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Title: Towards a holistic understanding of pastoralism.

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Summary

Pastoralism is globally significant in social, environmental and economic terms. However, it experiences crises rooted in misconceptions and poor interdisciplinary understanding, while being largely overlooked in international sustainability forums and agendas. Here we propose a transdisciplinary research approach to understand pastoralist transitions using i) social, economic and environmental dimensions, ii) diverse geographic contexts and scales to capture emerging properties, allowing for cross-system comparisons, and iii) timescales from the distant past to the present. We provide specific guidelines to develop indicators for this approach, within a social-ecological resilience analytical framework to understand change. Distinct systems undergo similar transitions over time, crossing critical thresholds and then either collapsing or recovering. Such an integrated view of multidimensional interactions improves understanding of possible tipping points, thereby supporting better-informed decision-making. The need for a paradigm shift in pastoralism science and policy is pressing. This research approach, including participatory methods, can provide the solutions urgently needed.

1. INTRODUCTION

Why pastoralism and why now?

Pastoralism is the most widespread land use worldwide (1–3). Present in over 100 countries through all inhabited continents (Fig. 1), its extent may be up to 60% of the world's terrestrial area – but see (4, 5) for gaps and uncertainties in estimates. With between 50 and 500 million people living from this practice (6–9), it represents an important contribution to the agricultural GDP in many nations – e.g., 88% in Mongolia (10) and 50% in Kenya (11). Beyond its economic value, extensive pastoralism also provides significant environmental, social and cultural contributions (12).

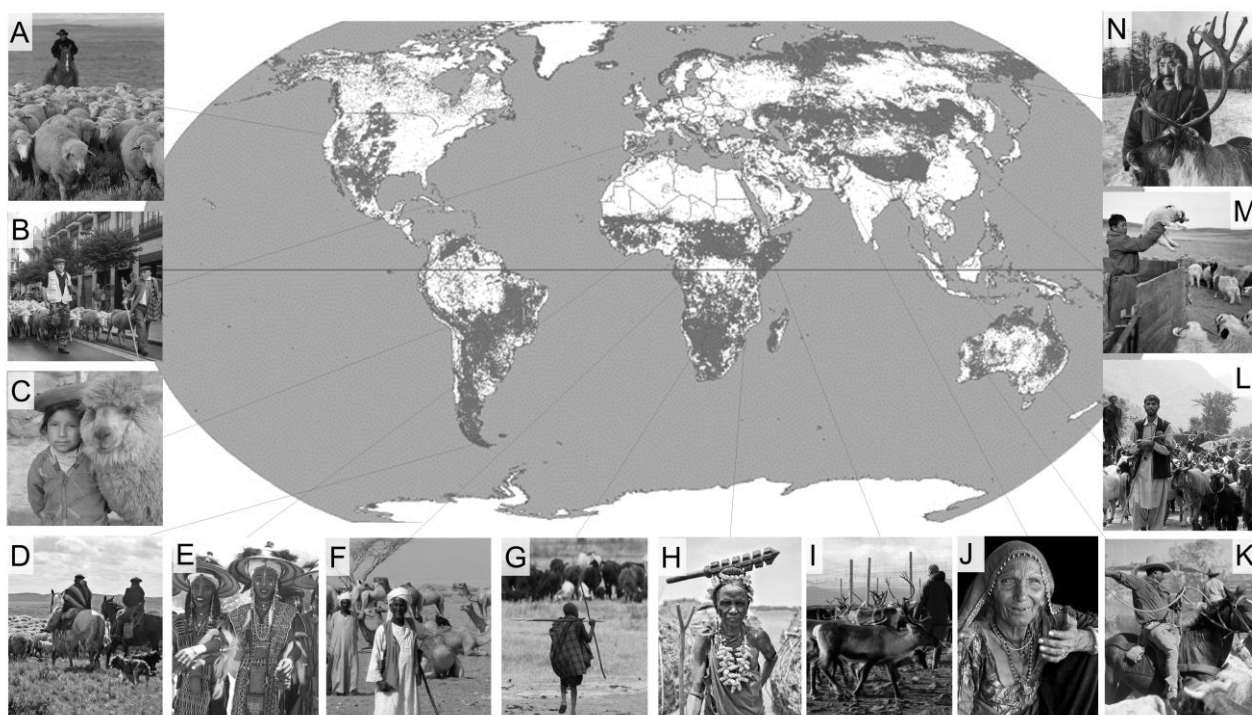


Figure 1. Pastoralism globally

The map shows an estimate of the extent of pastoralism, after (171), and pictures illustrate different pastoralist societies that herd diverse livestock (sheep, goats, cattle, camels, llamas, reindeer). We understand pastoralism as a production system based on **extensive livestock production** that has a **high reliance on common-pool** natural forage resources. The often high spatio-temporal variation of resources is managed through **livestock mobility**, although this can take place at very different scales. They are **low-input, low-output** systems (102). Pastoralism offers comparative advantages for sustainable food production and livelihoods in areas where cultivation is risky or unsuitable: tundra, boreal forests, mountains and drylands. Pictures: A) USA sheep herding¹; B) Spanish transhumance²; C) Quechua girl and alpaca³; D) Huaso⁴; E) Yaake⁵; F) Beja people⁶; G) Maasai⁷; H) Daasanach⁸; I) Sami reindeer herder⁹; J) Gujar lady¹⁰; K) Australian cattle rancher¹¹; L) Bakkerwals¹²; M) Mongolian goat herder¹³; N) Yakut reindeer herder¹⁴.

¹ Wikimedia Commons: ARS_sheep_herding.jpg (public domain)

² Barcex / Wikimedia Commons: Madrid_-_XX_fiesta_de_la_trashumancia_-_131006_105048.jpg (cc-by SA 3.0 Unported)

³ Donkeet / Wikimedia Commons: Gwalpaca.jpg (cc-by SA 3.0 Unported)

⁴ LBM1948 / Wikimedia Commons: Laguna_Blanca_06.jpg (cc-by SA 4.0)

⁵ Dan Lundberg / Flickr: 1997_276-18A_Yaake_demonstration.jpg (cc-by SA 2.0)

⁶ Nikswieweg / German Wikipedia: Bedscha.jpg (cc-by SA 3.0)

⁷ Andreas Lederer / Flickr: Young_Masai_herder.jpg (cc-by 2.0)

⁸ Rod Waddington / Flickr: Older_Woman,_Dassanech_Tribe,_Ethiopia_(21884095049).jpg (CC-BY SA 2.0 Generic)

⁹ Mats Andersson / Flickr: Reindeer_herding.jpg (CC-BY 2.0)

¹⁰ Nishit Dey / Pexels: <https://www.pexels.com/photo/gujjar-lady-from-pushkar-1150846/> (public domain)

¹¹ Wikimedia Commons: VRDcattle.jpg (public domain)

¹² Laportechicago / English Wikipedia: Bakkerwals.jpg (cc-by 2.5)

¹³ Taylor Weidman/The Vanishing Cultures Project / Wikimedia Commons: Mongolia_Herding_Life4.JPG (cc-by SA 3.0 Unported)

¹⁴ Somogotto / Wikimedia Commons: Yakut_Sakha_herder.jpg (cc-by SA 4.0)

Pastoralist systems are often present in harsh and highly variable regions (Fig. 1). These social-ecological systems (SES) have risen and fallen since their origins millennia ago, but the last decades have witnessed an increasing frequency and magnitude of sudden livestock production losses (13). This global pattern threatens the future viability of pastoral livelihoods and poses great challenges for achieving many of the U.N. Sustainable Development Goals (14) in many nations. In contrast, forecasted climatic changes threaten agricultural production in many limiting environments where, in turn, pastoralism may remain the most resilient and adaptive livelihood (15). Such characteristics, coupled with a growing human population and a predicted increase in meat demands (16), make investing in pastoralism research—and supporting policies—a timely endeavor.

The pressing need to advance the science and policy around pastoralism is justified by a number of reasons. First, crises in pastoralism have been linked to policies that undermine the adaptability of pastoralist systems, such as those promoting sedentarization and land privatization (1, 4, 17–19). These policy trends have been associated with the persistent demeaning of pastoralist livelihoods, often perceived as an obsolete or inferior alternative compared to other livelihoods (20, 21). Second, this marginalization is reflected in the weak presence of pastoralism at international environmental and economic policy forums and global sustainability agendas. UNFCCC COP24 showcased this problem, with panels specifically dedicated to mountains (22), oceans (23), farmers or indigenous peoples (24), but none on rangelands or pastoralists, and no organized presence of pastoral interest groups. Third, a recent UN report highlights widespread knowledge gaps as reasons behind detrimental policies (5), emphasizing (i) the challenge of studying the diverse systems—as depicted in Fig. 1—under a single umbrella, and (ii) interdisciplinary integration being essential if we want the most updated research to be incorporated into practice. It is important to point out that most research on pastoralism so far has been isolated and fragmented across disciplines and geographic regions, with few efforts cutting across them. To the best of our knowledge, there is no global appraisal that maps out the relevance of pastoralism in the context of planetary sustainability, and also the rangelands upon which they depend.

Analytical Framework and Theoretical Considerations

This paper uses a social-ecological resilience framework to develop a theory of pastoralism that incorporates multiple slow, controlling and fast-moving social, ecological, and institutional variables operating at multiple scales from the local to the global (25, 26). Maintaining resilience thus entails the management for a diverse set of parameters and their feedbacks. Social, ecological and political processes are path dependent (27–29), such that legacies of past events affect the dynamics of the current SES.

This social-ecological resilience framework includes both adaptive co-management and adaptive governance approaches (see Box 1 for definitions). These approaches, operationalized through institutional arrangements, have the potential to empower local decision-making and link local communities to vertical and horizontal organizations (e.g., for funding, policy), and emphasize the role of collaboration and social learning (30–33). This framework provides the ability to describe the broad-scale historical processes of pastoralism, the nested institutional arrangements across scales, the social and ecological outcomes, and the political, economic, and social drivers that constrain or enable pastoralism. Strategies to enhance social-ecological resilience include maintaining biological, economic and cultural diversity, sustaining a mix of stabilizing feedbacks and creative renewal that build natural and social capital (the productive base), fostering social learning and innovation through adaptive co-management, facilitating adaptive governance arrangements that are flexible, redundant and diverse to adapt to changing conditions, and taking advantage of windows of opportunity to transform the system to sustainable futures (34). The ultimate goal of the resilience-based framework

is aligned both with an understanding of pastoralism and the sustainable development goals (35) in its effort to provide the capacity for ecosystems to maintain the ecosystem services upon which people depend, while at the same time enhancing human livelihoods and well-being (36).

Box 1. Definitions of relevant terms for the resilience theoretical framework

Adaptive Co-Management: Process by which institutional arrangements and ecological knowledge are tested and revised in a dynamic, ongoing, self-organized process of learning-by-doing (after 172)

Adaptive Governance: Flexible, polycentric institutional arrangements that are nested across horizontal and vertical linkages; diverse, redundant and overlapping institutional arrangements (after 34, 173 & 174)

Governance: Formal and informal institutions, policies, rules and practices that shape human-environment interactions (after 34 & 174)

Social-Ecological Resilience: Capacity of groups and individuals to adapt or transform in the face of change in social-ecological systems, particularly unexpected change, in ways that continue to support human well-being (after 175)

Transdisciplinary research: Research process where academics from different disciplines, as well as stakeholders from the civil society and other sectors, co-produce knowledge (after 176).

A primary concern in resilience and resilience-based ecosystem stewardship is to understand the factors associated with exogenous controls and maintenance of critical slow and fast variables (37). Exogenous controls include regional climate and national-level policies, economics, and governance (Box 1). These are not managed for *per se* but should be recognized as regulating factors that condition the state of slow and fast variables.

Slow variables are controlling factors that regulate ecosystem structure and function, and are buffered by stabilizing effects so that they remain relatively constant over time. Critical slow variables include functional types of plants, disturbance regimes, or cultural ties to the land that regulate stability, maintain historical legacies, and provide ecological and social memory. Fast variables (e.g., annual growth, wildlife density, agent-specific preferences) respond to daily, seasonal and inter-annual variation. Rapid changes in fast variables may serve to overwhelm slow variables leading to a regime shift (38, 39). This is characteristic of systems in panarchy, hierarchical social-ecological systems that are interlinked in continual adaptive cycles of growth, accumulation, release and renewal (40, 41). During the two first phases of such cycles, the system undergoes a steadily accumulation of potential which is not clearly visible and gives an impression of stability, apparently conserving the balance among its elements. Such apparent balance is however broken when the accumulated potential approaches critical tipping points and is then released, giving way to a phase of crisis but also of renewal. Classic examples of these conservation-release patterns would be the accumulation of biomass that finally releases fires and germination of sun-loving seeds previously suppressed by shadow; or the accumulation of social tensions in the usual functioning of a society that finally escalate to the point of releasing social unrest and giving way to the proposal and construction of new, even revolutionary social structures. The founder conditions (plant community, governance scheme) established at the beginning of the new cycle are going to define and select the structure of the next conservation phase, which may not be equal to the old one because of the loss, addition or rearrangement of elements (species, ideas) in respect to the former cycle. Tempo over the cycle phases is not equal, for example, the conservation phase may be hundreds of years and the release may be in days. It is difficult to sometimes see the release phase, only that the system has changed. Therefore, maintaining resilience in SESs requires simultaneous monitoring of and management for slow and fast variables and their interactions to avoid undesirable state transitions (37). Additionally, it is important to recognize the role of historical specificity in explaining dynamics of the current SES (SES path dependency). Such a social-ecological resilience (Box 1) prism is largely missing in the study of pastoralism, despite pastoral systems having all the relevant characteristics. Better recognition, characterization and monitoring of slow and fast variables in these systems, as well as

their interactions and dependencies is paramount, as they condition the resilience and sustainability of pastoralism. With this framework in mind, the following sections address the elements needed to progress in this direction.

Need to move towards transdisciplinarity

Pastoralist Traditional Knowledge is inherently holistic (42–47), evolving from sustainable use of resources with millennia of adaptive management systems in their environment. In contrast, pastoralist research tends to be compartmentalized, failing to inform decision making in external interventions and national policies. Both scholars and practitioners have repeatedly pointed to the lack of comprehensive SES understanding as an underlying cause (5, 48) of current pastoralist crises.

Advances in both sustainability science and practice will require transcending disciplinary boundaries (49). This need is particularly important for strongly coupled SES – not because such systems would be particularly vulnerable or less resilient, but rather because connections between their elements and unexpected reactions due to non-linearities may make them more difficult to manage or understand. In these systems small changes in one factor such as a change in livestock prices, land tenure, access to markets or a drought event (fast variables), can cause abrupt, cascading effects at different nested system scales resulting in system-wide reorganizations (34), displaying consequences in apparently unrelated factors. Changes in slower variables, such as land degradation (50) or shrub encroachment (51), can also determine systemic changes. As the inter-relations between people and ecosystems change in scope and intensity, with globalization increasing the scales at which interactions occur, understanding the dynamics of SES through integrated approaches is needed to foster sustainable development (52).



Social patterns explained through environmental-economic perspectives

The cattle complex is often understood as a group of traits of socio-cultural origin and oftentimes dysfunctional or irrational. However, an environmental and/or economic perspective brings understanding to the functional value of these choices. For example, long-horn cattle, first thought of as of low productivity, have a necessary trait to facilitate heat dispersal in tropical environments (177). Similarly, the accumulation of cattle before a drought, can be better understood as a strategy to maximize the chances to rebuild the herd after the stress time (178).



Environmental patterns explained through economic perspectives

Overgrazing is an overarching concept routinely attributed to pastoralist practices, implying that grazing practices lead to degradation. Suspected factors are the use of livestock species that are ill-suited to local conditions, or climatic changes that force shifts in plant communities and increase the sensitivity to grazing. Evidence from Northern Africa (179), the Middle East (180) and reindeer-grazed lichen rangelands in Scandinavia (181) indicate, however, that fodder provision policies are probably behind many land degradation events by supporting herd sizes beyond sustainable numbers.



Economic patterns complemented by environmental perspectives

Life-cycle analysis of intensive vs. extensive livestock keeping indicates high greenhouse gas emission impact per product unit of the latter, but such economic evaluation does not consider many valuable ecosystem services that pastoralists are known to provide to society. However, greenhouse gas impacts are greatly balanced by the wide array of environmental benefits provided by the extensive system (182). Additional biological effects such as the lower albedo from forests also nuance life-cycle analysis considerations (183, 184).

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Although growing interest in SES has increased collaboration across disciplines, and between science and society in general (53), this progress is not yet well reflected in the science and policy on pastoralism (5). Admittedly, the degree of integration of the economic, social and environmental dimensions has been growing in pastoralism research (54–56). Yet, the focus remains, at most, on a

reduced number of interactions ('environmental \times economic', 'economic \times social', etc., e.g. Figure 2). Such limited integration has led to economic and environmental misconceptions that still permeate policy-making (1, 4, 17–21). A more integrated study of pastoralism will greatly improve our understanding of past transitions as well as ease the path towards achieving sustainability goals.

In this perspective we show how moving towards a more holistic, transdisciplinary (Box 1) and global understanding of pastoralism will support the 2030 Agenda for Sustainable Development (14). We refer to similar transitions brought about by Farming System Research to agricultural development (57, 58). Arising as a response to reductionist views and unexpected negative trade-offs from modern interventions, the Farming Systems field recognized the need to become more integrative, systemic and comprehensive, as well as needing to account for multiple spatial and temporal scales, including historical developments and geographic traits. This led to a new paradigm in late 1970s characterized by interdisciplinarity, and even transdisciplinarity involving farmers in the research process (57, 59). In order to advance in this direction we endorse an approach that uses (i) evidence across the social, economic and environmental dimensions of sustainability, (ii) diverse geographic contexts and scales to capture emerging properties and allow for cross-system comparisons, and (iii) timescales from the distant past to the present, allowing for the analysis of trajectories of pastoralist societies. We believe that such a diachronic, multi-scale analysis will not only add to the science of pastoralism but will also reveal the shortcomings of different development and governance interventions (60, 61). Such analysis will help uncover novel and transformative approaches to sustainable futures, thus laying out potential pathways to help solve some of the problems pastoralist systems face today. We discuss the use of suitable sustainability indicators, adapted to pastoralist systems, that support the identification of metrics that are locally-based, but globally-relevant. Finally, we elaborate on why the elements listed above are critical and how a common approach can integrate them across different spatiotemporal scales.

2. CALL FOR COMPARATIVE STUDIES ACROSS TIME AND SPACE

Unsurprisingly, in pastoralism research the more comprehensive the interdisciplinary effort has been, the narrower the geographical extent at which pastoralism has been studied. Despite some integrative works (56, 62–65), uncoordinated efforts have resulted in isolated, local or single-system studies that limit synthesis and generalizations across pastoralist systems. Such gaps have hampered transferability of policies, practices and lessons between systems and cultural contexts.

Examining geographical gradients and contexts

The geographic context of pastoralism is often characterized by the intersection of multiple environmental and social gradients. These typically include *productivity gradients* within a given pastoralist system, with limiting climatic factors that are optimally and dynamically exploited across seasons (15). Examples include the optimal use of pastures in Spanish (66) or Sahelian (67, 68) transhumance corridors extending over 1000km, the strategies to exploit patchy and ephemeral dryland resources among Fulani herders (15, 68) or the management of reindeer herd movement to avoid seasonally parasite-infested areas (69). Examples are also available for *aridity-humidity gradients* overlaying with distance to markets or population density, shaping *center-periphery gradients* in Eastern African pastoralist systems (70). Such heterogeneity comes with differing development challenges and calls for adaptation of policies to local contexts.

Similarly, different political, economic and cultural contexts may reveal differences in pastoralist adaptations under otherwise similar ecological conditions and explain large-scale land-use changes driving pastoral ecosystems to collapse. An example of this is the differing influence in the Serengeti-

Mara ecosystem surroundings exerted by the contrasting open vs. state-controlled economies of Kenya and Tanzania, respectively, causing much wider land use change and fragmentation in Kenya (71). Conversely, a less open economic and political system in China's Inner Mongolia Autonomous Region, where less space is given to traditional land management than in Mongolia, exemplifies drivers of land degradation (72-74). In the same line, cultural contrasts and modernization events with differential diffusion across communities have uneven consequences, well-illustrated by the penetration of firearms from conflict areas in Sudan that put at a disadvantage those accessing guns later (75).

Thus, in order to synthesize relevant patterns and processes across systems, pastoralism research should start embracing such multidimensional variability, along with its geographical variation (*gradients*). Research designed to cover variability in multiple factors will allow us to (i) better separate or identify drivers of change and (ii) better understand system dynamics, nonlinearities and the potential for successful interventions. The former is particularly relevant for central and debated topics in pastoralism research, such as rangeland degradation. Traditional grazing management, i.e. management by indigenous or traditional pastoralists, has often been seen as the driver of rangeland degradation, even if governance/management factors like regulation of use or botanical knowledge and non-equilibrium ecological dynamics show that traditional management has a neutral or beneficial effect on rangeland conditions (1, 76, 77). This misunderstanding of traditional practices has resulted in policies that encourage or mandate sedentarisation and land privatization under the pretext that mobile pastoralists have mismanaged and overstocked rangelands (78, 79). Only if we measure covariates (social, environmental and economic dimensions) over gradients or contexts, will we be able to identify the slow and fast variables at different scales that affect resilience. Such gradients, covering variability for the relevant domains, will often require comparing apparently disparate systems from across the world (see Fig. 1), in order to further our understanding of roles of governance, development, and market access, among other factors, on a number of processes in pastoralist systems. Such analyses can encompass such diverse systems as cattle herders in Switzerland, horse pastoralists in Mongolia and sheep herders in Algeria. In other cases, or for particular questions, sufficient variability will be found at smaller spatial scales, regionally or nationally.

Understanding the importance of scale

Noteworthy is also the integration across scales. Pastoralism has been described as a complex system characterized by fractal properties: properties or behaviors that are self-similar at different spatial or temporal scales. This applies both to territorial (66) and socio-economic domains (80). The concept of “nutag” (homeland) in Mongolia by which herders interchangeably refer to their grazing territory, province or country depending on where they are (81), or clan-related proverbs in the Horn of Africa and Middle East, e.g., *I and Somalia against the world; I and my clan against Somalia; I and my family against the clan; I and my brother against the family; I against my brother* (82) provide simple examples of social scalability. Such properties allow systems to scale up or scale down quickly in response to perturbations. Recognizing the properties of such systems is important for understanding escalating responses (e.g., violence, herd or people movements). Management options or interventions should therefore take advantage of such self-organized nestedness as a source of resilience, because disrupting it, either unintentionally or deliberately by e.g., bringing alternative, top-down imposed schemes, may also impair adaptation strategies and lead to undesired states as, for example, poverty traps (83, 84). This is because the components of the nested social organization are flexible and contingent on the issues or perturbations that affect the functioning of the SES. This flexibility is necessary because many pastoral systems are in harsh and highly variable regions (see definition of pastoral systems in Fig. 1). When systems of management become rigid in any single

scale (as in sedentarization), pastoralism can become vulnerable and therefore fall into poverty unless inputs into the system increase (e.g., alternative livelihoods). Yet, these scaling properties are rarely recognized, let alone studied formally. To advance understanding of these dynamics, we suggest developing comparative studies across time, geographic and socio-political contexts and over multiple scales in time and space. There are examples where common factors examined in separate studies can be integrated. This is the case for geographically explicit factors that condition the practice of pastoralism in environmental and socioeconomic terms, both at the local Southern Ethiopian scale (85) and at the regional East African one (70).

Temporal depth is key to advance understanding

A more comprehensive understanding of the past may help identify and prepare pastoralists for ongoing crises and critical tipping points, even though environmental drivers may have become less determinant in the present than they were in the past, and socio-economic drivers have potentially gained relative importance (86, 87). Accessing data from the past is challenging, however, and more so the farther back in time we look. Consequently, most of the integration has concentrated on the recent past (66, 88–91). Conversely, the long-written history of pastoralism and the abundance of archaeological records allow for integration along longer time periods. Since its emergence in Western Asia, at around 10 500 BP for goats (ca. 500 yr later for cattle), the development of pastoralism has been a process that involved both social and environmental drivers and varied from region to region (92–99). In Africa and Eurasia, the development of pastoralism was connected to increased variability in rainfall (99–101) but also to socio-economic dynamics. The repeated emergence of pastoralist societies and their shared attributes today is arguably associated with pastoralism being an optimal strategy adapted to harsh and uncertain environments (102). Yet, pastoral societies have undergone several important transitions, with small societies growing in number and complexity up to empires (103–105) followed by crises or collapses (106). Comprehensive understanding of past major transitions is still meager at best, with many crises attributed to environmental drivers due to a lack of consideration of social, political and economic perspectives (90). Modelling of complex systems based on archeological evidence that study pastoralist settings offer very promising results (107). Along these lines, an important remaining archaeological question is whether pastoralism developed as local adaptation within extensive agropastoral communities, or separately as mobile pastoralism (93–95, 108, 109). The past is therefore interesting by itself, with relevant archaeological questions, such as the origin of pastoralism. However, the past is also relevant to understand the present, since it can be connected to current processes through comparative transitions, whose study is possible thanks to improvements in technology, data and interdisciplinary analysis.

3. INTEGRATIVE KNOWLEDGE MANAGEMENT METHODS TOWARDS A SOLUTION

Exploring pastoralism transitions

We propose a comparative research approach based on aligning the trajectories of diverse pastoralist systems through history, which allows the inclusion of all the key elements described above. This approach is motivated by the recurrent pattern of decline and recovery observed for most pastoralist systems, whether measured as economic or environmental decays. For instance, land degradation pulses followed by recovery have been observed in Australia (110) and Mediterranean Europe (111); income reduction caused by high human population growth reverts after countries reach a demographic transition, when pastoralists achieve secure income and specialization in high-value niche markets (112–114). Some downturns, however, lead to system collapse. This has been the case in Southern Finland, for example, where intensive meat production completely displaced traditional

extensive practices, and associated High Nature Value habitats have consequently become the most threatened in the country (115). We build on the qualitative similarities of these trajectories and theorize that if thresholds or tipping points could be identified through systematic empirical data collection and analysis, interventions could be undertaken to prevent collapses or accelerate recoveries across all domains.

We find that the development of Kuznets curves and related theories (116) serves as a useful analogy in this regard. These curves were born as a graphic description of the process where nations undergoing industrialization first see their economic inequality increase, and later decrease. The use of the curve has been extended to diverse economic indicators against time – suitable for exploring trajectories of single systems/nations (117, 118) – or against development metrics or indicators of economic growth – used either to explore the evolution of a system or to compare across systems (119). Perhaps more influential have been extensions that focus on environmental degradation (116), suggesting that environmental quality first decreases and then starts recovering at certain levels of development, industrialization and/or environmental awareness of the population. While some empirical evidence gives support to the shape of the curve, its generalization has been debated (120), working better for some indicators than for others. We do not claim that pastoralism transitions follow a particular U-shape curve, but propose compiling empirical data and exploring patterns in a similar way along an x axis that indicates time or development. We believe the concept is useful for comparing disparate pastoralist systems that are undergoing transitions and are at different development stages. Indeed, we find some examples where pastoralism has been used in the representation of such curves (121).

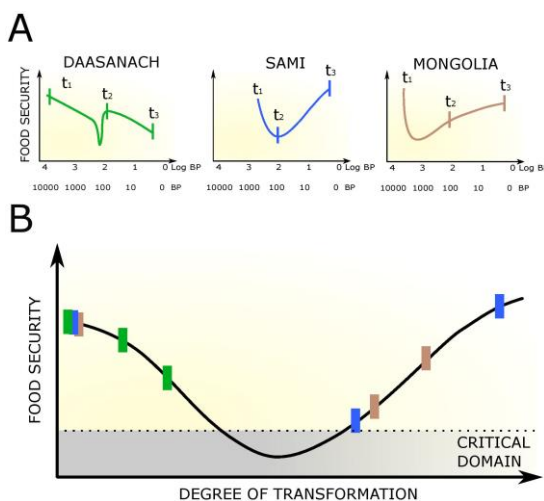
If we take overall pastoralism in the Sahara as a specific case, where efficiency of rangeland use is the metric of focus, we would observe a decline, followed by a long hiatus and a more recent recovery. The decline can be explained by the climatic trends leading to the Saharan desiccation (122). Yet, the recovery has not happened because of the climatic trend reverting, but rather because technological developments (e.g., truck transportation) have allowed pastoralists to access and graze short-lived pastures again (123). We are able to observe the decline-recovery dynamic described by Kuznets U-shape curve once we integrate elements from archaeology and modern agronomy. Few are the cases for which we have such an understanding, and Fig. 2 offers examples of the shortcomings derived from trying to understand pastoral systems without integrating information of several dimensions.

In Box 2 we illustrate the application of this approach to three different pastoralist systems and for longer time frames, based on qualitative interpretations. In the example, we draw on how the Goal 2, Zero Hunger, from the Sustainable Development Goals (14) evolves along time to measure one aspect of sustainability, using food security as a specific metric/indicator. Comparison of food security aspects in the distant past and in the present is challenging, as it is for other variables, because of limited data availability or quality for past indicators (Fig. 3; see also section on indicators below). Osteoarcheological studies (124) and new developments around palaeodemography (125) promise feasible comparisons. This conceptual exercise exemplified in Box 2 should be understood as a proposition for future exploratory research, where the Y axis should preferably include diverse quantifiable indicators across sustainability domains (see next section). We also show in Box 2 how one can similarly explore trajectories for single pastoralist systems through time (e.g. Pastoralism in Mongolia; Box Fig. A), or combine disparate pastoralist societies (East Africa, Central Asia, Arctic; Box Fig. B) in a single curve and at different points in time using an appropriate X-axis. The metrics we plot here on the Y-axis indicate that a system may move from a situation of high sustainability (e.g., high food security) and down to levels that approach sustainability limits when crossing critical domains. From those critical domains, the system may either collapse or recover as in the panarchy adaptive cycle (41). Such critical domains could be determined empirically through the comparisons

of multiple systems, and considering sustainability indicators pertaining to different dimensions. Note that when mapping different pastoralist systems along the same curve, we may observe responses at slower or faster paces. The pace of change is likely related to the slow and fast variables that affect where they are on the adaptive cycle (41), such as the placement of pastoralist societies along political or economic gradients of centrality-periphery. Pace of change can also correlate with the degree of cultural exchange, the innovations incorporated and also with how they enter into critical pitfalls or exit from them, with differing investments to conserve environmental, social or cultural elements. Such representations allow us to add temporal depth and compare trajectories looking for common patterns in transitions across systems. The drivers of major inflection points may be particular and revealed only when simultaneously studying connections with variables in multiple domains. Transferability of policies and management measures from the right-hand side of the curve to the left side should be encouraged, allowing tunneling through critical domains while avoiding points of no return (126).

Box 2

In a qualitative, exploratory exercise, we compare the trajectories of food security among three pastoralist societies in Eastern Africa (Daasanach), Central Asia (Mongolian) and the Arctic (Sami). The Daasanach's past in the area has experienced no major tipping point and their food security is increasingly threatened by a growing population (185), evolving from biodiverse, sustainably managed landscapes that the European explorers encountered in the 19th century (186) – it could be therefore described as having a “slow pace” of transition framed in a periphery situation. Mongolian pastoralists show a tipping point just before the expansion of the Mongolian Empire (103, 187): restrictions by the neighboring Chinese Empire were overcome through extraordinary good production years that would have triggered the dispersal of the population across Eurasia, initiating a phase of improvement in food security later prolonged by technological improvements – a “moderate pace” of transition. Sami reindeer herders would have evolved from a relatively rapidly deteriorating situation in the few last few centuries, coinciding with colonization and political marginalization (188, 189), to a very rapid transition that led them to adopt wellbeing standards of developed economies. This shows a “rapid pace” of transition that is a consequence of their placement close to the global centrality area of Northern Europe. Such differential paces and their outcomes point to the potential of differential transition paces to avoid collapse and shift out of the critical zone, or not. Moreover, the probability of a whole livelihood to collapse would be related to the livelihood's sector in crisis and its capacity to affect all other sectors.



Box figure. Dynamics and comparability of different pastoralist systems.

(A) Historical trajectories of food security domain for three different pastoralist systems plotted against the log of years before present (BP); Daasanach from northern Kenya/southern Ethiopia, Sami reindeer herders from Fennoscandia, and herders from Mongolia. Crashes such as the one observed for Pleuropneumonia and Rinderpest in the Daasanach curve would be present in all pastoralist systems but are diluted in the general trend of the curve. (B) Properties from different pastoralist systems at various times can be mapped along a standardized measure of degree transformation of the livelihood (see text). Pastoralist systems entering into the critical domain are prone to collapse.

We insist that the approach illustrated by Box 2 should not be limited to one indicator in a single domain (“food security” in the figure) but instead explore transformations in all domains, and their interactions. But to move forward, from the qualitative conceptualization presented to empirically based theories of pastoralism, requires first the development of a relevant set of sustainability indicators. We also need a better characterization of such measurable indicators as descriptors of slow and fast variables in different domains.

Sustainability indicators for pastoralism research and policy development

The research approach just discussed is not only useful to explore past transitions. Some of the key metrics used to identify accumulating slow variables, critical fast variables, important transitions and tipping points of past pastoralist trajectories can, similarly, be used to monitor current pastoralism sustainability and suggest paths for improving it in the future. Thus, sustainability goals can also be used to guide the selection of these metrics within the framework of social ecological system resilience. In this context, a number of general guidelines and indicator frameworks have been developed – e.g., Bellagio Principles (127), Sustainable Development Goals (128, 129) or the IPBES Conceptual Framework (130). Some review works extensively discuss the strengths and weaknesses of diverse sustainability indicators (131–135), providing advice on how to choose the right metrics, particularly for decision-making and policy implementation.

Yet, all around the world, pastoralism is often subject to pre-determined monitoring schemes and reporting indicators that are often externally codified, and that may not support the visions, goals and needs of pastoral communities. Moreover, indicators developed without community participation often overlook, misrepresent or discount the knowledge systems and values that underpin the connections between pastoral communities and their ecosystems (136, 137). For instance, development of these indicators have overlooked the particular characteristics of pastoralist systems (see below); hence, their suitability for capturing the vulnerabilities of these systems requires examination. As a first step we (i) summarize as a starting point, important characteristics of pastoralism that could be reflected in sustainability indicators, (ii) elaborate on the desired dual role of the indicators (i.e., to gain long-term system understanding and to advance policy implementation and evaluation) and their validity across temporal and spatial scales, (iii) identify available data sources or transferability of indicators across disciplines, and (iv) present a set of methods to put pastoralists at the center of the process of indicator development.

Considerable indicator work has been conducted for livestock production systems, but either for intensive livestock farms or for particular regions (133, 138, 139). The shift in focus we call for here highlights the need to consider pastoralism characteristics such as mobility dependence, common-pool resources, low-input/low-output processes and coexistence with natural or semi-natural values (see definition of pastoralism in Fig. 1). We stress that relevant indicators should thus capture changes in these characteristics in addition to other indicators identified as relevant for strongly linked social-ecological systems. The effort made by the Sustainable Rangeland Roundtable provides a good starting point with 64 potential indicators selected for rangeland systems (138). Some of the listed indicators map well the pastoralism characteristics mentioned above (e.g., indicators related to common access: *land tenure, land use, and ownership patterns by land size classes*; or indicators related to coexistence with nature: *population status and geographic range of rangeland-dependent species*), yet key indicators of mobility, and relevant indicators of resilient social structures are largely missing. Overall, environmental indicators identified to date are viewed as comprehensive or promising, whereas socio-cultural and economic indicators present more challenges, and are recognized as being in an earlier stage of development (138, 139). In fact, despite all the promising indicators identified, researchers call for (i) further development of particular indicator themes, (ii) a more manageable list of indicators that can better evaluate impacts and ease of data collection, and (iii) to empirically test interactions between indicators, within and between dimensions (139). The approach to explore trajectories presented here may offer this opportunity.

We have argued that a lack of a holistic system understanding is partially responsible for the pastoralism crises observed, and we have advocated for analyses at broader temporal scales, through

pre-history to present times. We contend that some sustainability indicators may also be suitable to explore past crises and find equivalents to recent or present ones (Fig. 3). We note that different proxies may be needed for different time periods. For example, indicators of food security that may reflect resilience of pastoral communities could be quantified through different measures of diet diversity, sourced from osteological composition from fossil bones for the past, from questionnaires, or participant observation in the present – all of these would be relevant to the example we present in Box 2. This will require careful consideration of paces of change (the slow and fast variables mentioned above) and choice of indicator units as well as adequate quantification of uncertainties. When possible, indicators should be measured with consistent methodologies through time. Indeed, some indicators often used in paleontological or archeological studies can be extended to infer and also compare present states – e.g., ecometrics (140–142). In particular, some relevant social and economic indicators will often be scarce for pre-history periods (such as indicators of erosion of traditional institutions, market access or market value) while others may only be important at present (e.g., incorporation of new technologies, or impact of international and national policies).

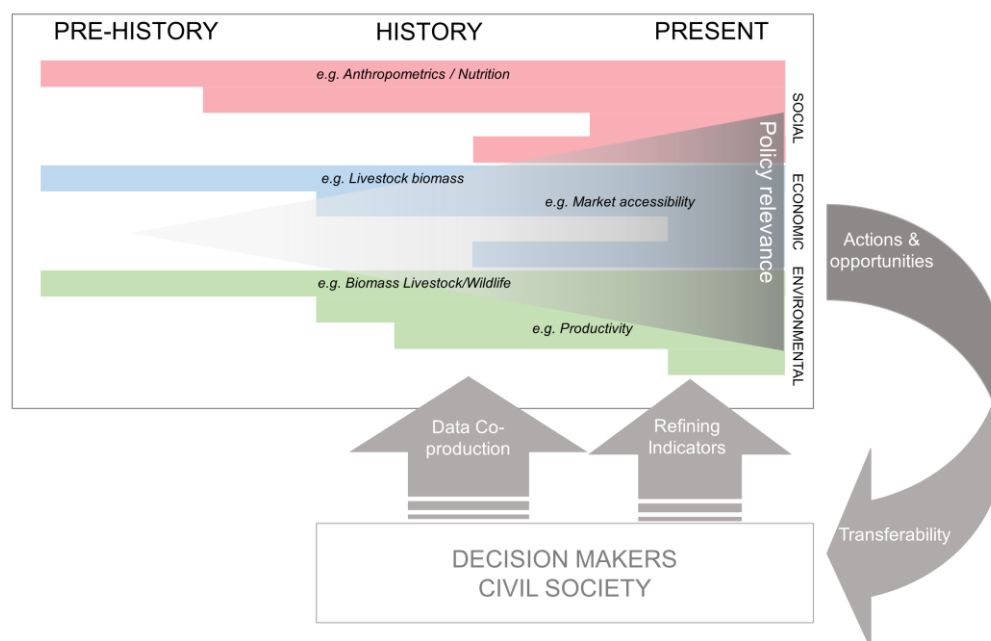


Figure 3. Model for developing pastoralism indicators that span across different time scales.

The graph shows potential indicators (color bars) for social, economic and environmental dimensions, with some indicators spanning across all periods of interest, while others are only available or relevant for more recent time periods. A few example indicators are suggested on some bars (cursive). While long-term indicators will favor large scale understanding of system dynamics, finer scale and recent times will be more relevant when monitoring management actions. The graph also depicts the involvement of decision-makers and civil society in the development of these metrics.

Importantly, indicators should be comparable for different geographical contexts and should not be susceptible to small differences in methods or measures across settings (e.g., follow developments of livestock grazing schemes such as the *livestock units* valid to compare across pastoralist systems (143) through space and time). We echo the calls for locally relevant yet globally applicable indicators, and when possible, consider interactions that link local to global sustainabilities in an increasingly interconnected or telecoupled world, noted as particularly important in the global livestock production system (144–146). Opportunely, valuable data are already available from multiple sources, yet with patchy distribution – thus requiring substantial efforts to complement such existing data.

To fill data gaps and identify indicators that are relevant for local community decision-making, it is paramount to work with pastoral communities within transdisciplinary, collaborative research settings that are co-designed and co-produced (147-149). Universalism in indicator development has often fallen short in recognizing culturally-grounded perspectives of sustainability (137), leading to calls for more active engagement of pastoral communities in research, in an effort to develop indicators that better reflect their needs, views and knowledge systems (136, 150). Here we propose taking advantage of participatory methods to support the identification of indicators that are culturally relevant and that provide legitimate knowledge-in-use for community decision-making. Such methods can take many different forms, including biocultural-oriented monitoring (137), models of continual engagement (136), knowledge co-production (151, 152), participatory action research (153) or a Multiple Evidence Base approach for connecting different knowledge systems (154), among many others. Endeavors in this vein can support the identification of metrics that are culturally appropriate and attuned to both local needs and global priorities. Finally, collaborative indicator development can serve a purpose in re-positioning pastoralists at the center of the research process itself (152), recognizing them not just as stakeholders, but also as knowledge- and rights holders (155). Given that many aspirationally participatory approaches perpetuate extractive dynamics with local communities, we urge researchers to carefully consider recommended guidelines for genuine engagement with Indigenous and pastoralist communities (156).

Indicator choice should not be carved in stone. Instead, paraphrasing Ostrom (157, 158), we need a multilevel, nested system of indicators, with both a set of variables relevant for studying a single SES, as well as a common set of variables that allows comparison among pastoral SES. The analytical framework presented here, the need to compare scales, and the need to integrate pastoralists' interests should steer the development of an indicator classification, and stimulate a global movement for collecting them. The IUBS-funded Global Integrative Pastoralism Program (159) and other initiatives from the League for Pastoral Peoples (160) or the International Livestock Research Institute (161) are following such steps and working to bridge these gaps, establishing databases that are likely to be reinforced with the possible declaration of an International Year of Rangelands and Pastoralists in 2026 (162).

4. WAY FORWARD

The understanding of trajectories in pastoralist societies, and the characterization of the factors that drive them through globally accepted indicators, should be used to find solutions by informing decision making at the macro-level (e.g., national policies). When applying our research approach, we propose it is possible to identify how external interventions interact with responses at the micro-level (pastoral undertakings; day to day local decisions), affecting this way the sustainability of the practice. To achieve this, we call for the integration of pastoral knowledge, interests, and values (163) in the indicator set through a co-production process (164, 165), as many solutions will actually arise from pastoralist communities themselves (61).

We acknowledge that our call for locally relevant metrics is sometimes in tension with the urgent need to develop globally comparable indicators. On the one hand, metrics capturing information in the same way regardless of place-based contexts often lack specificity (137). On the other, indicators developed at the local level are often difficult to upscale, given their place-based specificity. However, there are several mechanisms that allow for bridging the gap between local and global indicators (e.g., 166). In particular, there are different processes in which locally appropriate, yet globally applicable, indices have been developed, based on pre-defined broad domains that are comparable cross-culturally (i.e., indicator groupings), but based on locally-adapted and culturally-specific metrics and indicators (137, 167). Alternatively, indicator frameworks (158) also allow for

comparisons across indicator classes. Some of these approaches draw inspiration from middle range theories (i.e., generalizations that describe causal mechanisms within certain contextual bonds, see 168).

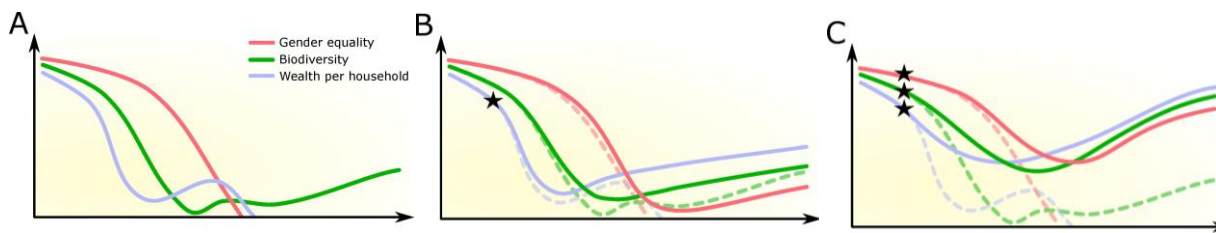


Figure 4. Evolution of indicators of sustainability domains under different policy/intervention scenarios. Graphs represent a selected social (red line), economic (blue line) and environmental (green line) factor as an example, related to the explanation in the main text. (A) System collapse dynamics driven by a fatal deterioration of social factors after a partial recovery of economic and environmental factors; (B) A well-guided single-domain intervention (e.g., on economics) can avoid the collapse vortex, yet it is not enough to successfully escape from low sustainability levels that can bring to future collapses or avoid the loss of some elements in each domain, such as species extinction or loss of cultural traits; (C) Early interventions that are simultaneous across all sustainability domains can avoid critical levels and facilitate the achievement of pastoralism's full potential.

The identification of solutions for pastoralism is inherently complex, not only because they are challenging to trace but also because the trajectories of the different sustainability domains are tightly interdependent. While progress can be observed e.g., in the trajectories of economic and environmental domains, deep shortcomings in the social domain can drive the whole system to collapse. An example of this would be the differential emigration of women (66). The loss of women's knowledge and capacities, as in, e.g., dairy production (169), renders generational continuity impossible (Fig. 4a). Conversely, while well-directed early action in one single domain could avert total collapse, approaching tipping points that are dangerously close to collapse would erode existing knowledge. For instance women's emigration may not reach the level of system collapse, but may be high enough to affect women-associated dairy processing knowledge, such as the elaboration of cheese varieties whose sale can boost the pastoralist economy. Such unsatisfactory social outcomes would negatively impact the future economic and environmental outcomes of the livelihood, even if total collapse is avoided (Fig. 4b). Other losses caused by approaching critically low sustainability levels include species extinctions in the environmental domain, or loss of culturally-adapted product consumption patterns in the economic domain. Only by understanding the need to act simultaneously across domains, early enough and through well-informed action, loss of knowledge, adaptation options and wasted economic development potential would be minimized (Fig. 4c).

To enable such identification of solutions, it is essential to establish global databases (preferably open access) that collect and avail data from a wide array of different pastoralist systems, and that turn such data into comparable, transferable indicators. The transdisciplinary and holistic nature of SES research should be extended to the solutions and implementation phase, where interventions nested in the different sustainability domains must be not only simultaneous but also coordinated. These phases should also include pastoralists from the systems targeted by the interventions. This includes adaptive co-management where users and resource managers, operating at different scales, can have the means to experiment, monitor, deliberate and reactively manage resources at the local level (170). It also includes adaptive governance, where the social dimensions associated with management and decision-making can be addressed (34).

In summary, we encourage an approach where: 1) sets of relevant indicators are compiled across scholars, practitioners and pastoralists globally; 2) the transferability of indicators across systems, temporal dimensions and scales is evaluated, and suitable standardizations applied; 3) their suitability to identify system transitions, especially tipping points, is assessed; and 4) the subset of indicators

found useful is collaboratively appraised and their use further promoted to monitor pastoralism sustainability both globally and locally, aiming at enhancing favorable policies across scales. We believe that the indicators developed through the proposed research approach may become better integrated into global science-policy interfaces and assessments, contributing to better recognize pastoralism in global environmental and economic forums or sustainability agendas. This will pave the way for producing better informed and more effective policies and interventions, which will ensure pastoralism resilience and sustainability in the long run.

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Author contributions: PM, MF, MC and NCS conceived the study; PM, DB, LC and MC developed the methodology, collected data, performed the analysis, prepared the visualization of data, wrote the initial draft, and administered the project; JTE, AF-L, SB, ØH, OS, MF, MEF-G, KAG and NCS revised and critically reviewed the draft; MC and NCS supervised the research; MF, MC and NCS acquired the funding.

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