wang, H., Wang, G. S., Song, W. M., Huang, Y., Li, S. G., et al. (2013). A comparison of methane emission measurements using eddy covariance and manual and automated chamber-based techniques in Tibetan Plateau alpine wetland. *Environ. Pollut.* 181, 81–90. doi:10.1016/j.envpol.2013.06.018

Zhang, Y. I., Singh, S., and Bakshi, B. R. (2010). Accounting for ecosystem services in life cycle assessment part I: a critical review. *Environ. Sci. and Technol.* 44, 2232–2242. doi:10.1021/es9021156

Zhang, W., Liu, C. Y., Zheng, X. H., Fu, Y. F., Hu, X. X., Cao, G. M., et al. (2014). The increasing distribution area of zokor mounds weaken greenhouse gas uptakes by alpine meadows in the QinghaiTibetan Plateau. *Soil Biol. Biochem.* 71, 105–112. doi:10.1016/j.soilbio.2014.01.005

Zhang, C., Li, J., and Zhou, Z. (2022). Ecosystem service cascade: concept, review, application and prospect. *Ecol. Indic.* 137, 108766. ISSN 1470-160X. doi:10.1016/j.ecolind.2022.108766

Zhao, Y., Liu, Z., and Wu, J. (2020). Grassland ecosystem services: A systematic review of research advances and future directions. *Landsc. Ecol.* 35 (4), 793–814. doi:10.1007/s10980-020-00980-3

Zhu, S.-Li (2014). Comparison and analysis of CO2 emissions data for China. *Adv. Clim. Change Res.* 5 (1), 17–27. doi:10.3724/SP.J.1248.2014.017

Zhuang, M. G., Li, W., and Li, W. (2017). Greenhouse gas emission of pastoralism is lower than combined extensive/intensive livestock husbandry: A case study on the Qinghai–Tibet Plateau of China. *J. Clean. Prod.* 147, 514–522. doi:10.1016/j.jclepro.2017.01.126

Zhuang, M., Zhang, J., Zhang, J., and Li, W. (2019). Community-based seasonal movement grazing maintains lower greenhouse gas emission intensity on Qinghai–Tibet Plateau of China. *Land Use Policy* 85, 155–160. doi:10.1016/j.landusepol.2019.03.032

Pastoralism
Research, Policy and Practice

TYPE Original Research
PUBLISHED 20 March 2026
DOI 10.3389/past.2026.15693

OPEN ACCESS

EDITED BY
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RECEIVED 03 October 2025
REVISED 02 March 2026
ACCEPTED 04 March 2026
PUBLISHED 20 March 2026

CITATION
Lkhamaachin A, Sukhbaatar L, Nyam-Osor N, Galaaraidii O, Cheng Y, Norovsambuu T, Janchivlamdan C, Amarsanaa M, Bayaraa B, Sukhbaatar J, Zhang M-Z and Sukhbaatar O (2026) Enteric methane emission factors for sheep in Mongolian extensive grazing systems: a Tier 2 approach. *Pastoralism* 16:15693.
doi: 10.3389/past.2026.15693

Enteric methane emission factors for sheep in Mongolian extensive grazing systems: a Tier 2 approach

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Methane emissions from livestock are a significant contributor to agricultural greenhouse gas outputs, yet region-specific emission factors are often lacking for nomadic pastoral systems. This study determined annual enteric methane emission factors for sheep across three major agro-ecological zones of Mongolia: Desert-steppe, steppe, and forest-steppe, considering animal sex and age categories. Animal performance data were collected for adult males (>3 years), adult females (>3 years), young sheep (1–2 years), and lambs (<1 year). According to the IPCC Tier 1 methodology, the default emission factor for adult sheep is 5 kg CH_4/head/year, while lamb values are estimated at approximately 2 kg CH_4/head/year. Nevertheless, these generalized values fail to capture country-specific differences in animal productivity, diet quality, seasonal feed availability, and grazing management, thereby introducing significant uncertainty into national greenhouse gas inventories. Results showed that females consistently exhibited higher emission factors than males, with values ranging from 6.0 to 6.1 kg CH_4/head/year, compared to 5.40–5.45 kg CH_4/head/year for males. Young sheep emitted between 4.3 and 4.9 kg CH_4/head/year, while lamb emissions were lowest at 1.6–1.8 kg CH_4/head/year. These findings provide updated, region-specific methane emission factors for Mongolian sheep, supporting the refinement of national greenhouse gas inventories and climate change mitigation strategies.

KEYWORDS

climate change, enteric fermentation, greenhouse gas inventory, IPCC Tier 2 methodology, livestock

Introduction

Mongolia sustains a large population of small ruminants, with around 23 million sheep and an equal number of goats (National Statistics Office of Mongolia, 2025). These animals are vital for rural livelihoods, contributing to food security, household income, and traditional cultural practices (Mearns, 2004). Globally, livestock production is a major contributor to agricultural greenhouse gas (GHG) emissions, accounting for roughly 60% of the sector's total output (FAO, 2021). Among GHG emissions, methane (CH_4) emissions from grazing ruminants represent about 29% of livestock-related GHG emissions, with 26.4% occurring in arid and semi-arid regions (Clark, 2017). Worldwide, sown pasture (SP) and native pasture (NP) supply nearly half of the feed consumed by grazing animals, supporting the livelihoods of an estimated 1.3 billion people (Belache et al., 2023; IPCC, 2019). Sheep, numbering around 1.2 billion globally, contribute approximately 6.4% of total enteric methane emissions from livestock (Patra, 2014a), making them the third largest ruminant source after cattle and buffalo (FAOSTAT, 2020). The sheep industry plays a role in advancing several United Nations Sustainable Development Goals (SDGs), and maintaining current production levels is considered desirable (Belanche et al., 2021). However, the predicted rise in global demand for meat (+73%) and milk (+58%) poses challenges to achieving CH_4 mitigation targets—estimated at up to 47% between 2010 and 2050—while sustaining productivity (Beauchemin et al., 2020). Meeting climate goals, such as limiting warming to 1.5 °C by 2030, will require mitigation strategies that do not compromise animal health, productivity, or welfare (Arndt et al., 2022). Accurate quantification of enteric CH_4 emissions across species, production systems, and regions is therefore essential. For sheep, however, comprehensive datasets covering different production environments remain scarce. The Intergovernmental Panel on Climate Change (IPCC) recommends estimating emissions using CH_4 conversion factors (Ym), which represent the fraction of gross energy intake lost as methane during enteric fermentation. The 2019 IPCC guidelines suggest a default Ym of 6.7% for all sheep categories and diets, with slightly adjusted values (7.0% or 6.5%) depending on dry matter intake (DMI) levels (Hammond et al., 2011). These estimates are based largely on New Zealand studies using high-quality forage diets (Swainson et al., 2018) and may not reflect the variability in diet quality, rumen fermentation, or animal class (e.g., lambs *versus* adults) in other regions (Moraes et al., 2014). Consequently, applying these default factors directly to grazing sheep in Mongolia could result in significant inaccuracies in national inventories or in cost-benefit analyses of mitigation measures.

Dry matter intake (DMI) is the most important predictor of enteric CH_4 production, as it shows a strong positive correlation with CH_4 emissions across all databases considered (Ellis et al., 2007). Consequently, forage quality is also a key predictor of greenhouse gas emissions, since it directly influences DMI (Belanche et al., 2023; Xie et al., 2023; Hammond et al., 2009; Patra, 2013). In Mongolia, animal performance is closely linked to both the quantity and quality of natural grasslands. For certain species, up to 98% of annual intake comes from native pasture. These grasslands, covering roughly 128.8 million hectares and hosting around 2,270 grass species (including 600 forage species), are distributed across six main zones:alpine tundra (3%) maintain taiga (4.1%) mountain steppe and desert steppe (25.1%), grass steppe (26.1), desert steppe (25.1) desert (14.5%) (Johnson et al., 2006; Amarsaikhan et al., 2023). Pasture growth is highly seasonal and climate-dependent, with new growth beginning as early as mid-April in forest steppe and steppe regions, and later in other zones. Grazing in early spring consists largely of senescent material, with fresh grass dominating intake from June to September (Munkhzul et al., 2021; Damiran et al., 2009). For roughly 200 days of the year, livestock rely primarily on senescent forage. Some areas are left ungrazed for haymaking or to serve as standing feed during winter (Togtokhbayar, 1995; Hu et al., 2023).

Over 90% of Mongolia's sheep belong to the native "Mongol" breed, which is evenly distributed nationwide. Breeding farms in Bayantsagaan (Tuv aimag), Erdenedalai (Dundgovi aimag), and Hotont (Arkhangai aimag) maintain purebred and improved stock for distribution to more than 70 soums (Chadraabal, 2013; Sambuu, 2003; Nergui et al., 2011). This homogeneity creates an opportunity: even modest improvements in breeding and feeding practices could be scaled nationally, delivering significant mitigation gains while supporting pastoral livelihoods.

The present study aimed to quantify enteric CH_4 emissions from major rangeland ecosystems desert-steppe, steppe and mountain forest—in Mongolia using the IPCC Tier 2 methodology. This approach incorporates animal energy requirements based on liveweight, productivity, diet quality, and age sex categories of sheep.

Materials and methods

This study was conducted in three specific locations in Mongolia. Khotont sum Arhkanhangai province represented forest steppe rangeland (47.369406, 102.473088°E), Bayantsagaan and Sergelen soum of Tuv province represented steppe rangeland (47.692664, 106.997982°E), Shivee-Govi soum of Gobi sumber province (46.157656, 108.545458°E)-represented rangeland sheep systems in semi-arid environments desert-steppe rangeland. For the selected sites, the use of seasonal weight change, energy partitioning calculation, and pasture quality analysis, combined with GPS-tracked locomotion data, ensures improved emission factor (EF) estimation relevant to extensive rangeland systems in the long-term studies.

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Animal characteristics and performance data

The study followed the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019) to estimate enteric CH_4 emissions. In additions, equations from IPCC (2000) and NRC (2001) were used for the estimation of net energy mobilized due to weight loss and net energy for activity utilizing the daily distance travelled.

Measurements were taken at the beginning and end of each season. Although Mongolia has four seasons, measurements were divided into two periods: summer-autumn (S-A) which is the weight gain season, and winter-spring (W-S), the weight loss season, based on changes in animal body weight.

After the initial visit to herders in early 2024, the researchers conducted repeated herder visits to collect data on live weight and, pasture samples. A representative sub-sample of the herd, 54 sheep in the Khotont, 28 Sheep in the Shivee govi sum, and 46 sheep in the Sergelen and Bayantsgaan sum were considered in the project. The animals were classified into the following age groups: adult male and female sheep (>3 years), young adult (1–2 years), and lamb.

Live weight measurement and average daily weight gain/loss

Live weights were measured using calibrated sheep weighing scale (dimensions: 1.2 m × 2 m × 1.3 m; YH-T3 Tscale Electronics MFG, Model KW; Kunshan, China) during each visit. The scale was calibrated with known weights before each weighing session in each household. The live weight measurements were taken at the beginning and end of the two distinct seasons in Mongolia: Summer- Autumn (15th August) and Winter-Spring (15th April). Average live weight change (LWC) was computed using the difference in live weight for each animal between seasons and divided by the number of days between measurements. If a live weight was missing, the average LWC of the herd was applied.

Forage sampling and chemical analysis

Representative forage samples were collected from three locations during the growing season, in mid-May and August, when pasture was fully green. To characterize the senescent forage consumed during winter–spring, additional samples were collected *in situ* in November and April, when sheep predominantly graze on mature or senescent grass. The chemical composition of all samples was analyzed, and the averages of the November and April samples were considered representative of the entire winter–spring season. This approach allows seasonal changes in forage quality to be captured while remaining logistically feasible under extensive grazing conditions.

Samples were dried in hot air oven at 55 °C for 48 h and then ground using a Wiley mill through mm sieve The chemical composition of the study sample was collected at the Nutrition Assessment Laboratory of the Research Institute of Animal Husbandry. The methods employed were moisture and crude ash by weight method (MNS 6548:2015), crude proteins by Kjeldahl method (MNS 6549:2015), fiber and its fractions by ANKOM method (MNS6551:2015), fats by Soxhlet method (MNS6554:2015), macro-microelements (MNS4655:2015). The dry matter digestibility DMD was estimated from the equation of Oddy et al. (1983), as follows:

$$\mathrm{DMD}\ (\mathrm{g/100g\ DM}) = 83.58 - 0.824 \times \mathrm{ADF}\left(\mathrm{g/100g\ DM}\right) + \left(2.626 \cdot \mathrm{N}\left(\mathrm{g/100g\,DM\ 100g\,DM}\right)\right) \quad (1)$$

GE content was estimated according to the equation described by Weiss and Tebbe (2019):

$$\mathrm{GE}\ (\mathrm{MJ/kg\,DM}) = [\mathrm{CP}\,\% \times 0.056 + \mathrm{EE}\,\% \times 0.094 + (100 - \mathrm{CP}\,\% - \mathrm{EE}\,\% - \mathrm{ash}\,\%) \times 0.042] \times 4.187 \quad (2)$$

Subsequently, the DE % was estimated from the DMD using Equation 4 derived from CSIRO (2007), as IPCC methodology utilizes digestible energy (DE, % of gross energy) for the calculation of net energy requirements,

$$DE\% = \frac{DMD\,(\%) \times 0.172 - 1.707}{0.81 \times GE\left(\frac{MJ}{kgDM}\right)} \times 100 \quad (3)$$

Where; DE % is the digestible energy as a percentage of feed gross energy; DMD is seasonal dry matter digestibility%, as estimated in Equation 1, 0.172 and 1.707 are constants used in a formula to convert DMD into megajoules (MJ) of metabolizable energy per kilogram of dry matter (DM); 0.81 is a factor that converts metabolizable energy to digestible energy; GE is gross energy of feed (MJ/kg DM).

Gross energy calculations

Gross energy (GE) values used in this study were derived from a combination of IPCC default values (IPCC, 2006; IPCC, 2019) and locally measured feed composition. Standard IPCC values were applied for components such as maintenance energy and general feed GE content. For parameters not provided by the IPCC—such as energy content and digestibility of Mongolian pasture species—we used data from chemical analyses of forage samples collected during the study (May, August, November, and April) and supplemented with published regional studies (Yan et al., 2010; Liu et al., 2020; Goopy et al., 2018). This approach ensures that energy intake and expenditure estimates reflect both internationally standardized methods and the specific conditions of Mongolian extensive grazing systems.

Net energy for maintenance: (NE m) is the net energy required for maintenance, which is the amount of energy needed to keep the animal in equilibrium where body energy is neither gained nor lost (IPCC, 2006).

$$NEm = Cf^{*}(Weiht)^{0.75} \quad (4)$$

Where:

NE m = net energy required by the animal for maintenance, MJ day^{-1}
Cf i = a coefficient for Sheep older than 1 year 0.217, lamb to 1 year 0.236 calculating NEm), MJ day^{-1} kg^{-1}
Weight = live-weight of animal, kg

Net energy for activity: (NE a) is the net energy for activity, or the energy needed for animals to obtain their food, water and shelter.

$$NEa = Ca^{*}Weight \quad (5)$$

Where:

NEa = net energy for animal activity, MJ day^{-1}
Ca = coefficient corresponding to animal's feeding situation 0.0240 for Grazing hilly pasture, MJ day−1 kg −1
weight = live-weight of animal, kg

Net energy for growth: (NE g) is the net energy needed for growth (i.e., weight gain).

$$NEg = \frac{WG\,lamb \cdot (a - 0.5b(BWi + BWf))}{365} \quad (6)$$

Where:

NE g = net energy needed for growth, MJ day-1
WG lamb = the weight gain (BW f–BW i), kg yr −1
BW i = the live body weight at weaning, kg
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BW f = the live body weight at 1-year old or at slaughter (live-weight) if slaughtered prior to 1 year of age, kg a, b = 2.1, 0.45

Net energy for lactation: (NE l) is the net energy for lactation. Milk production is not known, (Agricultural and Food Research Council, 1990) indicates that for a single birth, the milk yield is about 5 times the weight gain until august of the lamb.

$$NE_l = \left[\frac{(5 \times WGwean)}{365}\right]^{\circ} EVmilk \quad (7)$$

Where:

NEl = net energy for lactation, MJ day-1
WG wean = the weight gain of the lamb between birth and weaning, kg
EV milk = the energy required to produce 1 kg of milk, MJ kg −1. A default value of 4.6 MJ kg −1 (Agricultural and Food Research Council, 1993) can be used.

Net energy for wool production: Wool yield was determined by asking questions to the herdsman. (NE wool) is the average daily net energy required for sheep to produce a year of wool.

$$NE_{wool} = \left[\frac{(EV_{wool} \times Production_{wool})}{365}\right] \quad (8)$$

Where:

NE wool = net energy required to produce wool, MJ day-1
EV wool = the energy value of each kg of wool produced (weighed after drying but before scouring), MJ
kg −1. A default value of 24 MJ kg −1 (Agricultural and Food Research Council, 1993) can be used for this estimate.
Production wool = annual wool production per sheep, kg yr −1

Net energy for pregnancy: (NE p) is the energy required for pregnancy. For sheep, the NE p requirement is similarly estimated for the 147-day gestation period, although the percentage varies with the number of lambs born.

$$NEp = C\,pregnancy^{*}NE\,m \quad (9)$$

Where:

NEp = net energy required for pregnancy, MJ day-1
C pregnancy = pregnancy coefficient 0.007
NEm = net energy required by the animal for maintenance, MJ/day

Net energy for travel: The average daily distance traveled was determined using GPS collars. Collars were attached in the morning before releasing the animals for grazing on randomly selected sheep. Due to the limited number of collars and to obtain data from as many animals as possible per season, collars were changed between animals every 3 days (NRC. ,2001). As the animals were confined at night, only data collected between 8:00 a.m in the morning and 9:00 p.m. were considered.

$$NEt(Mj) = dist(km)^{*}0.0019\left(\frac{MJ/kg}{km}\right)^{*}MLW(kg) + 0.005\left(\frac{MJ}{kg}\right)^{*}MLW(kg) \quad (10)$$

Where: NEt is net energy for travel per day, MJ; Dist. is the average daily distance in km traveled per season, (data obtained from GPS collar); 0.0019 is energy cost of walking per kg body weight per km; MLW is the mean seasonal LW in kg; and 0.005 is the energy (MJ) required per kg LW during grazing.

While Mongolian fat-tailed sheep differ markedly from New Zealand sheep in terms of breed type, grazing management, and mobility, the estimation of energy expenditure for travel and grazing activity is based on fundamental physiological principles linking body weight, locomotion, and metabolic energy use. Currently, no alternative equations have been developed specifically for nomadic or transhumance grazing systems. Therefore, the coefficients derived from New Zealand studies represent the most robust and widely accepted framework for estimating locomotion-related energy requirements in grazing sheep and were applied in this study.

The GEI was calculated using Equation 10 derived from IPCC (2019), with the incorporation of the net energy mobilized (NE mob) due to weight loss as per IPCC (2000) and the calculation of net energy for travel (NEt) instead of net energy for activity (NEa) using the daily distance traveled as per NRC (2001).

$$GEI = \left[\frac{\frac{NEm+NEa+NEI+NEp+NEt}{REM} + \frac{(NEg+NEwool)}{REG}}{\frac{DE\%}{100}}\right] \quad (11)$$

Where GEI, Gross energy, MJ/day; NE m, Net energy required by the animal for maintenance, MJ/day; NE a, Net energy for animal activity, MJ/day; NE l, Net energy for lactation, MJ/day; NEt Net energy for travel, MJ/day; NEp, Net energy required for pregnancy, MJ/day; REM, Ratio of net energy available in a diet for maintenance to digestible energy consumed following Tier 2 equation from IPCC (2006); NEg, Net energy needed for growth, MJ/day; NEwool, Net energy required to produce a year of wool, MJ/day; REG, Ratio of net energy available for growth in a diet to digestible energy consumed following Tier 2 equation from IPCC (2006); DE%, Digestible energy expressed as a percentage of gross energy.

Enteric CH_4 emission. Based on the 2019 Refinement to the IPCC (2006), the daily enteric EF was calculated from gross energy intake (GE) and Ym (the fraction of gross energy intake released in the form of CH_4). The following Tier 2 equation (Equation 5) from IPCC (2019) was used to compute seasonal EF and annual EF:

$$EFseason\left[\frac{kgCH4}{season}\right] = \left[\frac{GE\left(\frac{MJ}{day}\right) * \frac{Ym(\%)}{100}}{55.65\left(\frac{MJ}{kgCH4}\right)}\right] * days\ is\ season \quad (12)$$

Where EF season represents the enteric CH_4 emission factor (in kg CH_4/head/season) estimated from seasonal animal characteristics and performance data based on the IPCC (2019) Tier 2 GE is the gross energy intake (in MJ/d) calculated using IPCC equations, and Ym is the CH_4 conversion factor, the IPCC (2019) default value of 6.5% was used due to the absence of site-specific value. The factor 55.65 (MJ/kg CH4) is the energy content of CH_4. Equation 12 shows how the annual EF for enteric CH4 emission (kg CH4/head/year) was estimated.

$$Annual\ EF\left[\frac{kgCH4}{season}\right] = \left[\frac{EF\ season1\left(\frac{KgCH4}{season1}\right) + EF\ season\ 2\left(\frac{KgCH4}{season1}\right)}{Number\ of\ seasons}\right] \quad (13)$$

Statistical analysis

Quantitative data analysis used descriptive statistics and oneway analysis of variance (ANOVA). The one-way ANOVA was employed to examine the variation in mean annual live weights, live weight change, and emission factors (EF) across the three locations. A *post hoc* test (Tukey test) was conducted to compare means. The analyses were carried out using Microsoft Excel. In all analyses, p-values less than 0.05 were considered statistically significant.

Results

Herd characteristics

Across all animal categories, there were no statistical differences in annual mean LWC among the three locations, except for adult males, where Shivee ovoo exhibited higher annual mean LWC compared to Khotont, Ikh-Tamir and Sergelen (Table 1).

The wool yield was 1.3 kg for male sheep, 1.2 kg for female sheep, 1.1 kg for young sheep, and 0.8 kg for lambs.

Feed quality

Across all three grazing systems, pasture constituted the primary feed source throughout the year, and supplementary feeding was uncommon. Therefore, feed quality was evaluated solely based on forage composition. The quality of sheep forage, as indicated by various parameters, varied among the three locations. Among the three locations, highest DE values were observed Desert Steppe area (Table 2). Because it has less acid detergent fiber (ADF), and higher nitrogen and protein content than forest steppe and steppe pasture.

Regarding the chemical composition of pasture plants, crude protein content was higher in the desert-steppe region compared than the Mountain-steppe region. Conversely, the Mountain-steppe pastures had higher acid-insoluble fiber, which could contribute to their lower digestibility. In this study, the dry matter digestibility (DMD) of the pasture vegetation ranged from 55% to 62%, falling within the 55%–75% range, as stated in recommended by the IPCC 2006 guidelines.

TABLE 1 Mean live weight, (kg, mean ± SE) for the three study sites in Mongolia.

Sheep category	Mountain-steppe area			Steppe area			Desert-Steppe area		
	Summer-autumn	Winter-spring	Gaining weigh	S-A	W-S	Gaining weigh	S-A	W-S	Gaining weigh
Adult male	48[a]	36[a]	12	48[b]	36[a]	16	50[b]	38[a]	12
Adult female	46[a]	35[a]	11	46[b]	35[a]	14	46[b]	35[a]	11
2-year-old	38[a]	29[a]	9	38[b]	30[a]	12	40[b]	32[a]	8
Lamb	28[a]	21[a]	8	25[b]	21[a]	4	25[b]	21[a]	4

S-A-summer to autumn, W-S-winter to summer; Adult females (≥3 years); Adult males (≥3 years); 2 years Lamb (≤1 year); Means with different superscript letters in the same row indicate significant differences at $p < 0.05$. NB: IPCC, Tier 1 values are derived from the pasture/range systems mentioned in the IPCC (2019) Guidelines Table 10.10 (New).

TABLE 2 Nutrient composition of pasture grazed by sheep.

Index	Pasture type in						
	Desert-steppe		Steppe		Forest-steppe		Winter and spring(senescent grass)
	Summer and autumn		Summer and autumn		Summer and autumn		
	15th May	15th August	15th May	15th August	15th May	15th August	15th Nov and 15th April
NDF, %	58.61 ± 0.4	57.92 ± 1.3	52.8 ± 1.3	59.7 ± 1.1	52.09 ± 1.5	53.40 ± 1.6	70.40 ± 1.1
ADF, %	34.35 ± 1.2	37.02 ± 1.4	36.8 ± 1.7	43.2 ± 1.2	36.68 ± 1.4	40.92 ± 1.3	48.08 ± 1.2
CP,%	14.25 ± 0.3	14.64 ± 0.5	13.8 ± 0.6	12.5 ± 0.8	12.19 ± 0.4	10.59 ± 0.8	10.09 ± 1.3
N, %	2.28 ± 0.2	2.34 ± 0.6	2.17 ± 0.7	2.0 ± 0.2	2.06 ± 0.2	1.69 ± 0.4	1.61 ± 0.4
Ether extract,%	3.1 ± 0.2	3.9 ± 0.4	3.6 ± 0.4	4.01 ± 0.2	2.7 ± 0.6	3.2 ± 0.2	2.7 ± 0.3
Ash,%	9.2 ± 0.6	8.4 ± 0.5	10.2 ± 1.1	8.1 ± 0.8	10.5 ± 0.8	9.8 ± 0.5	12.7 ± 0.5
GE, Mj/kg DM	17.46 ± 1.2	17.83 ± 1.2	17.00 ± 0.8	17.38 ±0.9	17.14 ± 0.6	17.32 ± 1.4	16.55 ± 0.5
DMD%	61.45 ± 1.3	59.37 ± 0.8	59.05 ± 1.2	56.44 ± 1.3	59.23 ± 1.2	55.23 ± 1.6	48.11 ± 1.4
DE%	62.29 ± 1.2	58.87 ± 1.4	61.36 ± 1.2	56.83 ± 1.2	61.06 ± 1.4	56.04 ± 1.5	48.97 ± 1.1

DM, dry matter; NDF, neutral detergent fiber; ADF, acid detergent fiber; N, nitrogen; GE, gross energy; DMD, Dry matter digestibility and DE, feed digestibility expressed as percent of gross energy; NA, no assessment.

We calculated the energy requirements of sheep for maintenance (NEm), walking (NEt), lactation (NEl), pregnancy (NEp), and growth (NEg), based on the gross energy (GE) of their feed. The relative energy for maintenance and other activities (REM) was 0.54 and 0.56 for improved and local sheep in summer–autumn, and 0.34 in winter–spring. The relative energy for growth (REG) was 0.26 and 0.28 in summer–autumn, and 0.28 in winter–spring (Equations 2, 3, 6, 7, 8, 9, 11, 13).

The estimated gross energy (GE) requirements of sheep varied markedly among agroecological zones, seasons, and physiological states (Table 3). Across all zones, GE values were consistently higher in the winter–spring period compared to summer–autumn. This pattern reflects increased maintenance energy (NEm) requirements in colder months, likely due to elevated thermoregulatory demands, as well as lower dietary digestibility during winter grazing.

Despite higher NEm in some summer cases for certain classes (e.g., Gobi steppe females), GE remained higher in winter–spring because of the combined effects of increased activity energy (NEa), pregnancy energy (NEp), and wool energy (NEwool), compounded by lower DE% in winter pastures. For example, Gobi steppe females required 20.61 MJ/day in winter–spring compared to 14.04 MJ/day in summer–autumn, representing a 47% seasonal increase. A similar seasonal gap was evident in forest–steppe females (21.37 vs. 11.02 MJ/day) and steppe females (21.41 vs. 13.63 MJ/day). These trends align with previous reports (Schlecht et al., 2019) that cold-season

TABLE 3 Estimated energy requirement values for different physiological components in sheep.

Agroecological zone	Season	Sheep	NEm, MJ/day	NEt, MJ/day	NEl, MJ/day	NEp, MJ/day	NEg, MJ/day	NE $_{wool}$, MJ/day	GE, MJ/day
Desert-steppe	W-S	Male	2.98	0.22	na	na	na	0.085	18.71
	S-A		3.83	0.53	na	na	na		11.23
	W-S	Female	2.98	0.22	na	0.37	na	0.078	20.61
	S-A		3.83	0.53	0.94	na	na		14.04
	W-S	Young	2.64	0.19	na	na	na	0.072	13.81
	S-A		3.70	0.51	na	na	na		6.57
	W-S	Lamb	0.78	0.035	na	na	na	0.05	16.49
	S-A		2.01	0.17	na	na	0.14		11.01
Steppe	W-S	Male	2.98	0.22	na	na	na	0.085	18.71
	S-A		3.83	0.53	na	na	na		11.08
	W-S	Female	2.98	0.22	na	0.37	na	0.078	21.41
	S-A		3.83	0.53	0.94	na	na		13.63
	W-S	Young	2.64	0.19	na	na	na	0.072	16.63
	S-A		3.70	0.51	na	na	na		8.47
	W-S	Lamb	0.78	0.035	na	na	na	0.05	5.2
	S-A		2.01	0.17	na	na	0.14		6.2
Forest-steppe	W-S	Male	3.12	0.22	na	na	na	0.085	19.47
	S-A		2.91	0.40	na	na	na		8.85
	W-S	Female	3.12	0.22	na	0.37	na	0.078	21.37
	S-A		2.91	0.24	0.94	na	na		11.02
	W-S	Young	2.49	0.17	na	na	na	0.072	15.57
	S-A		2.42	0.17	na	na	na		7.07
	W-S	Lamb	0.66	0.089	na	na	na	0.05	4.84
	S-A		1.61	0.026	na	na	0.14		5.04

NEm, net energy for maintenance; NEt, net energy travel; NEl, net energy for lactation,; NEp, net energy for pregnancy; NEg, net energy for growth; GE, gross energy; REM, used in GE, calculation for improved and local sheep for in the summer-autumn 0.54 and 0.56, respectively; in the winter-spring 0.34 REG, for improved and local sheep were 0.26 and 0.28 in the summer-autumn respectively; in the winter-spring 0.28.

grazing in Mongolia increases maintenance needs by 30%–60% relative to warm seasons due to low ambient temperatures and increased walking distances between sparse forage patches.

Physiological status had a substantial influence on GE requirements. Pregnant females (late gestation) exhibited additional NEp requirements (0.37 MJ/day in winter–spring), while lactating ewes in summer–autumn showed elevated NEl (0.94 MJ/day), contributing to higher total energy demand compared with non-reproductive animals.

For instance, in the steppe zone, summer–autumn GE for females reached 13.63 MJ/day, higher than that of males in the same zone and season (11.08 MJ/day), despite lower NEm, due to lactation energy costs. Wool production also contributed small but consistent amounts (0.072–0.085 MJ/day) to GE across all classes. Young and lamb categories exhibited distinct patterns. Young sheep had GE values ranging from 6.57 MJ/day in Gobi steppe summer–autumn to 16.63 MJ/day in steppe winter–spring, driven largely by higher NEm per unit metabolic weight and substantial seasonal differences in forage digestibility. Lambs in the Gobi steppe showed extremely high GE in winter–spring (16.49 MJ/day) compared with steppe summer–autumn (11.01 MJ/day), indicating greater cold stress susceptibility and faster relative growth rates in early life stages.

Seasonal methane emission factors (EFs) varied substantially among agroecological zones and animal categories (Table 4). Across all zones, methane emissions during the winter–spring period were consistently higher than during summer–autumn,

TABLE 4 Emission factors for sheep in the three agro-ecological zones of Mongolia.

Agro-ecological zone	Emission factors kg CH_4/head/year				IPCC default values
	Males	Female	2-year-old sheep	Lambs	
Desert-steppe	5.45 ± 0.4	6.1 ± 0.2	4.9 ± 0.7	1.7 ± 0.2	2-lamb 5- adult sheep
Steppe	5.43 ± 0.3	6.1 ± 0.5	4.9 ± 0.3	1.8 ± 0.4	
Forest steppe	5.40 ± 0.5	6.0 ± 06	4.3 ± 0.7	1.6 ± 0.5	

reflecting seasonal differences in forage availability, quality, and animal energy requirements.

The estimated enteric methane (CH_4) emission factors for Mongolian sheep varied by agro-ecological zone, age, and sex (Table 4). Across all zones, adult females (>2 years) consistently exhibited higher annual methane emissions than adult males, with values ranging from 6.0 to 6.1 kg CH_4/head/year compared to 5.40–5.45 kg for males. This difference is likely related to the greater feed intake of females due to pregnancy and lactation demands, which increase gross energy intake and consequently methane production. Young sheep (1–2 years old) showed lower methane emissions (4.3–4.9 kg CH_4/head/year) compared to adults, due to their lower body weight and reduced feed intake. Lambs (<1 year) had the lowest emissions (1.6–1.8 kg kg CH_4/head/year), consistent with their limited forage consumption and shorter grazing duration per year.

Discussion

Sheep across the study sites showed marked seasonal fluctuations. Autumn weights were consistently 11–12 kg higher than spring weights for adult males, 13–14 kg higher for adult females, 9–12 kg higher for two-year-olds, and 4–8 kg higher for lambs. These patterns reflect typical live weight dynamics under Mongolia's rangeland conditions, where body reserves are accumulated during summer–autumn and mobilized during winter–spring. Reported organic matter digestibility (OMD) in Mongolian pastures generally varies between 61% and 67% (Nergui et al., 2011; Ariunsuren et al., 2025). However, the digestibility of winter forage is relatively low, around 48%, and and sheep rely on this grass for most of the year (approximately 170–200 days). This may contribute to higher greenhouse gas emissions. The chemical composition of the herbaceous vegetation, including organic matter, crude protein (CP), fiber fractions (NDF and ADF) was within the range typically reported for Mongolian pastures (Daalkhajav, 2009; Tserendash et al., 2011). Vegetation quality reached its peak in summer-autumm season, characterized by high CP and low NDF and ADF, in line with observations by Tserendash et al. (2011), who noted that alpine pasture plants mature in August, leading to decreased CP and increased fiber content due to a higher proportion of stems (Daalkhaijav and Lkagvajav, 1997). Consistent with trends observed in Mongolian forest steppe (Tserendash et al., 2011). Crude protein content was comparable to previous reports for forest steppe, steppe (Otgonjargal, 2012), and desert steppe (Togtohkbayar, 1995), and was similar to values reported for central mountainous regions (Daalkhaijav and Lkagvajav, 1997). The combination of moderately low CP and digestibility, along with elevated fiber levels, suggests a gradual decline in pasture quality from south to nort. Crude protein content was comparable to previous reports for forest steppe, steppe, and desert steppe, and similar to values reported for central mountainous regions. The combination of moderately low CP and digestibility, along with elevated fiber levels, suggests a gradual decline in pasture quality from south to north, consistent with trends observed in Mongolia s forest steppe. For grazing distance, no real difference was observed in the sheep, and they grazed at a distance of 4–7 km in summer and autumn, and 3.5–5 km in spring and winter (Figure 1). Therefore, when calculating the energy expenditure for movement, an average of 6 km was used in summer-autumn and 4 km in winter-spring. The grazing distance of the sheep flock, regardless of age and sex, was the same. Also, since the herders involved in the study did not milk their sheep, the grazing distance of the lambs was the same as that of the flock. Following Lin et al. (2011) we considered our GPS data sufficiently reliable despite the absence of differential correction. The average distance traveled by sheep in our study (6 and 4 km day^{-1}) was in the same range of relevant the 4.7–6.4 km day^{-1} reported for sheep grazing Inner Mongolian steppes (Lin et al., 2011). Stocking pressure also played a role: densities of 2.5–7 sheep units (SU) per ha near Tsunkhul Lake and over 13 SU ha^{-1} around camp sites, likely contributed to longer travel distances in July and August. Animut et al. (2005) demonstrated that increased grazing pressure can extend animal itineraries under comparable climatic conditions (Yoshihara et al., 2009). In our case, sheep often had to walk several kilometers each morning to reach high-quality forage, beyond the overgrazed areas close to their camp. Joly et al. (2013) reported average grazing distances of 5.1 km from camp in the Mongolian Gobi, which aligns with our observed mean radius of 6.75 km day^{-1} and the 3.5–6.5 km range previously described for summer herding in Mongolia (Gendaram, 2011). Seasonal convergence in the daily travel distances of sheep is probably linked to the increasing forage availability from spring to early summer. According to Tsevegemed et al. (2019) the effective grazing distance for Mongolian Altai sheep and goats is approximately 10–11 km, which is influenced by the high altitude of the Altai Gobi and the availability of pasture plants. In mobile grazing systems, grazing area and associated energy expenditure are critical drivers of animal productivity and enteric methane emissions (Tsvegemed et al., 2018). Accordingly, the estimates derived from this study are not intended to represent national average conditions. In this context, reliance on IPCC Tier 1 default values constitutes a methodological limitation, as these values do not adequately capture the variability inherent in extensive and mobile grazing systems. Regarding net energy requirements, although seasonal and physiological effects were the main drivers of variation, differences among ecological zones were also evident. Forest–steppe sheep generally exhibited slightly higher NEm values compared with steppe or desert-steppe sheep of similar classes, likely reflecting the cooler and more variable climate as well as terrain-related increases in activity costs. For instance, gross energy intake (GE) of forest–steppe females during winter–spring averaged 21.37 MJ/day, which was comparable to steppe females (21.41 MJ/day) but slightly higher than desert-steppe females (20.61 MJ/day). This difference may be attributable to the availability of relatively better, yet more fibrous, forage in the forest–steppe, which increases energy expenditure for digestion and metabolism.

The estimated enteric methane (CH_4) emission factors for Mongolian sheep exhibited pronounced variation across agro-ecological zones (Figure 2), age classes, and sex. Adult females consistently showed higher emission factors than adult males, reflecting the greater nutritional demands associated with pregnancy and lactation. During the winter–spring season, emission factors ranged from 1.67 to 8.70 kg CH_4 head^{-1} season^{-1}. Adult females exhibited the highest emissions, particularly in the steppe and desert-steppe zones (both 8.46 kg CH_4 head^{-1} season^{-1}), while adult males showed the highest values in the steppe zone (8.70 kg CH_4 head^{-1} season^{-1}). Young animals displayed intermediate emission levels (6.42–6.90 kg CH_4/head/season), whereas lambs produced substantially lower emissions (1.67–1.76 kg CH_4/head/season consistent with their lower body weight, reduced feed intake, and incomplete rumen development. In the summer–autumn season, emission factors declined across all animal categories and agro-ecological zones, ranging from 2.76 to 5.66 kg CH_4/head/season. Adult females again exhibited the highest emissions, particularly in the steppe zone (5.66 kg CH_4 head^{-1} season^{-1}), followed by adult males (4.53–5.18 kg CH_4/head/season). Young animals and lambs maintained lower emission levels, consistent with their comparatively lower feed intake and metabolic demand. The overall reduction in methane emissions during summer–autumn likely reflects improved pasture quality, greater digestibility, and increased availability of green forage, which enhance animal productivity and reduce methane yield per unit of intake. Comparable patterns have been reported in small ruminant systems elsewhere, where physiological status strongly influences gross energy intake and subsequent methane production (Goopy et al., 2018; Gurmu et al., 2024; Lokupitiya, 2016). The elevated emissions observed in adult females emphasize the importance of accounting for reproductive status when developing emission factors, as reliance on a single default value may obscure substantial within-species variability. Similarly, age-related declines in emissions have been documented in Ethiopian and Kenyan smallholder sheep systems, where Tier 2 methodologies revealed that lambs contribute disproportionately less to total herd emissions than adult animals (Negussie et al., 2021; Wanjala et al., 2018). These findings highlight the necessity of differentiating age classes when constructing national greenhouse gas inventories, particularly in pastoral systems with high proportions of young animals. Clear spatial differences in emission factors were also observed among the desert-steppe, steppe, and forest-steppe zones. Overall, the steppe zone exhibited the highest methane emission factors, followed by the forest steppe and desert-steppe zones. This pattern likely reflects differences in pasture biomass, botanical composition, grazing intensity, and animal movement. Higher emissions in the steppe zone may be attributed to greater forage availability and intake, resulting in higher gross energy consumption and increased methane production. In contrast, the desert-steppe zone, characterized by limited biomass and poorer forage quality, exhibited lower emission factors, particularly during summer–autumn. Intermediate emission levels in the forest-steppe zone are consistent with its relatively favorable forage conditions and moderate climatic stress. This seasonal and spatial variability contrasts with observations from sub-Saharan Africa, where animals graze more diverse and protein-rich forages during the wet season, leading to greater fluctuations in methane emissions (Alemu et al., 2022; Goopy et al., 2018; Goopy et al., 2020). Collectively, these findings underscore the importance of developing region-specific emission factors rather than relying on global defaults that may not adequately represent local feeding ecology and production systems.

Several methodological and ecological factors must be considered when interpreting enteric methane (CH_4) emission estimates derived using the IPCC Tier 2 methodology under Mongolia's nomadic pastoral systems. In extensive grazing environments characterized by high mobility, long-distance seasonal movements, and extreme continental climates, animal energy expenditure varies substantially in response to seasonal temperature fluctuations, forage availability, and grazing distance (IPCC, 2006; NRC, 2001; Goopy et al., 2018). However, the Tier 2 equations do not explicitly incorporate the additional metabolic

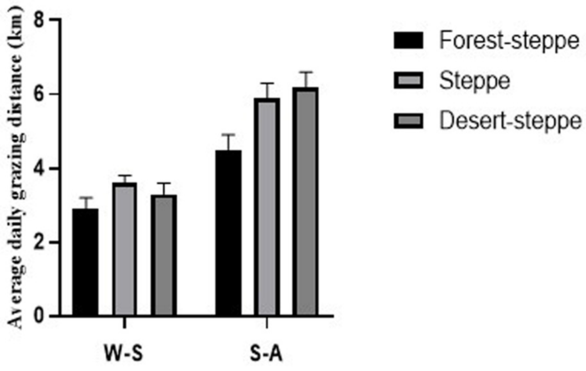

FIGURE 1
Average daily grazing distance (km) of sheep across three regions of Mongolia during Summer-Autumn and Winter-Spring. Bars represent mean values with standard deviations (mean ± SD). Distances were significantly higher in Summer-Autumn, especially in the Desert-steppe (6.2 ± 0.6 km/day). whereas Winter-Spring distances were shorter than Summer-Autumn (3.0–3.3 km/day).

costs associated with cold stress, thermoregulation, and long-distance movement, which are intrinsic features of Mongolian pastoral systems. Consequently, energy requirements and methane emissions may be under- or overestimated, particularly during the winter–spring season, when animals experience severe climatic stress and limited forage availability (Brosh et al., 2006; Fernández-Giménez et al., 2017; Alemu et al., 2022). A further limitation concerns the use of a fixed methane conversion factor (Ym), commonly set at 6.5% of gross energy intake (GEI). Accurate estimation of Ym ideally requires direct methane measurements and detailed assessment of feed digestibility, both of which vary markedly across seasons and rangeland types in mobile grazing systems (IPCC, 2006; Hristov et al., 2013; Moate et al., 2017). Previous studies have reported Ym values of 6.2% for housed sheep in Europe (Zhao et al., 2016), 7.5% for supplemented grazing dairy cattle in the Andes (Muñoz et al., 2018), and 6.9% for grazing beef heifers in temperate North America (Chaves et al., 2006). In contrast, grazing sheep in our study exhibited a higher CH_4 energy-to-GEI ratio (~8.0%), exceeding the IPCC default range of 6.5% ± 1%. This likely reflects the combined effects of harsh climatic conditions, extensive mobility, and the relatively low digestibility and high ash content of Mongolian steppe forages (Yan et al., 2010; Rushing et al., 2019; Liu et al., 2020). To reflect the pronounced seasonal dynamics of Mongolian rangelands, we divided the year into two functional periods: a summer–autumn season characterized by green, actively growing pasture and positive live-weight change, and a winter–spring season marked by senescent forage, negative energy balance, and body weight loss. Accordingly, Ym values mean of 6.5%. While this approach captures broad seasonal contrasts, it remains a simplification and may not fully reflect short-term fluctuations in forage quality, intake, and animal metabolism that typify nomadic grazing systems. These limitations highlight the need for seasonally resolved, region-specific Ym values derived from direct field measurements.

Enteric methane (CH_4) emissions in Mongolian sheep exhibited clear variation across seasons, ecological zones, and animal categories (Figure 3). Emission factors were highest during the winter–spring season, when animals grazed senescent pasture and experienced body weight loss, and lowest in summer–autumn, when green forage supported higher intake and digestibility. Adult females consistently produced more CH_4 than males and young animals, reflecting higher energy requirements associated with reproduction and lactation. These findings highlight the importance of accounting for age, sex, and seasonality in estimating emissions under highly mobile pastoral systems.

We did not collect detailed productivity data, such as slaughter weight, wool yield, or milk production, and therefore any statements regarding emission intensity per unit of product should be considered preliminary. Nevertheless, productivity in Mongolian pastoral systems is strongly influenced by herd structure. Productivity-based emission intensity is shaped by herd structure. Meat is primarily obtained from 2–5-year-old males, whereas most females are retained for breeding until 7–8 years of age. All sheep produce wool, with average yields of 0.8–1.2 kg per year, while meat yield from market-age males averages 16–22 kg per animal (MOFA, 2025; Mongolian Institute of Animal Husbandry, 2011). Milk, although culturally and nutritionally important, is largely consumed locally and was excluded from emission intensity calculations. Given these production patterns, methane emissions per unit of marketed product are likely higher than in intensive systems. Targeted nutritional interventions for breeding females, such as providing higher-quality supplements during periods of high energy demand, could reduce methane emissions per unit of intake while maintaining productivity (Beauchemin and McAllister, 2007; Patra and Yu, 2013; Hristov et al., 2013).

These results underscore the limitations of generalized methane estimation frameworks, such as IPCC Tier 2, when applied to extensive grazing systems. Aggregating all sheep into a single emission factor may misrepresent national emissions, particularly in systems with strong seasonal and ecological variation. The estimated emission factors for Mongolian sheep (1.6–6.1 kg CH_4/head/year) are lower than IPCC (2019) defaults for small ruminants in developing countries (8–10 kg CH_4/head/year), reflecting lower energy intake and productivity under extensive grazing. While per-head emissions are lower, emission intensity per unit of product may be higher, emphasizing the need to quantify emissions relative to productivity. Overall, developing region- and season-specific emission factors that incorporate animal category, mobility,

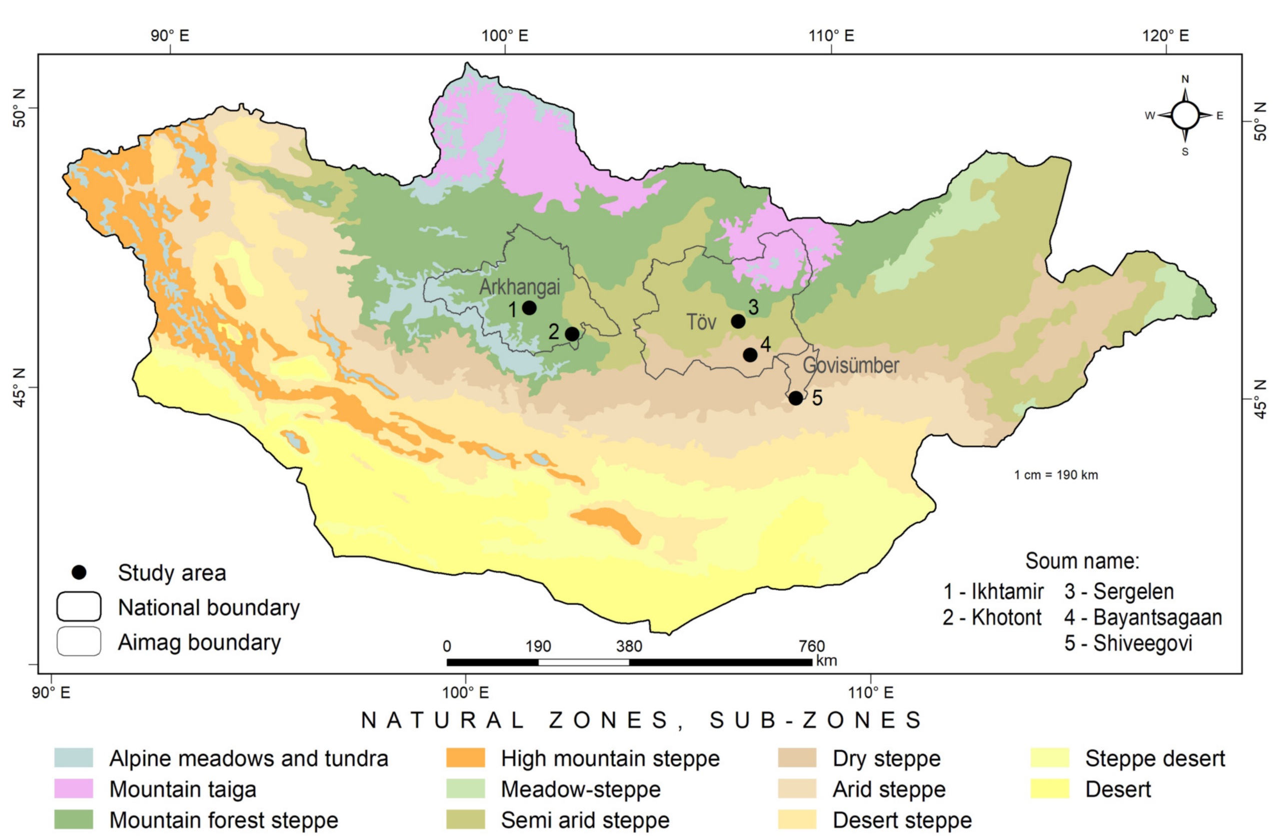

FIGURE 2
Study areas in Mongolia showing the natural zones and sub-zones. Black dots indicate the five study sites: 1 - Ikhtamir, 2 - Khotont, 3 - Sergelen, 4 - Bayantsagaan, and 5 - Shiveegovi. Different colors represent natural zones including alpine meadows and tundra, mountain taiga, mountain forest steppe, high mountain steppe, meadow-steppe, semi-arid steppe, dry steppe, arid steppe, desert steppe, and desert. National and aimag boundaries are outlined. Scale bar represents distance in kilometers.

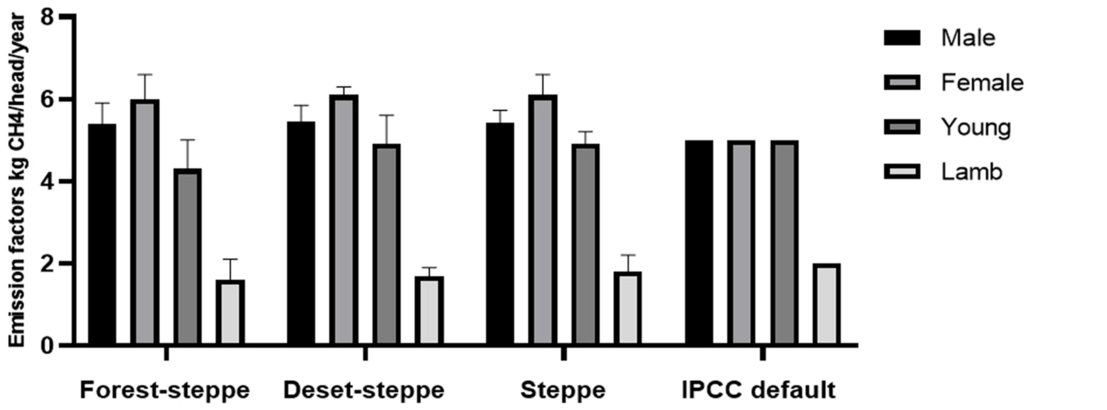

FIGURE 3
Annual methane emission factors (kg CH_4 head^{-1} year^{-1}) of Mongolian sheep by animal category across three agroecological zones, compared with IPCC default values.

forage quality, and climatic stress is essential for improving the accuracy of national greenhouse gas inventories and informing realistic mitigation strategies in Mongolian pastoral systems.

Conclusion

Overall, these findings underscore the critical importance of developing region-specific emission factors for improving the accuracy of national greenhouse gas inventories in pastoral livestock systems. The results also emphasize the emission level vary systematically, as a function of physiological status, forage quality, and seasonal energy dynamics, highlighting the limitations of applying global default values in the Mongolian context. By incorporating location specific on diet digestibility, seasonal weight change, and reproductive status, this work provides a more robust basis for Monitoring, Reporting, and Verification (MRV) under the UNFCCC Enhanced Transparency Framework. Beyond the methodological refinement, the results also emphasize that targeted management, particularly improved ewe nutrition during pregnancy and lactation can play vital role in reducing methane intensity. These outcomes bring Mongolia's capacity to design evidence-based mitigation strategies, while offering broader insights for rangeland-based livestock economies engaged in the Global Methane Pledge.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The animal studies were approved by Ethical Review Guidelines for the Use of Animals in Experiments of Mongolian University of Life Sciences. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent was obtained from the owners for the participation of their animals in this study.

Author contributions

OS: Writing – original draft, Methodology, Formal Analysis; LG: Data collection; AL: Data collection, NN-O: Data collection Resource mobilization; OG: Data collection Resource mobilization LS: Data cleaning; OS: Writing – review and editing, Methodology; YC: Writing – review and editing, Conceptualization, Methodology; TN: Writing – review and editing, Conceptualization, Methodology, Fund acquisition; JS: Writing – review and editing, Conceptualization, Methodology, Fund acquisition BB: Writing – review and editing, Methodology; MZ: Writing – Conceptualization, Methodology, Fund acquisition CJ: Writing – review and editing, Conceptualization, Methodology, Fund acquisition. All authors contributed to the article and approved the submitted version.

Funding

The author(s) declared that financial support was received for this work and/or its publication. The CCRCC project (Effects of differences in pasture type and plant species composition on GHG emissions from sheep) was funded by the Climate Change Research and Cooperation Center of Mongolian, Ministry of Environment and Climate Change.

Acknowledgements

The authors would like to thank the herders of conducted study. We would also like to thank Harider Makkar for the guidance on data analysis.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was used in the creation of this manuscript. While preparing the manuscript AI was utilized to check and improve the language.

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References

Agricultural and Food Research Council (1990). *Technical committee on responses to nutrients. Report no. 5: nutrient requirements of ruminant animals—energy*. Wallingford, UK: CAB International.

Agricultural and Food Research Council (1993). *Energy and protein requirements of ruminants*. Wallingford, UK: CAB International.

Alemu, A. W., Dijkstra, J., Bannink, A., France, J., Kebreab, E., and Appuhamy, J. A. D. R. N. (2022). Quantification of enteric methane emissions from small ruminants: a review. *Animal Feed Sci. Technol.* 287, 115250. doi:10.1016/j.anifeedsci.2022.115250

Amarsaikhan, E., Erdenebaatar, N., Amarsaikhan, D., Otgonbayar, M., and Bayaraa, B. (2023). Estimation and mapping of pasture biomass in Mongolia using machine learning methods. *Geocarto Int.* 38 (1), 2195824. doi:10.1080/10106049.2023.2195824

Animut, G., Goetsch, A. L., Aiken, G. E., Puchala, R., Detweiler, G., Krehbiel, C. R., et al. (2005). Grazing behavior and energy expenditure by sheep and goats co-grazing grass/forb pastures at three stocking rates. *Small Rumin. Res.* 59, 191–201. doi:10.1016/j.smallrumres.2005.05.014

Ariunsuren, P., Damiran, D., and Stevens, P. (2025). "Results of assessment of the current status anddegree of disturbance of the desert-steppe rangelands of western Mongolia," in *Studies on Mongolian rangelands and grazing animal nutrition*. Editor D. Damiran

Arndt, C., Hristov, A. N., Price, W. J., McClelland, S. C., Pelaez, A. M., Cueva, S. F., et al. (2022). Full adoption of the most effective strategies to mitigate methane emissions by ruminants can help meet the 1.5 ∘ C target by 2030 but not 2050. *Proc. Natl. Acad. Sci. U. S. A.* 119, e2111294119. doi:10.1073/pnas.2111294119

Beauchemin, K A., McAllister, T A., and McGinn, S. M. (2007). Dietary mitigation of enteric methane from cattle. CAB reviews: perspectives in agriculture, veterinary science, *Nutr. Nat. Resour.* 2 (060), 1–18. doi:10.1079/pavsnnr20094035

Beauchemin, K. A., Ungerfeld, E. M., Eckard, R. J., Wang, M., et al. (2020). Review: Fifty years of research on rumen methanogenesis: lessons learned and future challenges for mitigation. Animal 14, s2-s16. doi:10.1017/S1751731119003100

Belanche, A., Martín-Collado, D., Rose, G., and Yáñez-Ruiz, D. R. (2021). A multi-stakeholder participatory study identifies the priorities for the sustainability of the small ruminants farming sector in Europe. *Animal* 15, 100131. doi:10.1016/J.ANIMAL.2020.100131

Belanche, A., Hristov, A. N., van Lingen, H. J., Denman, S. E., Kebreab, E., Schwarm, A., et al. (2023). Prediction of enteric methane emissions by sheep using an intercontinental database. *J. Clean. Prod.* 384, 135523. doi:10.1016/j.jclepro.2022.135523

Belache, A., Wondmagegn, T., et al. (2023). Enteric methane emissions and mitigation strategies in small ruminant production systems. *Animals* 13, 1–15.

Brosh, A., Henkin, Z., Ungar, E. D., Dolev, A., Orlov, A., Yehuda, Y., et al. (2006). Energy cost of cows' grazing activity: use of heart rate and GPS methods. *J. Animal Sci.* 84 (11), 3049–3057. doi:10.2527/jas.2006-046

Chadraabal, G. (2013). *The science of sheep of sixty years*. Ulaanbaatar.

Chaves, A. V., Waghorn, G. C., Brookes, I. M., and Woodward, S. L. (2006). Effect of pasture type on methane emissions by grazing cattle. *N. Z. J. Agric. Res.* 49 (4), 411–421. doi:10.1080/00288233.2006.9513722

Clark, H. (2017). *Methane emissions from sheep fed fresh pasture*. New Zealand.

CSIRO (2007). *Nutrient requirements of domesticated ruminants*. Collingwood, VIC, Australia: CSIRO Publishing.

Daalkhaijav, D., and Lkagvajav, N. (1997). Rumen degradability and chemical composition of Mongolian highland's pasture grass. *Mong. J. Agric.* 2, 15–22.

Daalkhajav, T. (2009) "Pasture and livestock management in Mongolia," in Ulaanbaatar, Mongolia: Mongolian State University of Agriculture Press.

Damiran, D., DelCurto, T., Bohnert, D., and Findholt, S. (2009). Comparison of techniques and equipment for estimating forage intake of grazing ruminants. *Small Ruminant Res.* 84, 19–26.

Ellis, J. L., Kebreab, E., Odongo, N. E., McBride, B. W., Okine, E. K., and France, J. (2007). Prediction of methane production from dairy and beef cattle. *J. Dairy Sci.* 90 (7), 3456–3466. doi:10.3168/jds.2006-675

FAO (2021). "Pastoralism in Mongolia, a needed balance between production and sustainable use of natural resources," in *This policy brief describes how Mongolia's sparse population and vast high plains act as "vast open pastures for livestock herds" and that pastoralism is "one of the main occupations in Mongolia."*.

FAOSTAT (2020). Statistical databases. *Food Agriculture Organization U. N.* Available online at: http://www.fao.org/faostat/es/#data (Accessed 27 July 2021).

Fernández-Giménez, M. E., Batkhishig, B., and Batbuyan, B. (2017). Cross-boundary and cross-level dynamics increase vulnerability to severe winter disasters (dzud) in Mongolia. *Glob. Environ. Change* 42, 44–57. doi:10.1016/j.gloenvcha.2016.11.001

Goopy, J. P., Onyango, A. A., Dickhoefer, U., and Butterbach-Bahl, K. (2018). A new approach for improving emission factors for enteric methane emissions of cattle in smallholder systems of East Africa – results for nyando, Western Kenya. *Agric. Syst.* 161, 72–80. doi:10.1016/j.agsy.2017.12.004

Goopy, J. P., Goopy, J. P., Korir, D., Korir, D., Pelster, D., Ali, A. I. M., et al. (2020). Severe below-maintenance feed intake increases methane yield from enteric fermentation in cattle. *Br. J. Nutr.* 123 (11), 1239–1246. doi:10.1017/S0007114519003350

Gurmu, E. B., Ndung'u, P. W., Wilkes, A., Getahun, D., Graham, M. W., Leitner, S. M., et al. (2024). Comparison of methodologies for estimating enteric methane emission factors from sheep in smallholder systems in Africa: a case study from Ethiopia. *Small Ruminant Res.* 240, 107362. doi:10.1016/j.smallrumres.2024.107362

Hammond, K. J., Muetzel, S., Waghorn, G. C., Pinares-Patiño, C. S., and Burke, J. L. (2009). The variation in methane emissions from sheep and cattle is related to feed intake and digestibility. *Animal Feed Sci. Technol.* 153 (1–2), 121–131. doi:10.1016/j.anifeedsci.2009.06.002

Hammond, K. J., Burke, J. L., Koolaard, J. P., Muetzel, S., Pinares-Patiño, C. S., and Waghorn, G. C. (2011). The effect of feed intake on methane emissions from sheep. *J. Animal Sci.* 89 (11), 3540–3549. doi:10.2527/jas.2010-3304

Hristov, A. N., Oh, J., Firkins, J. L., Dijkstra, J., Kebreab, E., Waghorn, G., et al. (2013). Mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. *J. Animal Sci.* 91 (11), 5045–5069. doi:10.2527/jas.2013-6583

Hu, R., Yoshihara, Y., Gantsetseg, B., and Kinugasa, T. (2023). Different regrowth patterns after repeated clipping in two Mongolian pasture species. *Plant Ecol.* 224, 843–853. doi:10.1007/s11258-023-01338-w

Intergovernmental Panel on Climate ChangeMasson-Delmotte, V., and Zhai, P. (2000). "IPCC," in *Good practice guidance and uncertainty management in national*.

IPCC (2006). "Emissions from livestock and manure management," in *2006 IPCC*.

IPCC (2019). "Emissions from livestock and manure managemen," in *2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories, volume 4 agriculture, forestry and other land use*. Editors Buendia, E. C., Tanabe, K., Kranjc, A., Jamsranjav, B., Fukuda, M., and Ngarize, S. (Geneva).

Johnson, D. A., Sheehy, D. P., Miller, D., and Damiran, D. (2006). Article scientifique Mongolian rangelands in transition. 17(1-2):133–141.

Joly, F. J., Samdanjigmed, T., Cottereau, V., and Feh, C. (2013). Ecological constraints on and consequences of land use heterogeneity: a case study of the Mongolian gobi. *J. Arid. Environ.* 95, 84–91. doi:10.1016/j.jaridenv.2013.03.014

Lin, L., Dickhoefer, U., Müller, K., and Susenbeth, A. (2011). Grazing behavior of sheep at different stocking rates in the inner Mongolian steppe, China. *Appl. Anim. Behav. Sci.* 129, 36–42. doi:10.1016/j.applanim.2010.11.002

Liu, Y., Zhang, Y., Wang, Z., and Yan, T. (2020). Forage chemical composition and its effect on methane production in grazing systems. *Grass Forage Sci.* 75 (2), 123–134. doi:10.1111/gfs.12471

Lokupitiya, E. (2016). Country-specific emission factors for methane emission from enteric fermentation: a case study from a non-annex 1 country. *J. Natl. Sci. Found. Sri Lanka* 44 (2), 137–144. doi:10.4038/jnsfsr.v44i2.7994

Mearns, R. (2004). Sustaining livelihoods on Mongolia's pastoral commons: insights from a participatory poverty assessment. *Dev. Change* 35, 107–139. doi:10.1111/j.1467-7660.2004.00345.x

Moate, P. J., Williams, S. R. O., Grainger, C., Hannah, M. C., Ponnampalam, E. N., and Eckard, R. J. (2017). Effects of feeding strategies on methane emissions. *Animal Prod. Sci.* 57 (1), 131–143. doi:10.1071/AN15506

MOFA (2025). Ministry of Food, Agriculture and Light Industry of Mongolia. *Livestock sector statistics/report*. Available online at: https://mofa.gov.mn/files/pdf-files/ohurk0agh6/66026b82a53d8535c7a1c96d.pdf (Accessed March 11, 2026).

Mongolian Institute of Animal Husbandry (2011). Munkhiin Useg Group Ltd., 345. (In Mongolian).*Ulaanbaatar, Mong.*

National Statistics Office of Mongolia (2025). *Mongolian statistical information service: livestock statistics 2024–2025*. Mongolia: Ulaanbaatar.

Moraes, L. E., Strathe, A. B., Fadel, J. G., Casper, D. P., and Kebreab, E. (2014). Prediction of enteric methane emissions from cattle. *Glob. Change Biol.* 20 (7), 2140–2148. doi:10.1111/gcb.12411

Munkhzul, O., Oyundelger, K., Narantuya, N., Tuvshintogtokh, I., Oyuntsetseg, B., Wesche, K., et al. (2021). Grazing effects on Mongolian steppe vegetation—A systematic review of local literature. *Front. Ecol. Evol.* 9, 703220. doi:10.3389/fevo.2021.703220

Muñoz, C., Yan, T., Wills, D. A., Murray, S., and Gordon, A. W. (2018). Comparison of methane emissions from dairy cows grazing perennial ryegrass and supplemented with concentrates. *Animal* 12 (1), 115–124. doi:10.1017/S1751731117001137

Negussie, E., Goopy, J. P., Mekasha, Y., Rischkowsky, B., Solomon, A., and Butterbach-Bahl, K. (2021). Variability in enteric methane emissions among small ruminants in sub-Saharan Africa: implications for IPCC tier 2 inventories. *Animal* 15 (1), 100016. doi:10.1016/j.animal.2020.100016

Nergui, D., Jigjidpurev, S., Otgoo, T., Dugersuren, S., Lkhagvajav, D., and Enkhtsetseg, B. (2011). *Animal feed and feeding. Research. Review for the 50th anniversary ofthe Mongolian institute ofAnimal husbandry*. Munkhiin Useg Group Ltd.: Ulaanbaatar, Mongolia, 664.

NRC (2001). *Nutrient requirements of dairy cattle*. 7th rev. National Academies Press.

Oddy, V., Robards, G., and Low, S. (1983). "Prediction of *in vivo* dry matter digestibility from the fibre and nitrogen content of a feed," in *Feed information and animal production*. Editors G. E. Robards and R. G. Packham (Farnham Royal, United Kingdom: Commonwealth Agricultural Bureaux), 395–398.

Otgonjargal, A (2012). *Nutritive value, methane and CarbonDioxide production fromPastures ofMountainous steppe*. Ph.D. Dissertation, Mongolian University of Agriculture, Ulaanbaatar, Mongolia, p. 124. (In Mongolian).

Patra, A. K. (2013). The effect of dietary fats on methane production in ruminants. *J. Sci. Food Agric.* 93 (5), 1054–1061. doi:10.1002/jsfa.6198

Patra, A. K. (2014a). Trends and projected estimates of GHG emissions from Indian livestock in comparisons with GHG emissions from world and developing countries. *AJAS Asian-australas. J. Anim. Sci.* 27, 592–599. doi:10.5713/AJAS.2013.13342

Patra, A. K., and Yu, Z. (2013). Effects of essential oils on methane production. *Animal Feed Sci. Technol.* 183 (1–2), 1–22. doi:10.1016/j.anifeedsci.2013.04.007

Rushing, J. B., Ward, J. D., and Archer, D. W. (2019). Environmental impacts of forage quality on methane emissions. *Agric. Syst.* 176, 102651. doi:10.1016/j.agsy.2019.102651

Sambuu, G. (2003). *The science of sheep ulaanbaatar*. printing shop of the Agricultural University Science.

Schlecht, E., Buerkert, A., et al. (2019). Livestock production and feed resources in dryland pastoral systems. *Animal* 13 (S1), s1–s10.

Swainson, N., Muetzel, S., and Clark, H. (2018). Updated predictions of enteric methane emissions from sheep suitable for use in the New Zealand national greenhouse gas inventory. *Anim. Prod. Sci.* 58, 973–979. doi:10.1071/AN15766

Togtokhbayar, N. (1995). *Nutritive values of forb dominated pasture in forest steppe and steppe zones in Mongolia*. Ph.D. Dissertation, Mongolian University of Agriculture, Ulaanbaatar, Mongolia, p. 116. (In Mongolian).

Tserendash, S., Lkhagvajav, N., and Altanzul, T. (2011). Pasture land research; review for the 50th anniversary of the

Tsevegemed, M., Norovsambuu, T., Jordan, G., and Schlecht, E. (2019). Feed intake of small ruminants on spring and summer pastures in the Mongolian Altai Mountains. *Sustain. Switz.* 11 (20), 5759. doi:10.3390/su11205759

Tsvegemed, M., Shabier, A., Schlecht, E., Jordan, G., and Wiehle, M. (2018). Evolution of rural livelihood strategies in a remote Sino-Mongolian border area: a cross-country analysis. *Sustainability* 10, 1011. doi:10.3390/su10041011

Wanjala, B. W., Onono, J. O., and Njage, P. M. K. (2018). Estimation of methane emissions from small ruminants in pastoral and agro-pastoral systems in Kenya. *Pastoralism* 8 (1), 22. doi:10.1186/s13570-018-0125-8

Weiss, W. P., and Tebbe, A. W. (2019). Estimating digestible energy values of feeds and diets and integrating those values into net energy systems. *Transl. Anim. Sci.* 3, 953–961. doi:10.1093/tas/txy119

Xie, K., Liu, F., Zhang, C., and Hou, F. (2023). Nitrogen utilisation, energy utilisation and methane emissions of sheep grazing in two types of pasture. *Animal* 17 (2), 100705. doi:10.1016/j.animal.2023.100705

Yan, T., Porter, M. G., and Mayne, C. S. (2010). Prediction of methane emissions from beef cattle. *Animal* 4 (1), 1–10. doi:10.1017/S1751731109990683

Yoshihara, Y., Chimeddorj, B., and Buuveibaatar, B. (2009). Heavy grazing constraints on foraging behavior of Mongolian livestock. *Grassl. Sci.* 55 (1), 29–35. doi:10.1111/j.1744-697X.2009.00134.x

Zhao, Y. G., O'Connell, N. E., Yan, T., and France, J. (2016). Methane emissions of sheep housed indoors. *J. Agric. Sci.* 154 (4), 681–693. doi:10.1017/S0021859615000520

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TYPE Perspective
PUBLISHED 01 June 2026
DOI 10.3389/past.2026.16429

Pastoral lands and the green transition: opportunities and challenges

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RECEIVED 17 February 2026
REVISED 04 May 2026
ACCEPTED 07 May 2026
PUBLISHED 01 June 2026

CITATION
Davies J, Bhati SPS, Wario H, Rawat M and Waters-Bayer A (2026) Pastoral lands and the green transition: opportunities and challenges.
Pastoralism 16:16429.
doi: 10.3389/past.2026.16429

The green transition–the global response to the climate and biodiversity crises–is generating demand for land to implement renewable-energy and carbon-sequestration projects. Rangelands have been attractive to investors because of their large extent, their high potential for wind and solar energy and for carbon sequestration and storage, and the perception that they are currently misused and easily available. In theory, green-transition projects could benefit pastoralists, but many projects alienate pastoralists' land, undermine their rights, and weaken their livelihoods. A few projects have been implemented in ways that respect or strengthen pastoralist rights, engage pastoralist communities in meaningful consultation, and ensure equitable benefit sharing. These experiences demonstrate that pastoralists are not inevitable victims of the green transition and do not need to be excluded from green transition opportunities. A just green transition depends on upholding pastoralist rights, enabling their effective participation, and ensuring equitable allocation of benefits.

KEYWORDS
green transition, just transition, land, pastoral, rangeland

Introduction

Climate change and global biodiversity loss are driving a move towards a low-carbon, resource-efficient economy that contributes to sustainable development and is commonly referred to as the green transition (UNEP, 2011). The green transition has implications for pastoralists, creating both opportunities and threats that have not been systematically examined. Pastoralists and their rangelands have historically been undervalued and starved of much-needed investment, leading to poor performance against human-development indicators and to high levels of poverty among the pastoralist communities (McGahey et al., 2014). This creates a clash of opportunities and constraints: pastoral lands offer a significant opportunity to invest in the green transition, but underdevelopment leaves pastoralists vulnerable in the face of those opportunities and they risk becoming casualties of land alienation and displacement by green-transition projects (Waters-Bayer and Wario, 2022).

Pastoralists' territories are usually marginal for crop production and face climatic extremes, such as high or low temperatures, aridity and seasonal water scarcity, combined with high levels of climatic uncertainty. Their lands are among the areas worst affected by the impacts of climate change, with temperature increase, changing precipitation patterns, and an increasing frequency and severity of extreme climate events (Oba, 2020). Climate change is projected to increase climate extremes and the severity of climate hazards and to amplify uncertainty, which will place strain on pastoral systems, which are often already stressed by population growth, resource loss and other threats (Davies et al., 2015b; Herrero et al., 2016).

Most pastoralists use herd mobility as an adaptive management strategy, but this has been viewed by some policymakers as retrogressive and environmentally destructive. Lands that are used seasonally have been labelled as underused and unclaimed and this, combined with prejudice against pastoralists' cultural identity, has been used to justify dispossessing them of their land, withholding development investment and enforcing laws that have weakened their societies and economies (Johnsen et al., 2019; Scoones, 2021). Pastoralists can identify as Mobile Indigenous Peoples according to the United Nations (United Nations General Assembly, 2007) although not all pastoralists identify as such, and not all governments recognise pastoralists as Indigenous peoples. Pastoralists are ethnic minorities in several countries and are politically underrepresented. Many pastoralist societies face weak land tenure and have lost valuable land to other uses, such as wildlife conservation and crop farming (Davies et al., 2016).

Pastoralists have a long history of land alienation. Crop-farming communities have expanded into pastoral rangelands in many countries, often aided by public policy and research and development into drought-resistant crops and technologies. Pastoral land has also been annexed by governments–colonial and post-colonial–for irrigation projects, protected areas, urban growth, infrastructure development and other purposes, usually with no recognition of the existing rights of pastoralists and no compensation (IUCN, 2011; Johnsen et al., 2019; UNCCD, 2024). Now climate change is driving governments and private companies to seek new land for green transition investments, posing new threats to pastoral lands (Gabbert et al., 2021).

This perspective paper examines evidence of the potential of pastoral lands to support green-transition projects, including renewable-energy and carbon-sequestration schemes. We map renewable-energy potentials in the rangelands and present recent research into opportunities for carbon sequestration in rangelands. The paper examines selected green-transition projects particularly from India, Kenya and Mongolia to illustrate the risks to pastoralists and the opportunities for projects to secure the resource rights of pastoralists and to enable their sustainable management of rangelands. This paper relies on published experiences, and the cases that are used may require closer scrutiny to verify their impacts. The purpose of the paper is to emphasise the potential contribution of pastoral lands to the green transition, highlight that the green transition is likely to perpetuate demands for pastoral land, and show the approaches and policies that need to be developed if a just green transition is to be achieved.

Implications of the green transition for pastoral lands

The Intergovernmental Panel on Climate Change (IPCC) reports that human activities have unequivocally caused global warming, primarily through greenhouse gas (GHG) emissions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production. Human-caused climate change has been shown to affect weather and climate extremes in every region, leading to widespread adverse impacts on nature and people. Vulnerable communities contribute least to climate change and are disproportionately affected. Adaptation measures have progressed in all sectors and regions, with mixed results and with maladaptation in some sectors and regions. Further deep, rapid and sustained reductions in GHG emissions are needed to limit climate change to 1.5 °C (IPCC, 2023). At the same time, all global indicators on the state of nature show a decline. Monitored wildlife populations have shrunk by 73% on average and more than half the Sustainable Development Goal (SDG) targets will not be achieved by 2030, with 30% of them stalled or declining from the 2015 baseline (WWF, 2024).

Growing concern over climate change, biodiversity loss and other environmental threats has led to a substantial increase in policies and investments to develop green economies (UNDP, 2023). Inevitably, the green transition has generated interest in pastoral lands (rangelands) as potential targets for renewable-energy, biofuel and carbon-sequestration projects (McGahey et al., 2014; Johnsen et al., 2019). This in turn raises important questions over the scale of opportunity for rangelands to contribute to the green transition and the opportunities and risks this presents to pastoralists. The 2015 Paris Agreement introduces the idea of a just transition, focusing on the creation of "decent work and quality jobs in accordance with nationally defined development priorities" (UNFCCC, 2015). Consideration of a just green transition reflects concerns that many of those most vulnerable to the impacts of climate change and environmental degradation are poor and are largely excluded from global economic progress (King and Harrington, 2018).

Several dimensions of injustice have been identified in green-transition projects and programmes, including injustice around distribution of benefits, recognition of rights, and participation of citizens. Injustice can be viewed along two axes: social equality to inequality and ecocentrism to anthropocentrism. Green-transition projects that give strong moral primacy to nature but contribute to social inequality lead to environmental injustice (Stevis and Felli, 2016). Examples of this kind of environmental injustice include the annexation of pastoral land to create national parks in several countries (Yilmaz et al., 2019) and the use of pastoral land for afforestation projects to offset GHG emissions (Briske et al., 2024).

Environmental injustice can also stem from geographical power imbalances and the relations between rich and poor countries and between central authorities and vulnerable communities in less developed countries. Injustice also arises when the rights of capital take precedence of democratic process (Stevis and Felli, 2016). However, much of the literature on just transitions is based on experiences in industrialised countries, while evidence of the impact of power dynamics on just transition outcomes in developing countries is comparatively weak (Wang and Lo, 2021).

The current low-carbon transition taking place globally may be delivering environmental and economic benefits but does not guarantee a more just world. Indeed, the current transition may create new injustices and increase vulnerabilities, undermining claims of sustainability. Important questions must be addressed about the impact of the green transition and the distribution of benefits. The concept of a just transition is not new, but the rapid emergence of climate action is raising new questions across several dimensions of justice, including labour, income, energy access and others (Wang and Lo, 2021).

The profound transition in energy systems towards large-scale, low-carbon energy systems is helping to reframe energy justice, improve understanding of the resistance to energy projects, and mitigate potential or perceived injustices (Van Uffelen et al., 2024). A just green transition in rangelands does not relate exclusively to renewable energy but to transition of the agriculture sector (encompassing pastoral livestock production). The issues overlap, since energy poverty is high in rural areas, with 1.1 billion people globally considered to be energy impoverished (Min et al., 2024). However, green transition in the agriculture sector encompasses questions about the environmental impacts of food production, and the sector faces pressure to reduce its environmental footprint. Significant questions of justice arise since many agricultural communities face underlying challenges to their wellbeing, rights, opportunities for workers, and collective power. Crop farming and pastoralism are more than livelihoods: they represent ways of life and culture for communities, raising questions not only of distribution of benefits, but also recognition of rights and participation of citizens (Chatterjee and Swarnakar, 2023).

The threats of climate change can aggravate existing social injustices, particularly among communities reliant on climate-sensitive production and with constraints to their adaptive capacity due to low economic development: features that are common to many pastoralist societies. Achieving a just transition will require strengthening the capacity of pastoralists with respect to finance, technology development and innovation, skills training and education, and access to information. Communities need stronger capacity to self-organise and navigate the green transition and its opportunities and threats. Underlying risk factors need to be addressed, such as regenerating soil health, restoring degraded land, protecting natural ecosystems and biodiversity, and developing markets (Mapfumo et al., 2025).

A just green transition of the pastoral livestock sector should ensure environmental sustainability while delivering fairness and inclusiveness. The sector needs to meet future consumer demand while managing increasing frequency and severity of climate change hazards, while meeting targets for emissions, water, biodiversity, social resilience and economic development. This requires further consideration not only of the impacts of a just transition *on* pastoralism, but a just transition *of* pastoralism, raising difficult questions over the contribution of pastoralism to environmental threats and what responsibilities rest with pastoralists.

Livestock is the largest contributor to agrifood systems GHG emissions, accounting for 26% of sector emissions in 2023 (4.3 out of 16.5 Gt CO_2eq). Livestock-sector emissions grew by 22% from 2001 to 2023, with the strongest growth (80%) recorded in supply chain and consumption processes (FAO, 2025). Measures exist to help pastoralists adapt to climate change and reduce emissions, but major information gaps and uncertainties persist around the contribution of pastoral livestock to GHG emissions and carbon sequestration and storage. Nevertheless, the sector offers significant opportunity for carbon sequestration in pasture soil and biomass and grassland management (Thornton et al., 2025).

A just transition of the pastoral livestock sector also raises questions over risks to livelihoods along value chains, workers' rights, increasing the voice of marginalised producers and other complex issues. Several measures can be found that address the dimensions of injustice discussed earlier (Stevis and Felli, 2016). Procedural justice can be advanced through improved participation in decision making, respect for local knowledge, and improved monitoring and evidence. Distributive justice can be strengthened through better distribution of resources, opportunities and responsibilities. Recognition justice can be strengthened through legal avenues, addressing power imbalances, reviving human-nature relationships, and enabling adaptation of local actors (Thornton et al., 2025).

The green transition can, in theory, contribute to the sustainable development goals of pastoralists. UNEP's definition of a green economy, cited above, emphasises human wellbeing and social equity, yet fears have been raised about historical injustices towards pastoralists being repeatedly perpetrated by green-transition projects. In practice, the green transition raises fears of a new wave of rangeland acquisitions in places where resource rights are poorly protected and where pastoralist communities have faced decades of prejudice, impoverishment, governance failures and marginalisation (McGahey et al., 2014). There is a contrast between projects motivated by the pursuit of land to deliver global environmental benefits and projects motivated by the pursuit of local sustainable development outcomes. The latter is consistent with what is generally considered a just green transition (Tavares, 2022).

Development opportunities that could be created through green transition are at risk of being lost on account of the insecurity of pastoralists' land rights and pastoralists' low political representation (Waters-Bayer and Wario, 2022). Social equity can be assured only if green-economy investments deliberately address the underlying weaknesses in pastoralists' capabilities and traditional rights and contribute to pastoralist resilience. A just green transition requires that projects do not leave poor and marginalised groups further behind but instead create opportunities to protect them and to accelerate their development (Davies, 2024).

Green transition opportunities in pastoral lands

Several sectors involved in the green transition have identified significant opportunities in pastoral lands, including renewable energy, carbon sequestration, and biofuel production. Global funding for renewable energy is similarly growing, illustrated by the 30% climate spending target and EUR 4 billion earmarked for climate finance by the European Union and its member states (European Commission, 2023). The Africa–Europe Green Energy Initiative, launched in 2022, aims to increase renewable-energy generation by 300 GW and secure access to affordable, reliable and sustainable energy in Africa. This is likely to lead to a growing number of large green-transition projects using blended finance and creating further opportunities and risks for pastoralists (Davies, 2024).

Renewable-energy potentials in the rangelands

Methodology for mapping wind- and solar-energy potential in rangelands

Expansion of renewable green energy is at the centre of decarbonisation efforts, particularly expansion of solar and wind power (IRENA, 2025). Rangelands have emerged as the prime sites favoured for generating solar and wind power, turning them into new economic frontiers with adequate spaces that can be utilised for the much-needed energy for industrialisation, particularly in developing countries (Mosley and Watson, 2016; Lind et al., 2020, 202).

Pastoral lands offer considerable potential for generating renewable energy from solar and wind power. To explore this potential, we overlaid maps of global solar and wind potential with a map of the global distribution of rangelands. This allows us to identify pastoral areas that are well-suited for renewable energy development and to compare rangelands and non-rangelands in terms of renewable-energy potential.

We compare global datasets for photovoltaic (PV) power potential and wind power potential with a global map of rangelands as developed by the International Livestock Research Institute (ILRI, IUCN, FAO, WWF, UNEP, and ILC et al., 2021). The rangelands shapefile uses the World Wildlife Fund (WWF) terrestrial ecosystem dataset, identifying ecoregions using keywords in the ECO_NAME and G200_REGIO fields. Keywords used to identify rangeland ecosystems include grass, grasslands, savanna(h), shrublands, scrub, deserts, xeric, tundra, steppe, parklands and for South America we included caatinga, matorral, chaco, monte, espinal, puna, and pampas.

We estimate the solar-energy potential of rangelands using Practical Photovoltaic Power Potential (PVOUT). PVOUT provides an estimate of how much electricity can realistically be generated per year by solar panels. This is a more useful indicator of solar-energy potential than measuring how much sunlight reaches the ground (raw solar irradiance). PVOUT (kWh/kWp) reflects annual electricity generation per unit of installed PV capacity while incorporating system-level performance losses. To highlight the differences in the PV potentials, we distributed the PV potential between five categories: <3, 3–4, 4–5, 5–6 and >6. Categories <3 and 3–4 are classified as low potential, whereas 4–5 represents moderate potential and above 5 signifies high potential (World Bank Group and Solargis, 2020).

Land suitability for wind energy can be assessed by measuring the wind power density or meteorological potential, the geographic potential and the technical potential of a region (Jung and Schindler, 2021). While referring to wind energy, there are different classes of wind turbines to be considered. Typically, a wind speed above 6.5 m/s is considered commercially viable at 80 m height (Center for Sustainable Systems, 2025). However, the typical cut in speed at which a turbine starts generating energy ranges between 3 and 4 m/s, and peak power generation is reached between 10 and 15 m/s, depending on the class of turbine (Lledó et al., 2019).

The International Electrotechnical Commission (IEC) classifies wind-resource conditions, which are used to categorise wind-speed regimes for utility-scale wind-energy development (IEC, 2019). Given that 98% of rangelands receive wind speeds less than 10 m/s, and commercial viability usually starts above 6, we have divided wind speed into five classes (<6 being very low and = />9 being very high). This gives us an overall potential of wind-energy development at 100 m in rangelands while considering the seasonal variation by providing a yearly average for wind speed (IEC, 2019; Lledó et al., 2019; Center for Sustainable Systems, 2025).

Solar-energy potential of rangelands

Our results show that over 82% of rangelands fall into a moderate to high range of solar electricity production (4–6 kWh/kWp) (Figure 1). In simple terms, this means that many pastoral areas receive enough sunlight to make solar power a viable option. Large solar installations also require wide, open land with little shading, a condition that is common in rangelands.

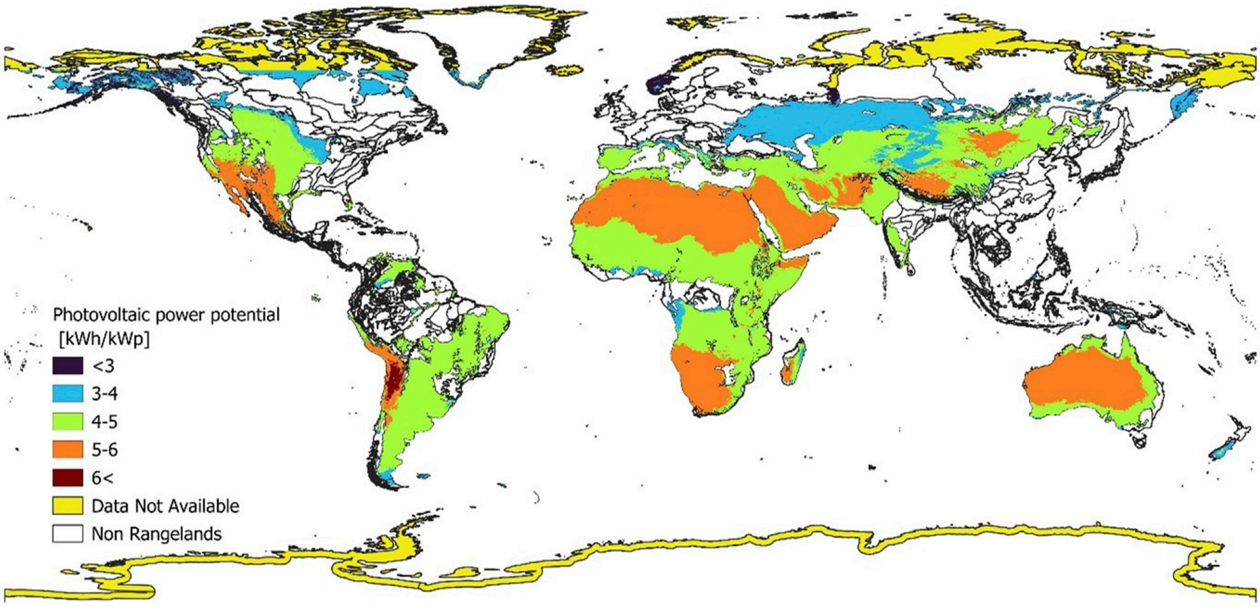
Wind-energy potential of rangelands

Our results show that around 60% of global rangelands are commercially viable for wind energy at 100 m hub height (Figure 2). These estimates represent a conservative estimate, as wind speed typically rises with height. For instance, India's wind potential stands just above 300 GW at 100 m hub height, while it is above 1150 GW at 150 m hub height, signifying nearly four times increase (National Institute of Wind Energy, 2018; National Institute of Wind Energy, 2023).

Surface-power density and renewables

Another useful concept in understanding the linkages between pastoral land and renewable energy is surface-power density: how much land different energy sources need to produce power. Surface-power density is measured in watts per square metre (W/m^2) and describes the amount of power obtained per unit of the earth's surface used by any specific energy system. Fossil fuels generate a large amount of energy from relatively small areas, while solar panels and wind turbines need more space to produce the same amount of energy. Fossil fuels have high surface-power densities–hundreds of W/m^2 (e.g., fossil gas 482 W/m^2). On a comparative scale, solar power has a median surface-power density of 6.63 W/m^2 while wind has a median surface-power density around 2–3 W/m^2 (Smil, 2016; van Zalk and Behrens, 2018). While this may vary with turbine types and panel/site infrastructure, these are the typical values for a utility-scale plant.

Since rangelands cover approximately 54% of the earth's land area (ILRI, IUCN, FAO, WWF, UNEP, and ILC et al., 2021), and are often sparsely populated, they offer significant space for solar and wind development. While surface-power density does not itself determine the feasibility of renewables, it is critical for



PV potential (kWh/kWp)	Percentage of rangeland area
< 3	1.68
3–4	15.99
4–5	50.73
5–6	31.45
6 <	0.15

FIGURE 1
Photovoltaic power potential of rangelands.

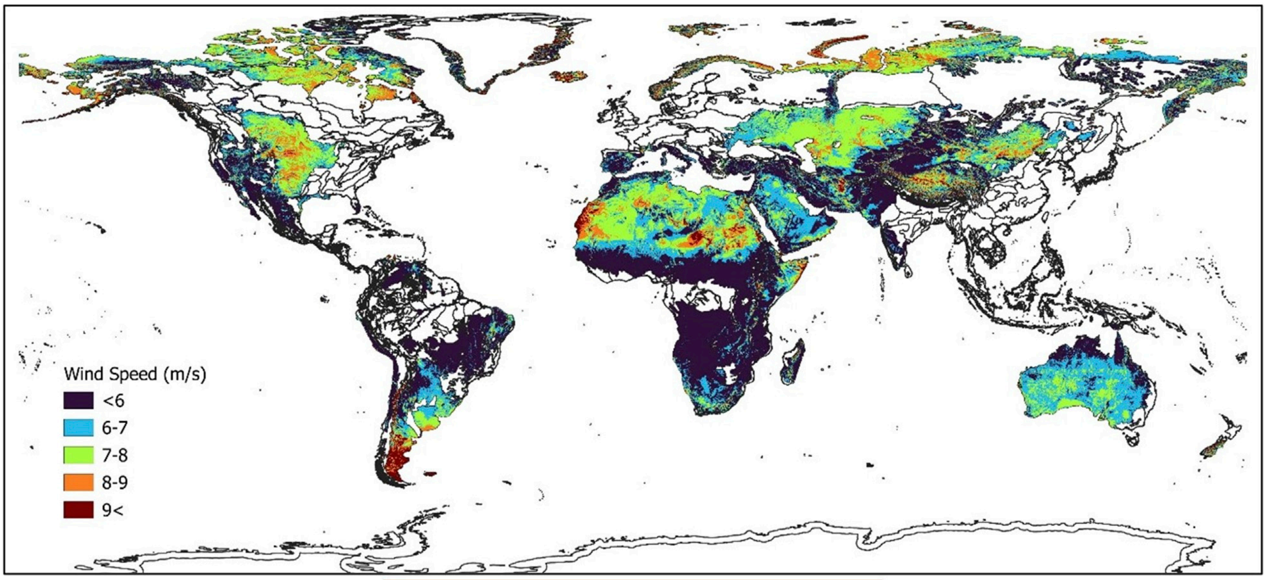
understanding the land requirements for the switch to renewables. As demonstrated, rangelands are some of the most viable spaces in terms of feasibility of renewables, for both solar and wind energy.

The evidence presented above indicates where renewable energy could be produced, but it is equally important to consider where energy is most needed. While these maps illustrate the potential for producing solar and wind energy in pastoral lands, they may underestimate the importance of demand, since a significant proportion of rangelands is found in developing countries with the greatest energy deficits. For example, Africa has the greatest regional demand on account of comparatively low production of energy *per capita*, and renewable-energy solutions offer opportunities to leapfrog dependency on fossil fuels. The continent has particularly high wind-energy potential, and the highest-potential countries–Algeria, Egypt, Libya, Mauritania, Morocco, Nigeria, South Africa, Sudan and Tunisia–are all dominated by rangelands (Mentis et al., 2015).

Carbon sequestration

Restoring and protecting rangeland multifunctionality can contribute to climate change mitigation and biodiversity conservation while maintaining production of high-protein foods for marginalised populations (Briske et al., 2024). Many studies on carbon sequestration focus on the grassland area, which accounts for approximately two thirds of the estimated global rangeland area (ILRI, IUCN, FAO, WWF, UNEP, and ILC et al., 2021). Grasslands store an estimated third of the global terrestrial carbon stocks and can act as an important soil carbon sink; improved grassland management could sequester between 240 and 2000 million tonnes of atmospheric carbon per year (Smith, 2008; Tennigkeit and Wilkes, 2008; Gerber et al., 2013; Bai and Cotrufo, 2022).

Global estimates of carbon sequestration potential are typically based on estimation of net primary production (NPP). NPP is influenced by climate factors; non-climatic natural factors such as soil property, landforms, and biomes; and land-management practices. Land-management practices can be manipulated to improve carbon sequestration, and global potential for carbon sequestration can be estimated according to the gap between current land-management and optimal land-management practices. Grasslands have the highest global carbon gap of all land uses because they have the highest carbon gap density (138.3 gC m^{-2} yr^{-1}) and cover the largest area of land (46.97 million km^2). The global carbon gap of grasslands has been estimated at 6.5 PgC yr^{-1}, which represents approximately half the global carbon gap. Grasslands also



Wind speed (m/s)	Percentage of rangeland area
<6	38.07
6–7	25.09
7–8	25.39
8–9	7.99
>9	3.46

FIGURE 2
Wind energy potential of rangelands.

respond more rapidly to human activities than do forests and other woody vegetation. The high potential for carbon sequestration combined with the high rate of impact mark grasslands out as high-potential target areas for carbon-sequestration projects (Sha et al., 2022).

Global estimates of carbon-sequestration potential in grasslands face methodological challenges, including difficulties in interpreting remote sensing data to gauge the state of rangeland health and the restoration potential (Zhang et al., 2025). Methodologies for estimating NPP and extrapolating below-ground biomass using a root-to-shoot ratio (RSR) have been developed for forest biomes and have not been well adapted to grasslands. Below-ground plant biomass is an important measure of ecosystem health and organic carbon storage potential, and grasslands store comparatively more carbon below ground than standard models predict. Mean RSR in some subtropical grasslands was approximately five times higher than the global average. When global estimates were regenerated using more suitable NPP and RSR figures for subtropical grasslands, they were found to store 2.7 times more plant organic carbon than would be predicted using global defaults (Slooten et al., 2026).

Various approaches have been tested to boost carbon sequestration and soil organic carbon stocks in grasslands. Soil organic carbon can be increased by increasing plant species diversity, modifying grazing management, and restoring biodiversity. The potential for soil organic carbon sequestration in global grasslands has been estimated at 2.3–7.3 billion tons of carbon dioxide equivalents per year for biodiversity restoration, 148–699 megatons of $CO_2e\ yr^{-1}$ for improved grazing management, and 147 megatons of $CO_2e\ yr^{-1}$ for sown legumes in pasturelands (Bai and Cotrufo, 2022). However, improving carbon sequestration through land conversion is not widely acceptable, and what may be perceived by some as the optimal land-management practice may conflict with the socioeconomic goals of local land users (Sha et al., 2022).

Uncertainties over the state of grassland carbon, the opportunities to increase carbon stocks, and the suitability of land-management practices are among the factors that contribute to underinvestment in rangeland carbon. Knowledge gaps persist in relation to the net carbon balance, taking into consideration ruminant emissions as well as the role of ruminant management in carbon sequestration. The evidence gap is exacerbated by a historical bias towards research in sedentary land-use systems and prioritisation of tree planting over rangeland rehabilitation (Briske et al., 2008; Henry et al., 2024). Deeper insights from transdisciplinary research are needed to better manage the complexity and multifunctionality of rangelands to boost carbon sequestration as one among a number of co-benefits of sustainable rangeland management (Mgalula et al., 2021).

Despite the uncertainties, rangelands are beginning to attract higher levels of carbon finance due to their large areas and significant rates of primary productivity (Lorenz and Lal, 2018). Carbon sequestration in rangelands can be enhanced in various ways, including grazing management, restoration of degraded areas, sowing favourable forage species, fertiliser application and irrigation. Pastoralists' herd management mimics the natural ecological relationship between ungulates and grasses and contributes to rangeland restoration and sustainable management that captures and stores carbon (Briske et al., 2025). Carbon finance may offer the means to incentivise sustainable rangeland management that delivers the range of benefits highlighted above (Davies et al., 2015a).

However, adoption of carbon-sequestering management and technologies can be hindered by underlying land-degradation processes, institutional weaknesses, changing climate, and data and capacity gaps (Ghosh and Mahanta, 2014). There is a persistent risk that climate change mitigation projects promote afforestation, which is detrimental to the health of rangeland ecosystems and can lead to biodiversity loss, decline in ecosystem functions, impoverishment of land users and, in some cases, an overall loss of carbon from the system. Evidence of the ecological importance of rangelands, the damage that land-use change can cause to ecosystem integrity, and the existing carbon-holding capacity of these lands is driving interest in rangeland carbon-sequestration projects (Briske et al., 2024).

Growing interest in projects that increase soil carbon, as opposed to vegetation, may further increase interest in rangelands and may help improve methodologies for measuring the climate impact of rangeland-restoration projects (Lal, 2007). It may be possible to restore as much as 700 million hectares of Africa's rangelands through sustainable livestock-management and other practices, which would make a significant contribution to mitigating climate change (UNECA, 2022). Nevertheless, concerns persist over what approaches to carbon sequestration are appropriate and what impacts they will have on pastoralists. Carbon schemes in Africa have raised fears of exacerbating inequalities in pastoral areas and some in East Africa have been reported as coercive and non-consensual, prone to corruption and aggravating land conflicts (Kubitza et al., 2025). Some schemes have alienated pastoralists' land and promoted afforestation, leading to social, economic and environmental failures (Briske et al., 2008; Henry et al., 2024).

Selected experiences of the green transition in pastoral lands

Renewable energy

The surge in investment in renewable energy has driven up demand for pastoral lands around the world, although the approach to acquiring or using land differs greatly between projects, even within the same country. Examples range from large-scale land acquisition without consent, to small- and large-scale leasing arrangements with different degrees of impact on pastoralism and widely varying rents and co-benefits.

The most disruptive projects for pastoralists have ignored the complex use and access rights of different ethnic groups and favoured one ethnic group over others in consultations and benefit sharing (Hughes and Rogei, 2020; Wanyoro, 2021; Drew, 2022). Benefit sharing has been minimal in some projects, and pastoralists have not been adequately compensated for land occupied by energy projects or for the disruption during construction (Waters-Bayer and Wario, 2022; Schilling and Werland, 2023; Hughes and Rogei, 2020). For example, geothermal-energy projects in Kenya have occupied significant areas of land, blocked access to water resources and contributed to pollution of drinking water (Hughes and Rogei, 2020).

Kenya has made significant and rapid progress in developing renewable energy with numerous projects in rangelands, several of which have impacted negatively on pastoralists. Renewable-energy projects have stimulated competition among local actors to capture the benefits and have fuelled insecurity and resource competition in several areas (Greiner, 2022). Wind-farm projects in rangelands have driven up land values, creating a rush to claim private land titles and increasing tension between and within communities (Cormack and Kurewa, 2018). The heavily criticised Lake Turkana Wind Power Project has annexed large areas of pastoral land, blocked migration routes and denied access to sites of cultural importance. Benefit sharing from the project has been negligible and token benefits, such as employment as security guards, has favoured certain ethnic groups, fostering conflict with other ethnic groups that have claims over the same land (Waters-Bayer and Wario, 2022).

Pastoralists can face challenges in defending their resource rights where rangelands legally belong to the State. In some cases, the State may declare pastoral lands as degraded and abandoned and use this as justification for annexing the land for power projects. This has been reported in Mongolia, for example, where the public sector has allocated significant areas of land to renewable-energy projects (Nilsson et al., 2021).

India has identified significant areas of rangelands considered suitable and available for renewable energy. Much of this land is legally designated as "wasteland", which allows investors to overlook the prior occupation and to discount the economic value of established land uses such as pastoralism. Large-scale solar-energy projects have taken land out of pastoral production, created unfavourable microclimates around the installations, caused loss of land productivity, and reduced livestock health and productivity (Hemalatha, 2019; Patel, 2024; Rathore and Zargar, 2024).

Livestock farmers and pastoralists in several Indian states have protested against the proposed renewable-energy projects, arguing that they will endanger livestock and contradict efforts to protect community grazing lands. Protests in Gujarat led to the return of project land to community ownership and agreement by the company to enter into a 25-year lease agreement (Patel, 2024). However, other pastoralist groups have been denied their land rights on the basis of their nomadic culture, and compensation payments have been set low because of the undervaluation of pastoralist livelihoods and the social as well as economic costs (Hemalatha, 2019). A significant part of the commons used by the pastoralists in India is identified as wastelands and is under the State's control. These *de facto* commons are vital to the pastoralists' livelihoods. The Ladakh State Administration is planning a pilot solar-power project designed for livestock grazing to gain the trust of the local community ahead of a much larger solar-power project (U. Gupta, 2025).

In the United States, various advantages were observed when solar-panel installations allowed sheep grazing between and beneath the panels. For example, sheep benefitted from the shade of solar panels and were observed to graze more than sheep on open rangelands. Solar panels also affected vegetation through improvement of shade and soil moisture, increasing forage digestibility and protein content (Kampherbeek et al., 2023). The potential to graze within solar installations can reduce their impact on pastoralists and has been exploited in India, where community consultations led to modification of the installation to allow controlled grazing (U. Gupta, 2025).

Projects may provide benefits alongside negative impacts or may inadvertently deliver benefits to pastoralists. Solar projects in Morocco, for example, have improved living conditions in adjacent communities (e.g., Noor Solar Power Station) and have stimulated regional socioeconomic and infrastructure development. However, these projects also exacerbated social conflict, rivalry and feelings of envy between communities, exclusion of local stakeholders, powerlessness in decision-making and decreased water security in the community (Terrapon-Pfaff et al., 2019). Some pastoralist communities in Kenya have benefited from improved road access and employment opportunities from energy projects, although these benefits have also aggravated tensions by favouring one ethnic group over others (Achiba, 2019; Drew, 2022).

Some renewable-energy projects have reported more favourable outcomes for pastoralists through compensation or through effective consultation with herders over installation plans. Mongolian wind-farm projects, such as the Sainshand Wind Park, have compensated herders by identifying alternative seasonal residences, building animal shelters and wells, and assisting herders to register the new land. Herders usually retain grazing access to all land apart from the small areas where turbines are constructed, although residences are usually prohibited within 500 m of the turbines to safeguard against falling ice. Communities that temporarily lose pasture access during construction have been compensated with replacement fodder and, in the case of both the Sainshand Wind Park and the Salkhit Wind Farm, the company provided new wells to the community (Oyunchimeg and Wall, 2017; Sukhbaatar, 2018).

Solar installations use more land than do wind farms to generate the same power. Therefore, the impact on herders may be greater, although the scale of solar farms in Mongolia has thus far been relatively small and not greatly disruptive to pastoralists. A 2020 project in Mongolia to construct five new renewable-energy facilities reported that construction would not entail permanent or temporary land acquisition, land-use restriction, demolition or structures, or relocation of people (ADB, 2021). Herders have tended to welcome new installations because they expect to benefit from improved energy supply (e.g., Darkhan Solar Farm) or they have influenced construction to minimise impact on their livelihoods. For example, Sermsang Khushig Khundii Solar Power Plant and its transmissions lines were re-sited after communities raised concerns during consultations over access to important salt ponds (TGC, 2019).

Kenya's Kipeto Wind Farm stands out for being developed through a significantly more equitable approach. The project leases the land occupied by turbines and transmission lines from the local community. Project developers hired a local lawyer to carry out negotiations with community members, in view of the complexity of the negotiations, and established a community implementation committee. A community trust holds a 5% share in the wind farm, and landowners also receive 1.4% of the gross revenue of each turbine located on their land (Sena, 2018; Kazimierczuk, 2019).

Households in Kipeto that were required to relocate their homestead were compensated with newly constructed homes with solar power, and the project also established a health centre and other corporate social responsibility projects. It should be noted that the land in Kipeto was formerly privatised, and some agreements have been reached by individuals within the community. The County Government has not insisted on a formal change of land use (i.e., from grazing land to industrial wind park), avoiding an increase in land rates that might otherwise have been payable by the landowners (Sena, 2018). This example demonstrates that land acquisition for development projects does not need to result in dispossession and that co-existence of energy projects and pastoral livelihoods is a viable approach that provides opportunity for the project's social acceptance and better economic returns (Ndi, 2024).

Despite the large scale of many renewable-energy projects, many pastoralists remain off-grid and energy projects typically fail to address pastoralists' energy security (Schilling and Werland, 2023). Small-scale options are available, and greater attention to appropriate energy solutions for pastoralists is needed as part of the bigger conversation about a just transition. As an example, Mongolia has achieved considerable success in rural electrification, which has been decentralised since 2000 through the 100,000 Solar Ger Programme that provides portable solar home systems to pastoralists. These systems are designed to meet household energy needs for lighting, radio, TVs and satellite dishes. An estimated 95% of all people living in rural areas of Mongolia were reported to have access to electricity by 2018 (Shippe, 2021).

Carbon sequestration and storage in pastoral lands

Sequestering carbon emissions has become an established mechanism for reducing the rate of increase of atmospheric concentration of carbon dioxide and is an important component of the global effort to mitigate climate change. Carbon-sequestration projects include approaches to capture carbon in biomass and soil and have proven to be cost-effective natural processes that bring numerous co-benefits, including restoration of biodiversity and ecosystem functions (Lal, 2007).

Rangeland ecosystems store more than a third of the world's soil carbon, and restoring degraded rangelands can significantly enhance soil carbon storage. Rangeland restoration can be incentivised through investments that enhance pastoralist livelihoods and provide investors with profits as well as social and environmental impacts (Sircely et al., 2025). Voluntary carbon markets (VCM) currently stand at an estimated USD 3 billion per year and are projected to grow by 10–30 times by 2030. The VCM allows actors to voluntarily offset their GHG emissions through the purchase of carbon credits, which are commonly from reforestation but can theoretically be any carbon-removal initiatives, including rangeland restoration. Projects must be registered under a carbon-crediting standard and audited by an independent body to ensure delivery of results and compliance with standards, which include equitable benefit sharing and avoiding the conversion of natural grassland into forest (VERRA, 2024; UNCCD, 2025).

Rangeland carbon projects face specific challenges, for example, related to their spatial scale and the complex and often insecure land-tenure arrangements involved. Rangelands include large areas with high rainfall variability and uncertainty, where restoration outcomes can be unpredictable in the short term. These challenges can be addressed with sufficient evidence, establishing effective local institutions, and ensuring due diligence. Published experiences indicate strong technical quality of rangeland carbon projects but variable quality of social engagement and highly variable costs and risks. Effective projects depend particularly on the quality of regulatory frameworks (Sircely et al., 2025).

Some carbon-finance projects have failed to consult pastoralist communities and, in some cases, have delivered little or no benefits to land users. Certification methodologies have sometimes failed to respect the rights of land users and have not secured their consent. Concerns have been raised about the relative importance of trees and grasses in generating carbon credits for rangelands and the risks associated with afforestation projects, which can drive ecosystem change in a direction that is unsuitable for pastoralism (Davies, 2024).

India may have significant opportunity to restore rangelands using carbon finance. Approximately 17% of the country is covered by savanna grassland, and an estimated 20 million hectares of grassland were lost between 1880 and 2010. Much of this former savanna grassland has been converted to other land uses, such as forest projects, irrigated agriculture, biofuel plantations, and urban and industrial uses, but the country has nevertheless significant scope for grassland restoration (Paul and Vanak, 2020).

Carbon-finance projects in India have historically favoured afforestation, driven by the misconception that grasslands are degraded forests (Ratnam et al., 2016). Major Indian grasslands have existed as open-canopy tree-grass mixtures for thousands of years (Pillai et al., 2018) and, rather than grasslands being the result of human cultivation and settlement, it is now thought that agropastoralism in places like the Deccan Plateau was possible due to the pre-existence of grasslands and savannas (Riedel et al., 2021). The misperception of grasslands as degraded ecosystems originates from the colonial period in India and led to native grasslands being allocated for plantations of exotic trees. In some cases, these trees became invasive in grasslands, causing biodiversity and habitat loss. Nevertheless, grasslands continue to be perceived as wastelands despite documented economic and ecological failure of afforestation (Joshi et al., 2018).

Afforestation has been promoted as a nature-based solution in Rajasthan in line with India's national afforestation targets. Afforestation has been proposed in areas affected by desertification, which is exacerbated by climate change and unsustainable land use. These projects identify land degradation and desertification as threats to agricultural production and water availability and promote a range of response measures, including silvopastoral regeneration, highlighting the benefits for re-integrating trees into crop-farming and pastoral landscapes in arid regions (Gupta et al., 2024).

Carbon finance has been used for rangeland restoration in the Makame Savannah Project in Tanzania. The project is implemented in a wildlife-rich savanna and dry forest area adjacent to the Tarangire National Park, where conversion of rangeland to cropland is threatening wildlife migratory routes. It is implemented in a Wildlife Management Area (WMA) covering 104,065 ha, involving five village communities and 15,000 people. The project is implemented with local communities through participatory resource planning, with the WMA providing a legal land-use plan that reflects community land-use and herding practices. Revenue from the project supports both land protection and livelihood development for the local Maasai community, including establishment of village schools, improving health services, community development initiatives, salaries for Village Game Scouts, boosting local governance, and enforcing village bylaws (Davies, 2024).

The Northern Kenya Rangeland Carbon Project of the Northern Rangeland Trust follows a comparable approach and is also implemented in a biodiversity-rich landscape that hosts several large conservation areas, and where pastoralists generate revenue from biodiversity-related enterprises (e.g., ecotourism) alongside livestock production. The Northern Kenya Rangeland Carbon Project is implemented through community conservancies and provides investment in those local organisations to enhance community rangeland management and deliver other services to pastoralists. Revenue from the carbon project is used for salaries for scouts and guards, strengthening local governance and enforcing bylaws, and implementing community projects to improve health and education services. Communities receive 60% of revenue from carbon projects, while 40% is received by the project operator and the local government. Community rangeland management institutions are the primary decision-makers on grazing and rangeland management, with variable influence of projects or project implementers. Community institutions have the authority to regulate rangeland management and are strongly influenced by customary leadership of participating ethnic groups (Sircely et al., 2025).

At the time of writing, Verra has suspended the issuance of credits to the Northern Kenya Rangeland Carbon Project. The initial suspension followed a report by a human rights group identifying flaws in the process for obtaining consent from participating communities and breaches of the Community Land Act (Counsell, 2023). This suspension was lifted following a review that identified areas in need of improvement (VERRA, 2023). The project was re-suspended following a local court ruling that discredited the process of establishing two of the 43 community conservancies involved in the project (KEELC, 2025).

Carbon finance projects in Mongolian rangelands have also followed community-driven approaches, including a "carbon-plus" approach in which carbon-sequestration projects contribute to livelihood benefits, nomadic herders' wellbeing, conservation of biodiversity, and other ecosystem services. This approach collaborates with more than 100 nomadic households, covering 77,000 ha, and targeting 100,000 t CO_2 sequestration over 4 years through improved grazing-management practices. The project emphasises community responsibility and the active participation of herders in restoration and supports herder groups to secure their land-tenure rights over seasonal pastures in line with legal provision such as the 2002 Land Law. Fair and equitable resource access, including for the poorest and most vulnerable, has been enshrined in agreements developed by the participating herder groups (Plan Vivo, 2020).

Mongolia's Scaling up Climate Ambition on Land Use and Agriculture (SCALA) programme proposes a Carbon Crediting and Market Mechanism for carbon sequestration through sustainable rangeland management that will also deliver livelihood benefits to herder communities. Mongolia could sequester approximately 4.69 million tons of carbon per year if restoration approaches are widely adopted, with a rate of 0.103 t C/ha annually (Enkhtaivan and Dolgorsuren, 2024). Research indicates that herders may be willing to adopt appropriate practices if the incentives are sufficient. The level of awareness of carbon sequestration among herders is low, but up to 60% of herding households were willing to participate in carbon schemes if projects enhanced household income and came with adequate subsidies, and if the schemes responded to a call for ecological environment protection from the government (Zhao et al., 2018).

Rangeland restoration delivers several of the objectives of the green transition, including contributing to climate-change mitigation, restoring and protecting biodiversity, strengthening adaptive capacity and reducing poverty. It is an example of a "nature-based solution". Nature-based solutions are defined as actions that "protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human wellbeing and biodiversity benefits" (IUCN, 2020). Rehabilitation of degraded rangelands can contribute simultaneously to the goals of the United Nations (UN) Framework Convention on Climate Change, the UN Convention on Biological Diversity and the UN Convention to Combat Desertification (Akhtar-Schuster et al., 2016), which could make it attractive to governments and private investors alike.

Biofuels

Biofuels can play a role in combatting global warming and reducing GHG emissions. Companies and governments have argued that biofuel production can contribute to agricultural growth and economic development in pastoral lands while addressing climate change and, in the early 2000s, pastoral lands were identified as high-potential areas for biofuel production (Exner et al., 2015; Sulle and Nelson, 2009). However, expanding biofuel production often competes with land needed for food production and creates land-use conflict that can lead to deforestation, soil degradation and loss of natural habitats, exacerbating GHG emissions (Rial, 2024). In common with earlier attempts to annex pastoral lands for other uses, proponents of biofuel production have underestimated the existing value of the land and the legitimacy of pastoralism as a land-use practice (Sulle and Nelson, 2009).

Land acquisitions for biofuel projects in Tanzania have led to migration and resettlement of pastoralists. The drive to increase biofuel production has created tensions between private, local and government actors over the right to use and allocate land. A 2009 report found that companies had applied to produce biofuel, particularly from jatropha, sugarcane and oil palm, on over 4 million ha of land in Tanzania. While 640,000 ha had been allocated by 2009, companies had only been granted formal rights of occupancy on 100,000 ha (Sulle and Nelson, 2009).

Biofuel investments have contributed to landlessness, food insecurity and environmental degradation in Tanzania. Compensation payments under Tanzania's Village Land Act of 1999 have been insufficient to allow alternative livelihood opportunities, and the compensation process has been unreliable, poorly understood by many landowners and badly implemented by many companies (Veit, 2019). Resettlement of pastoralists by biofuel schemes has triggered new conflicts. Biofuel schemes have also diverted water resources away from the rangelands while the incoming crop-farming communities have placed new pressure on natural resources such as wood fuel (Johansson, 2013).

Lessons for a just green transition in pastoral lands

Rangelands clearly have high potential for generating renewable energy and sequestering carbon and this, combined with the perception that they are large, underutilised areas that are easy to acquire, has made them attractive to investors. Not only do pastoralists face the threat of new investors attempting to acquire their land, but an 'economy of anticipation' may be driving people within pastoral areas to secure legal title over communal lands with a view to capturing benefits from potential future investments (Drew, 2022). Pastoral lands offer many opportunities for the green transition, and green-transition projects–implemented the right way–could offer opportunities to pastoralists. However, if land governance remains weak and pastoralist rights are not upheld, projects are likely to have harmful consequences for pastoralist livelihoods, resource rights, and political and social relations (Lind et al., 2020).

The green-transition implies complicated social and technological changes that will have a profound social impact. Rangelands are shaped by existing sociocultural inequalities along the lines of gender, caste and class. Vulnerable groups may lack individual land ownership and are disproportionately dependent on commons. An in-depth understanding of local realities should be integral to any green-transition projects to respect rights and ensure equitable benefit sharing. Further, the transition must avoid reproducing the environmental and socioeconomic injustices and inequalities that are intrinsic to the existing energy regime (Wang and Lo, 2021).

Examples presented in this paper demonstrate the harmful impacts on pastoralists when projects do not respect their rights. Green-transition projects have led to alienation of land, fragmentation of rangeland landscapes, displacement of communities, conflict between and within communities, weakening of customary institutions and erosion of cultural identity. Renewable-energy projects have been implemented without adequate compensation to land users and in violation of their human rights. In some cases, renewable-energy projects have stoked local conflicts and led to loss of life and property (Waters-Bayer and Wario, 2022). Such outcomes should be anticipated when investors underestimate the existing value of rangelands and fail to accept the legitimacy of pastoralism as a land-use practice (Exner et al., 2015; Sulle and Nelson, 2009).

Some large-scale renewable-energy projects have been developed in rangelands without adequately consulting land users and right holders. Weak stakeholder analysis has allowed investors to consult one claimant over communal resources at the expense of others, creating new conflicts or aggravating underlying resource competition. Some large-scale investments have not been required to secure free, prior and informed consent (FPIC) by governments and, in some cases, governments have allocated pastoral land to investors while ignoring legal requirements to consult right holders (Waters-Bayer and Wario, 2022).

Carbon finance could be a source of revenue for pastoralists to rehabilitate and sustainably manage their rangelands to sequester and store carbon. Rangeland rehabilitation can often be achieved through adaptation of herding strategies, implemented by pastoralist communities and contributing to increased productivity, conservation of biodiversity and enhanced resilience. Such projects can play an important role in climate change adaptation. They rely on local and indigenous knowledge and depend on strengthening local governance (Louhaichi et al., 2022). However, some rangeland carbon-finance projects have been developed without consulting communities and, in some cases, with no benefit flowing to the land users. Certification methodologies have failed to respect the rights of land users, including their FPIC (Davies, 2024). Concerns have also been raised over the use of carbon credits to fund afforestation in rangelands, which is neither ecologically nor socially acceptable (Briske et al., 2024).

The projects discussed in this paper that have been received more favourably by pastoralists are those that have been more recognisant of pastoralists' land rights and have engaged local communities in meaningful negotiations over project implementation. Where resource rights are not legally recognised, projects may be designed to contribute to strengthening tenure and thereby promoting pastoralist development. Projects can strengthen local governance by working through community institutions, actively developing their capacity, and effectively consulting community members. Several projects have negotiated lease arrangements with pastoralist communities, which implicitly recognise both the land rights and the value of the land on which the projects are implemented. In the best-case scenario, consultations are treated as ongoing dialogue rather than one-off events. Dialogue has helped to reinforce local governance for effective decision-making and can strengthen local institutions. Participatory rangeland-management planning has been an important part of implementing carbon-sequestration projects.

Incentives to pastoralists from green-transition projects have ranged from co-design and co-ownership of projects to sometimes trivial and tokenistic gifts or incidental benefits (e.g., roads or water infrastructure built to serve the project). While some projects have placed greater emphasis on material incentives, all the successful projects demonstrate effective engagement with relevant local stakeholders, respect for local resource rights, and willingness to adjust investment plans according to consultations. Projects can also provide meaningful economic reward to hosting communities, although this is not always in-kind (i.e., electricity supply). For example, communities have been compensated through investment in infrastructure projects and rural services. The Kenyan case (Kipeto Wind Power) in which the community became a shareholder in the wind farm is unusual but could inspire similar projects that deliver significant development co-benefits around energy projects.

The cases reviewed for this paper hint at other incentives that could be developed through green-transition projects. For example, projects could support local associations to enhance community capacity to govern and manage natural resources, to negotiate with investors and to protect cultural institutions. Stronger support can be given to communities to restore and sustainably manage rangelands through sustainable grazing within project sites, generating greater environmental and social co-benefits of green-transition projects. Whether green-transition projects translate into opportunities or threats to pastoralists may depend on whether pastoralists' land rights are respected, or indeed strengthened, whether pastoralists are adequately consulted in project development, whether the project development does not have adverse effect on pastoralist livelihoods, and whether projects deliver meaningful benefits to pastoralist communities.

This perspective paper does not attempt a thorough framing of a just green transition for pastoralists. The intention was to examine how a global green transition may impact on pastoralists and their land and to what extent those impacts would present threats or opportunities. Further examination of a just green transition in the pastoral sector is warranted, to understand green-transition pathways in the livestock sector including mitigation of emissions from livestock value chains and promotion of benefits through rangeland carbon sequestration and storage. Climate change and biodiversity loss already have adverse effects on rangelands and pastoralists, and global measures to address these threats are advancing rapidly. Pastoralists need tailored support to ensure a just green transition in the pastoral livestock sector, including finance, policy, technical support, research and development, and monitoring to incentivise new or modified practices at scale (Thornton et al., 2025).

Conclusion

Evidence has been presented that the green transition offers opportunities for pastoralists and that projects could be implemented in ways that are consistent with a just green transition, providing those projects are motivated by the development needs of pastoralist communities and not only by global environment goals. Projects that ignore pastoralist rights and fail to ensure equitable benefit sharing are likely to aggravate loss of resources and increase poverty and marginalisation. A just green transition does not depend exclusively on developing innovations for pastoralists, but it requires implementation of basic development and rights that have historically been denied to pastoralists. Guidance on implementing FPIC is available from FAO's Governance of Tenure series (FAO, 2014).

Green-transition projects should be developed as part of a multifunctional land-use strategy in rangelands. Further consideration should be given to combining approaches–for example, carbon sequestration in rangeland rehabilitation alongside green-energy investments–in ways that secure pastoralists' rights and contribute to their livelihood resilience and conserve biodiversity. Rather than exploit loopholes and governance vacuums, projects should explicitly aim to strengthen the voice and agency of pastoralists and enable them to negotiate desirable outcomes (Waters-Bayer and Wario, 2022).

Pastoralist livelihood systems and resource rights must be legitimised and protected by governments and private investors to ensure a just green transition. Pastoralist resource rights can be complex, and several communities may have overlapping rights, requiring detailed stakeholder analysis and conflict sensitive consultation, not as a one-off event but as a continual process that respects the existing land-tenure mechanisms. Guidance is available for implementing the FAO Voluntary Guidelines on Responsible Governance of Tenure in pastoral lands (Davies et al., 2016). Consultations should be informed of the need to protect seasonal resource access and migration routes, and key resources and corridors need to be safeguarded. Projects should develop and equitably share incentives that contribute to pastoralist livelihood resilience and reflect a fair estimation of the value of foregone resources. The best projects will go beyond benefit sharing to involve pastoralists as core stakeholders and development partners.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Funding

The author(s) declared that financial support was not received for this work and/or its publication.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

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References

Achiba, G. A. (2019). Navigating contested winds: development visions and anti-politics of wind energy in Northern Kenya. *Land 2019* 8, 7–8. doi:10.3390/LAND8010007

ADB (2021). *Upscaling Renewable Energy Sector Project: Environmental Monitoring Report (June-December 2020)*. Text. Ulaanbaatar, Mongolia: Asian Development Bank.

Akhtar-Schuster, M., Amiraslani, F., Diaz Morejon, C. F., Escadafal, R., Fulajtar, E., Grainger, A., et al. (2016). Designing a new science-policy communication mechanism for the UN Convention to combat desertification. *Environ. Sci. Policy* 63, 122–131. doi:10.1016/j.envsci.2016.03.009

Bai, Y., and Cotrufo, M. F. (2022). Grassland soil carbon sequestration: current understanding, challenges, and solutions. *Science* 377, 603–608. doi:10.1126/science.abo2380

Briske, D. D., Derner, J. D., Brown, J. R., Fuhlendorf, S. D., Teague, W. R., Havstad, K. M., et al. (2008). Rotational grazing on rangelands: reconciliation of perception and experimental evidence. *Rangel. Ecol. Manag.* 61, 3–17. doi:10.2111/06-159R.1

Briske, D. D., Vetter, S., Coetsee, C., and Turner, M. D. (2024). Rangeland afforestation is not a natural climate solution. *Front. in Ecol. and Environ.* 22, e2727. doi:10.1002/fee.2727

Briske, D. D., Cromsigt, P. G. M., Davies, J., Fernández-Giménez, M. E., Luizza, M. W., Manzano, P., et al. (2025). Pastoralism can mitigate biodiversity loss on global rangelands. *Bioscience* 76, 78–89. doi:10.1093/biosci/biaf158

Center for Sustainable Systems (2025). Wind Energy Factsheet. *Pub. No. CSS07-09*. Michigan, USA: University of Michigan.

Chatterjee, R., and Swarnakar, P. (2023). Just energy transition in agriculture: a systematic review from social-ecological perspectives. *Soc. Sci. Res. Netw.* 37. doi:10.2139/ssrn.4534120

Cormack, Z., and Kurewa, A. (2018). The changing value of land in Northern Kenya: The case of Lake Turkana Wind power. *Crit. Afr. Stud.* 10, 89–107. doi:10.1080/21681392.2018.1470017

Counsell, S. (2023). *Blood Carbon: How a Carbon Offset Scheme Makes Millions From Indigenous Land in Northern Kenya*. London: Survival International.

Davies, J. (2024). *Opportunities and Challenges of the Green Transition for Pastoralism and Indigenous People in Africa*. Brussels, Belgium: European Parliament.

Davies, J., Ogali, C., Laban, P., and Metternicht, G. (2015a). *Homing in on the Range: Enabling Investments for. Sustainable Land Management*. Nairobi: International Union for Conservation of Nature.

Davies, J., Robinson, L. W., and Ericksen, P. J. (2015b). Development process resilience and sustainable development: insights from the drylands of Eastern Africa. *Soc. Nat. Resour.* 28, 328–343. doi:10.1080/08941920.2014.970734

Davies, J., Herrera, P., Ruiz-Mirazo, P., Mohamed-Katerere, J., Hannam, I., and Nuesiri, E. (2016). *Improving governance of pastoral lands Implementing the Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security*. Rome: FAO.

Drew, J. (2022). Protest, middlemen and everyday meanings of place: Reconceptualising the scramble for East Africa's drylands. *J. East. Afr. Stud.* 16, 160–179. doi:10.1080/17531055.2022.2070303

Enkhtaivan, S., and Dolgorsuren, S. (2024). Scaling up carbon sequestration in Mongolian rangelands through a carbon crediting and market mechanisms. *Food Agric. Organ. U. N.* 8. Available online at: https://www.undp.org/mongolia/publications/scaling-carbon-sequestration-mongolian-rangelands-through-carbon-crediting-and-market-mechanisms.

European Commission (2023). *2023 Annual Report: on the Implementation of the European Union's External Action Instruments in 2022*. Brussels: International Partnerships.

Exner, A., Bartels, L. E., Windhaber, M., Fritz, S., See, L., Politti, E., et al. (2015). Constructing landscapes of value: capitalist investment for the acquisition of marginal or unused land—The case of Tanzania. *Land Use Policy* 42, 652–663. doi:10.1016/J.LANDUSEPOL.2014.10.002

FAO (2014). *Respecting Free, Prior and Informed Consent: Practical Guidance for Governments, Companies, NGOs, Indigenous Peoples and Local Communities in Relation to Land Acquisition. Governance of Tenure Technical Guide 3*. Rome: Food and Agriculture Organisation of the United Nations.

FAO (2025). "Greenhouse gas emissions from agrifood systems. Global, regional and country trends," in *FAOSTAT Analytical Brief* (Rome, Italy: Food and Agriculture Organisation of the United Nations), 115, 2001–2023.

Gabbert, E. C., Gebresenbet, F., Galaty, J. G., and Schlee, G. (2021). *Lands of the Future: Anthropological Perspectives on Pastoralism, Land Deals and Tropes of Modernity in Eastern Africa. 1st ed.* 23 (Oxford and New York: Berghahn Books). doi:10.2307/j.ctv2tsxkm5

Gerber, P. J., Steinfeld, H., Henderson, B., Mottet, A., Opio, C., Dijkman, J., et al. (2013). *Tackling Climate Change Through Livestock: A global Assessment of Emissions and Mitigation Opportunities*. Rome: Food and Agriculture Organisation of the United Nations.

Ghosh, P., and Mahanta, S. K. (2014). Carbon sequestration in grassland systems. *Range Manag. Agrofor.* 35, 173–181. Available online at: https://indianjournals.com/article/rma-35-2-001.

Greiner, C. (2022). "African pastoralism: plus ça change? From constant herders to social differentiation," in *African Futures* (Bellville, South Africa: Institute for Poverty, Land and Agrarian Studies, University of Western Cape), 36–46. doi:10.1163/9789004471641_005

Gupta, U. (2025). Ladakh plans livestock grazing-friendly solar plant. *P.v. Magazine India*. Available online at: https://www.pv-magazine-india.com/2025/01/03/ladakh-plans-livestock-grazing-friendly-solar-project/.

Gupta, S. K., Kanga, S., Meraj, G., Singh, S. K., Singh, S., Sajan, B., et al. (2024). Optimizing land use for climate mitigation using nature based solution (NBS) strategy: a study on afforestation potential and carbon sequestration in Rajasthan, India. *Discov. Geosci.* 2, 36. doi:10.1007/s44288-024-00046-w

Hemalatha, K. (2019). *Why India's Solar Push Could Kill The Livelihood Of Pastoral Communities*. Vikalp Sangam. Available online at: https://vikalpsangam.org/article/why-indias-solar-push-could-kill-the-livelihood-of-pastoral-communities/.

Henry, B., Allen, D., Badgery, W., Bray, S., Carter, J., Dalal, R. C., et al. (2024). Soil carbon sequestration in rangelands: a critical review of the impacts of major management strategies. *Rangel. J.* 46, 27. doi:10.1071/RJ24005

Herrero, M., Addison, J., Bedelian, C., Carabine, E., Havlik, P., Henderson, B., et al. (2016). Climate change and pastoralism: impacts, consequences and adaptation. *Revue scientifique et technique (International Office of Epizootics)* 35. *Rev. Sci. Tech.* 35, 417–433. doi:10.20506/RST.35.2.2533

Hughes, L., and Rogei, D. (2020). Feeling the heat: responses to geothermal development in Kenya's Rift Valley. *J. East. Afr. Stud.* 14, 165–184. doi:10.1080/17531055.2020.1716292

IEC (2019). *Wind Energy Generation Systems – Part 1: Design Requirements (IEC 61400-1:2019)*. Geneva: International Electrotechnical Commission.

ILRI, IUCN, FAO, WWF, UNEP, and ILC (2021). *Rangelands Atlas*. Nairobi, Kenya: ILRI.

IPCC (2023). "Summary for policy makers," in *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Geneva, Switzerland: IPCC).

IRENA (2025). "R," in *Enewable Energy Statistics 2025*. Abu Dhabi: International Renewable Energy Agency.

IUCN (2011). *The Land We Graze: A Synthesis of Case Studies About How Pastoralists' Organizations Defend Their Land Rights*. Nairobi: IUCN.

IUCN (2020). *Global Standard for Nature-Based Solutions. A User-Friendly Framework for the Verification, Design and Scaling Up of NbS*. Gland, Switzerland: IUCN.

Johansson, E.Li (2013). *A Multi-Scale Analysis of Biofuel Related Land Acquisitions in Tanzania*. Lund: Lund University.

Johnsen, K. I., Niamir-Fuller, M., Bensada, A., and Waters-Bayer, A. (2019). *A case of benign Neglect: Knowledge Gaps About Sustainability in Pastoralism and Rangelands*. Nairobi, Kenya: United Nations Environment Program.

Joshi, A. A., Sankaran, M., and Ratnam, J. (2018). Foresting' the grassland: historical management legacies in forest-grassland mosaics in southern India, and lessons for the conservation of tropical grassy biomes. *Biol. Conserv.* 224, 144–152. doi:10.1016/j.biocon.2018.05.029

Jung, C., and Schindler, D. (2021). A global wind farm potential index to increase energy yields and accessibility. *Energy* 231, 120923. doi:10.1016/j.energy.2021.120923

Kampherbeek, E. W., Webb, L. E., Reynolds, B. J., Sistla, S. A., Horney, M. R., Ripoll-Bosch, R., et al. (2023). A preliminary investigation of the effect of solar panels and rotation frequency on the grazing behavior of sheep (*Ovis aries*) grazing dormant pasture. *Appl. Animal Behav. Sci.* 258, 105799. doi:10.1016/j.applanim.2022.105799

Kazimierczuk, A. H. (2019). Wind energy in Kenya: a status and policy framework review. *Renew. Sustain. Energy Rev.* 107, 434–445. doi:10.1016/J.RSER.2018.12.061

KEELC (2025). Osman & 164 others (suing on their behalf and behalf of Residents of Merti Sub-county, chari, and cherab wards in Isiolo county) v Northern Rangelands trust & 8 others [2025] KEELC 99 (KLR). *Legal Proceeding, Petition E006 of 2021. Isiolo, Kenya Environ. Land Court*. Available online at: https://new.kenyalaw.org/akn/ke/judgment/keelc/2025/99/.

King, A. D., and Harrington, L. J. (2018). The inequality of climate change from 1.5 to 2 °C of global warming. *Geophys. Res. Lett.* 45, 5030–5033. doi:10.1029/2018GL078430

Kubitza, C., Grislain, Q., Rivera, N., Sonderegger, G., Lay, J., Samndong, R., et al. (2025). *Large-Scale Land Acquisitions for Carbon Offsetting: Green Grabbing or Just Transition? Analytical Report on Land-Based Offset Projects*. Bern, Switzerland: University of Bern. doi:10.48620/91000

Lal, R. (2007). Carbon sequestration. *Philosophical Trans. R. Soc. B Biol. Sci.* 363, 815–830. doi:10.1098/rstb.2007.2185

Lind, J., Okenwa, D., and Scoones, I. (2020). Land, investment & politics: reconfiguring Eastern Africa's pastoral drylands. *Martlesham, Suffolk Boydell Brew* 10, 14. doi:10.1186/s13570-020-00179-w

Lledó, Ll., Torralba, V., Soret, A., Ramon, J., and Doblas-Reyes, F. J. (2019). Seasonal forecasts of wind power generation. *Renew. Energy* 143, 91–100. doi:10.1016/j.renene.2019.04.135

Lorenz, K., and Lal, R. (2018). "Carbon sequestration in agricultural ecosystems," in *Carbon Sequestration in Agricultural Ecosystems*. Springer International Publishing, 1–392. doi:10.1007/978-3-319-92318-5/COVER

Louhaichi, M., Davies, J., Gamoun, M., Hassan, S., Abu-Zanat, M., Mohamed, N., et al. (2022). *Sustainable Rangeland Management Toolkit for Resilient Pastoral Systems*. Tunis, Tunisia: ICARDA.

Mapfumo, P., Rurinda, J., Cramer, L., Mushore, T. D., and George, W. (2025). Developing just transition pathways for Africa's agriculture towards low emission and climate resilient development under a 1.5 °C global warming. *CABI Rev.* 20, 0006. doi:10.1079/cabireviews.2025.0006

McGahey, D., Davies, J., Hagelberg, N., and Ouedraogo, R. (2014). *Pastoralism and the Green Economy: A Natural Nexus?* Nairobi: IUCN and UNEP.

Mentis, D., Hermann, S., Howells, M., Welsch, M., and Siyal, S. H. (2015). Assessing the technical wind energy potential in Africa a GIS-based approach. *Renew. Energy* 83, 110–125. doi:10.1016/j.renene.2015.03.072

Mgalula, M. E., Wasonga, O. V., Hülsebusch, C., Richter, U., and Oliver, H. (2021). Greenhouse gas emissions and carbon sink potential in Eastern Africa rangeland ecosystems: a review. *Pastoralism* 11, 19. doi:10.1186/s13570-021-00201-9

Min, B., O'Keeffe, Z. P., Abidoye, B., Gaba, K. M., Monroe, T., Stewart, B. P., et al. (2024). Lost in the dark: a survey of energy poverty from space. *Joule* 8, 1982–1998. doi:10.1016/j.joule.2024.05.001

Mosley, J., and Watson, E. E. (2016). Frontier transformations: Development visions, spaces and processes in Northern Kenya and Southern Ethiopia. *J. East. Afr. Stud.* 10, 452–475. doi:10.1080/17531055.2016.1266199

National Institute of Wind Energy (2018). *Guidelines for Offshore Wind Power Assessment Studies and Surveys*. India: Ministry of New and Renewable Energy.

National Institute of Wind Energy (2023). *Wind Potential Estimates at 150 m Hub Height*. India: Ministry of New and Renewable Energy.

Ndi, F. A. (2024). Land acquisition, renewable energy development, and livelihood transformation in rural Kenya: the case of the Kipeto wind energy project. *Energy Res. and Soc. Sci.* 112, 103530. doi:10.1016/j.erss.2024.103530

Nilsson, A., de Vivero, G., Lopez Legarreta, P., Day, T., Pudlik, M., Seyfang, B., et al. (2021). *Green Hydrogen Applications in Mongolia: Technology Potential and Policy Options*. Germany: Fraunhofer ISI, NexClimate, GIZ. INIS-DE–3489.

Oba, G. (2020). *African Environmental Crisis: A History of Science for Development*. London: Routledge. doi:10.4324/9781003002161

Oyunchimeg, N., and Wall, L. (2017). *Sainshand Wind Park project resettlement action plan*. Ulaanbaatar. Ulaanbaatar, Mongolia: Tecol LLC and Shared Resources Pty Ltd.

Patel, S. (2024). *Land, Livelihoods, and Solar Infrastructure: An Overview From Radhanesda Village*. Banaskantha, Gujarat.

Paul, M. M., and Vanak, A. T. (2020). *India's Savanna Grasslands: The Unsung Tale*. Conseravtion India: India's Savanna Grasslands: The Unsung Tale.

Pillai, A. A. S., Anoop, A., Prasad, V., Manoj, M. C., Varghese, S., Sankaran, M., et al. (2018). Multi-proxy evidence for an arid shift in the climate and vegetation of the Banni grasslands of western India during the mid-to late-Holocene. *Holocene* 28, 1057–1070. doi:10.1177/0959683618761540

Plan Vivo (2020). Pastures, conservation, climate action – mongolia. *Plan. Vivo Found.* Available online at: https://www.planvivo.org/pastures-conservation-climate-actionu.

Rathore, V., and Zargar, S. (2024). in *Ladakh, a Massive Energy Project is Shrouded in Mystery* (Business and Human Rights Resource Centre). Available online at: https://scroll.in/article/1073644/in-ladakh-a-massive-energy-project-is-shrouded-in-mystery.

Ratnam, J., Tomlinson, K. W., Rasquinha, D. N., and Sankaran, M. (2016). Savannahs of Asia: antiquity, biogeography, and an uncertain future. *Philosophical Trans. R. Soc. B Biol. Sci.* 371, 20150305. doi:10.1098/rstb.2015.0305

Rial, R. C. (2024). Biofuels *versus* climate change: exploring potentials and challenges in the energy transition. *Renew. Sustain. Energy Rev.* 196, 114369. doi:10.1016/j.rser.2024.114369

Riedel, N., Fuller, D. Q., Marwan, N., Poretschkin, C., Basavaiah, N., Menzel, P., et al. (2021). Monsoon forced evolution of savanna and the spread of agro-pastoralism in peninsular India. *Sci. Rep.* 11, 9032. doi:10.1038/s41598-021-88550-8

Schilling, J. I. D., and Werland, L. I. D. (2023). Facing old and new risks in arid environments: the case of pastoral communities in Northern Kenya. *PLOS Clim.* 2, e0000251. doi:10.1371/JOURNAL.PCLM.0000251

Scoones, I. (2021). Pastoralists and peasants: perspectives on agrarian change. *J. Peasant Stud.* 48, 1–47. doi:10.1080/03066150.2020.1802249

Sena, K. (2018). *Kipeto Wind Energy project: a case study on best practice in community engagement in energy projects*.

Sha, Z., Bai, Y., Li, R., Lan, H., Zhang, X., Li, J., et al. (2022). The global carbon sink potential of terrestrial vegetation can be increased substantially by optimal land management. *Commun. Earth and Environ.* 3, 8. doi:10.1038/s43247-021-00333-1

Shippe, S. (2021). Investing in renewable energy in Mongolia. *Borgen Proj.* Available online at: https://borgenproject.org/renewable-energy-in-mongolia/.

Sircely, J. A., Hientz, L., Umutoni, C., and Flintan, F. E. (2025). *Opportunities and Potential for Carbon Projects and Markets to Support Large-Scale Rangeland Restoration*

Through Investments in Rangeland Carbon Value Chains. Nairobi, Kenya: International Livestock Research Institute.

Slooten, E., Raath-Krüger, M. J., Archibald, S., and Siebert, F. (2026). Subtropical grassland root-to-shoot ratios and plant organic carbon estimates: why global averages fall short. *Ann. Bot.* 2026, 1–10. doi:10.1093/aob/mcag027

Smil, V. (2016). *Power Density: A Key to Understanding Energy Sources And Uses*. Cambridge, Massachusetts London, England: The MIT Press.

Smith, P. (2008). Land use change and soil organic carbon dynamics. *Nutrient Cycl. Agroecosyst.* 81, 169–178. doi:10.1007/s10705-007-9138-y

Stevis, D., and Felli, R. (2016). Green transitions, just transitions. *Kurswechsel* 3, 35–45.

Sukhbaatar, T. (2018). Supplementary report of Salkhit Wind Farm's detailed environmental impact assessment. Ulaanbaatar, Mongolia: Clean Energy LLC.

Sulle, E., and Nelson, F. (2009). *Biofuels, Land Access and Rural Livelihoods in Tanzania*. London: IIED.

Tavares, M. (2022). *A Just Green Transition: Concepts And Practice so far. Future of the World Policy Brief*. New York: United Nations Department of Economic and Social Affairs.

Tennigkeit, T., and Wilkes, A. (2008). An assessment of the potential for carbon finance in rangelands. *ICRAF Work. Pap. No.68. ICRAF*, 42. Available online at: https://www.fao.org/fileadmin/templates/agphome/scpi/cgwg/ICRAF_WP68.pdf.

Terrapon-Pfaff, J., Fink, T., Viebahn, P., and Jamea, El M. (2019). Social impacts of large-scale solar thermal power plants: assessment results for the NOORO I power plant in Morocco. *Renew. Sustain. Energy Rev.* 113, 109259. doi:10.1016/j.rser.2019.109259

TGC (2019). *Initial Environmental and Social Examination Sermsang Khushig Khundii Solar Power Project, Mongolia, for Asian Development Bank*. Mongolia: Tenuun Gerel Company.

Thornton, P., Wollenberg, E., Cramer, L., and Flintan, F. (2025). Options for a just transition for livestock under climate change. *Outlook Agric.* 54, 222–233. doi:10.1177/00307270251365668

UNCCD (2024). "Global land outlook thematic report on rangelands and pastoralism," in *Global Land Outlook* (Bonn: United Nations Convention to Combat Desertification).

UNCCD (2025). *From Carbon to Co-Benefits: Scaling Carbon Finance for Land, Livelihoods, and Long-Term Resilience*. Bonn, Germany: United Nations Convention to Combat Desertification UNCCD.

UNDP (2023). *Managing Complexity While Building Consensus. Governance Nexus Series 01, UNDP*. New York: United Nations Development Program.

UNECA (2022). *Africa Sustainable Development Report 2022*. Addis Ababa, Ethiopia: United Nations Economic Commission for Africa.

UNEP (2011). *Towards a Green Economy: Pathways to Sustainable Development and Poverty Eradication - A Synthesis for Policy Makers*. Nairobi: United Nations Environment Program.

UNFCCC (2015). *Paris Agreement*.

United Nations General Assembly (2007). *United Nations Declaration on the Rights of Indigenous Peoples*. New York, United States: United Nations.

Van Uffelen, N., Taebi, B., and Udo, P. (2024). Revisiting the energy justice framework: doing justice to normative uncertainties. *Renew. Sustain. Energy Rev.* 189, 113974. doi:10.1016/j.rser.2023.113974

van Zalk, J., and Behrens, P. (2018). The spatial extent of renewable and non-renewable power generation: a review and meta-analysis of power densities and their application in the U.S. *Energy Policy* 123, 83–91. doi:10.1016/j.enpol.2018.08.023

Veit, P. (2019). *Biofuels and Land Use in Tanzania*. Seattle: Gates Open Research.

VERRA (2023). *Section 6 Quality Controll review: Findings and non-conformities report*. 1468_Section 6 QC Review_20231122_Closed. VERRA.

VERRA (2024). *Verified Carbon Standard (VCS) Standard, Version 4.7*. Washington DC, United States: VERRA.

Wang, X., and Lo, K. (2021). Just transition: a conceptual review. *Energy Res. and Soc. Sci.* 82, 102291. doi:10.1016/j.erss.2021.102291

Wanyoro, C. (2021). Kenya: Turkana wind Project title deeds nullified in land row. *All Afr*.

Waters-Bayer, A., and Wario, H. T. (2022). Pastoralism and large-scale REnewable energy and green hydrogen projects: potential and threats. *Berlin, Germany: brot für die Welt and Heinrich Böll Stiftung*.

World Bank GroupSolargis (2020). *Global Solar Atlas 2.0*. Washington DC: World Bank.

WWF (2024). *Living Planet Report 2024 - A System in Peril*. Gland, Switzerland: WWF.

Yilmaz, E., Zogib, L., Urivelarrea, P., and Çağlayan, S. D. (2019). Mobile pastoralism and protected areas: conflict, collaboration and connectivity. *Parks* 25, 7–24. doi:10.2305/iucn.ch.2019.parks-25-1ey.en

Zhang, M., Sun, J., Wang, Y, Li, Y., and Duo, J. (2025). State-of-the-art and challenges in global grassland degradation studies. *Geogr. Sustain.* 6, 100229. doi:10.1016/j.geosus.2024.08.008

Zhao, Y., Yan, Y., Liu, Q., and Li, F. Y. (2018). How willing are herders to participate in carbon sequestration and mitigation? An inner Mongolian grassland case. *Sustainability* 10, 2808. doi:10.3390/su10082808