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INNOVATIVE VIEWPOINT

Special Feature: Dynamic Deserts

Implementing a resilience-based management system in Mongolia's rangelands

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Abstract

A primary challenge in advancing sustainability in rangelands and drylands is the lack of governance systems that are linked to information about highly variable ecosystem conditions. Here, we describe the national-scale implementation of a resilience-based management system in the rangelands of Mongolia. The system comprises several interacting elements. Land type-specific information about rangeland conditions was captured in vegetation state-and-transition models (STMs) that allow interpretation of monitoring data and locally tailored restoration recommendations. Rangeland monitoring systems based on standardized protocols were developed and have been adopted by national government agencies, which provide annual, high-quality data on rangeland conditions on which to base and adjust management decisions. Rangeland use agreements between local governments and herders' collective organizations, called Pasture Users' Groups, define their respective rights and responsibilities and introduce economic and policy incentives for management changes. Pasture Users' Groups also provide a platform for information sharing and collective action. Rangeland condition data and other indicators are linked to the Responsible Nomads product traceability system that provides consumers and industry a means to associate products with sustainable rangeland management practices. The collaboration between national agencies, international donors, scientists, and herders has been essential to initial success, but longer term support and monitoring will be needed to assess whether the adoption of resilience-based management leads to positive social and ecological outcomes. We draw generalizations and lessons learned from this effort, which can lead to the successful implementation of new management systems across global rangelands.

KEYWORDS

community-based management, grazing, monitoring, natural resource management, rangeland health, Special Feature: Dynamic Deserts, traceability

INTRODUCTION

The development of strategies to transform social-ecological systems to guide them toward sustainable paths is the primary challenge of our time (Sachs et al., 2019). Successful strategies following the "leverage point" metaphor require pushing on "deep" system properties, including knowledge, perceptions, incentives, and social structures that govern human–environment interactions (Fischer & Riechers, 2019; Leventon et al., 2021; Scoones et al., 2020). Creating change in these deep properties involves the integration of multiple advances, including environmental monitoring systems that enable adaptive management, knowledge coproduction about how specific changes can be achieved, and new institutions and technologies that promote and sustain changes in the use of natural resources (Abson et al., 2017; Chambers et al., 2022; Fesenfeld et al., 2022; Montambault et al., 2015).

The urgency and challenges inherent in creating deep leverage for transformation are nowhere more apparent than in global rangelands. This urgency was recognized in 2022 with the designation of 2026 as the International Year of Rangelands and Pastoralists (IYRP) by the United Nations (Briske & Coppock, 2023). Rangeland is the dominant land type globally (International Livestock Research Institute, 2021), but rangeland-based livelihoods throughout the world are threatened by climate change, increasing demands on limited rangeland forage and water resources, and land use transitions to more intensive uses that reduce rangeland area (Bestelmeyer et al., 2015; Godde et al., 2020; Lark et al., 2015). Rangeland sustainability is also challenged by the perception that many rangeland agricultural systems are underutilized or degraded land, leading to under-investment and flawed management prescriptions that routinely undermine sustainability goals (Hoover et al., 2020; Sayre et al., 2013; Stafford-Smith, 2016). Strategies to sustain rangeland productivity, the multiple ecosystem services supported by rangelands, and pastoralist prosperity at regional to global scales are therefore fundamental to achieving global Sustainable Development Goals (Johnsen et al., 2019).

Although there are well-known rangeland management strategies to build resilience at the scale of individual properties (Holechek et al., 1995), strategies that can be applied at the scale of regions and countries are highly complex and not well developed in the Global South. This is especially true in situations where rangelands are common pool resources (Reid et al., 2014). Regional-to-national strategies need not only to address the sustainable management of rangeland resources but also to address monitoring and evaluation of rangeland ecosystems at broad spatial extents, how to balance multiple ecosystem services, animal welfare, governance, and marketing of products to reinforce sustainability goals.

In this paper, we describe the design, initial outcomes, and prospects for a new resilience-based management system developed for rangelands of Mongolia. Mongolia's rangelands are of global significance due to their intactness and preservation of nomadic pastoralist culture alongside biodiversity (Batsaikhan et al., 2014; Reid et al., 2008; Scholtz & Twidwell, 2022). The need for a new approach to sustaining rangeland livelihoods in Mongolia was precipitated by the breakdown of governing institutions subsequent to Mongolia's transition to democracy in the 1990s, which has been associated with progressive increases in livestock numbers, periodic livestock die-offs and associated hardships, and the perception of widespread rangeland degradation (Fernández-Giménez et al., 2017). Our contributions began with the establishment of the Green Gold Project in 2004, which was initiated in response to a weather-and-management–caused crisis known as "dzud" in 1999–2001 that caused severe, widespread animal mortality. The management system we developed to respond to this crisis is rooted in the concept of social-ecological resilience: to sustain productive and biodiverse rangeland ecosystems, and the pastoralist livelihoods that depend on them, in the face of extreme weather events and climate change.

The resilience-based management system involves the integration of several concepts and innovations from dryland and rangeland science, including (1) measurable science-based criteria for evaluating rangeland ecosystems; (2) a robust rangeland monitoring system within government agencies; (3) linking monitoring data to local participatory management activities, novel governance strategies, and incentives for rangeland management; and (4) using ecosystem monitoring data in product marketing. Together, these advances represent a transformation of rangeland management (Pereira et al., 2020) that is spreading across Mongolia and has the potential to be applied globally. Nonetheless, as in other rangelands (Stafford-Smith & Metternicht, 2021), significant challenges remain for sustaining and strengthening the institutions and processes that have been developed.

We briefly synthesize the state of knowledge about rangeland social-ecological systems in Mongolia and then describe a suite of tools that comprise "resilience-based management" (Bestelmeyer & Briske, 2012). These tools include (1) mixed precision rangeland monitoring systems; (2) livestock stocking rate recommendations, land classifications, and state-and-transition models (STMs) that link monitoring results to management actions; and (3) the use of monitoring data in rangeland governance involving "Pasture Users' Groups" (PUGs). We also discuss the potential for a raw materials traceability system linked to monitoring data to incentivize rangeland management activities. We conclude with the prospects for sustaining resilience-based management in Mongolia and generalizing resilience-based management systems to other rangelands throughout the world.

DRIVERS OF TRANSFORMATION IN MONGOLIA'S RANGELANDS

Although Mongolia's economy is expanding and diversifying, rangelands continue to be an important source of livelihood and national identity (Marin, 2008; Upton, 2010). Rangeland management, however, changed dramatically with the transition from socialism to a free-market economy. Prior to 1990, land and animals were state-owned and publicly used. Management was closely controlled via socialist livestock production collectives, including the number and type of animals, who herded them, and where they grazed throughout the year (Dorligsuren et al., 2012; Fernández-Giménez et al., 2017). Seasonal movements were used to take advantage of differences in annual plant growth and to allow for the maintenance and recovery of grazed plant species. Seasonal movements were carefully planned, supported by government, and locally enforced. Because forage limitations associated with droughts and severe winter weather (*dzuds*) are common, reserve pastures were maintained, and additional hay and fodder preparation were part of risk management plans. Transfer of animals or fodder among *soums* (districts similar to counties) during droughts or dzuds was coordinated by local and national governments. Natural disasters occurred, but animal numbers were more or less stable at a national level. Herders received regular salaries and extreme poverty was rare (Fernández-Giménez, 2002), reflecting social-ecological resilience.

After 1990, livestock were privatized but land continued to be owned by the state (Fernández-Giménez et al., 2017). Concurrently, the institutions responsible for livestock management and herder support dissolved and no new policies for rangeland management were established. Private ownership of livestock, economic incentives, and lack of regulation led to dramatic increases in livestock numbers at a national level. This increase has been associated with equally dramatic livestock declines during severe dzuds, which were not apparent in the earlier era. Lack of coordination of animal movements among herder families, consequent overstocking and depletion of forage, and lack of fodder preparation contributed to animal mortality (Fernández-Giménez et al., 2012; Middleton et al., 2015). The lack of management of animal numbers and grazing periods also underpin the widespread perception of severe rangeland degradation in portions of Mongolia, from both researchers and from herders themselves (Bruegger et al., 2014; Eckert et al., 2015; Kakinuma et al., 2008; Khishigbayar et al., 2015; Sankey et al., 2009), which has been amplified and sensationalized by the global media. Nonetheless, there is high uncertainty about the extent and nature of rangeland degradation. Degradation estimates span 9%–90% of rangeland area, and the degree to which degradation is reversible with changes in grazing management has been debated (Addison et al., 2012; Jamsranjav et al., 2018). Rangeland degradation attributable to livestock grazing is compounded by (or directly caused by) long-term trends in regional aridification and loss of surface water sources associated with climate change (Pederson et al., 2014; Tao et al., 2015). The period from 2000 to 2009 was estimated to be one of the driest periods on the Mongolian plateau in the past 2000 years (Lu et al., 2019). Overall, the progressive loss of rangeland productivity (Eckert et al., 2015; Hilker et al., 2014; Nandintsetseg et al., 2021) is viewed as an imminent threat to the sustainability of Mongolia's rangeland social-ecological systems (Fernández-Giménez et al., 2017).

In response to concerns about rangeland and pastoral sustainability, the government of Mongolia sought to develop a new monitoring and management/governance strategy for Mongolia's rangelands (National Agency for Meteorology and Environmental Monitoring and Ministry of Environment, 2015). Specifically, the government sought clarity on the nature of rangeland degradation and to employ that knowledge, in conjunction with community-based rangeland management institutions (Ulambayar et al., 2017), to improve rangeland conditions and herder livelihoods.

MONITORING AND ASSESSMENT TOOLS

Rangeland monitoring

Unified, repeatable methods to evaluate ecosystem health that are linked to restoration strategies are fundamental to environmental stewardship but have seldom been adequately developed and sustained (Lindenmayer & Likens, 2010; McCord & Pilliod, 2022). Two "core" methods and an associated database structure for the monitoring of vegetation and soil health (Courtright & Van Zee, 2011; Herrick et al., 2017) were introduced by the U.S. Department of Agriculture staff and formally adopted by the Mongolian government in 2011. Core methods include line point intercept to estimate ground and foliar cover, with plant identification to the species level, and measurement of basal gaps (measuring changes in unvegetated gaps that relate to soil erosion). The methods were then trained by Green Gold staff to over 700 existing technicians of the National Agency for Meteorology and Environmental Monitoring (NAMEM). Government technicians have been supported by local communities since the socialist era and provide a fortuitous, critical infrastructure for management activities. These technicians carried out rangeland vegetation measurements at >1500 locations annually using the standard methods beginning in 2012 as part of the national monitoring program. The monitoring data are now used by the Mongolian government and designated partners to generate periodic national reports on rangeland conditions across Mongolia (Densambuu, Sainnemekh, et al., 2018; National Agency for Meteorology and Environmental Monitoring and Ministry of Environment, 2015). These reports generated significant media coverage and have highlighted that while a majority of Mongolian rangelands have experienced alteration from reference conditions and that persistent degradation is possible, the notion that widespread, persistent rangeland collapse has already occurred (which has been highlighted in Western media) was not supported (and see Jamsranjav et al., 2018). That most Mongolian rangelands have not "crossed the irreversibility threshold" and are ultimately capable of being restored (or are already functioning to their ecological potential) has been critical for motivating efforts to improve rangeland management, rather than giving up on a lost cause (Bestelmeyer, 2006). The belief in natural restoration with changes to management is also reflected in a recent assessment of local knowledge (Gantuya et al., 2021).

The national monitoring effort of NAMEM provides highly precise data suitable for interpreting long-term trends in vegetation cover and species composition. The density of observations, however, is not sufficient for management decisions at local (community, pasture) levels, and adding more high-intensity monitoring plots was infeasible given agency staffing levels and the time needed. Thus, a photopoint monitoring method (Booth & Cox, 2008) was developed to provide information on the cover of plant functional groups that is adequate for the identification of discrete classes of ecological conditions called "ecological states" (see below; Appendix S1). This method is simpler to implement and requires less training than monitoring methods used by NAMEM. The Agency for Land Administration, Geodesy and Cartography (ALAGAC) adopted this method and implemented it nationally as a basis for informing soum- and community-level grazing management decisions. Unlike the core methods monitoring carried out by NAMEM, herders are involved in the ALAGAC photo-monitoring program by assisting with site selection of plots placed in each seasonal pasture and are involved in interpreting annual monitoring data (see below).

Defining livestock carrying capacity

The lack of a consistent method for calculating livestock carrying capacity has been a primary source of confusion that leads to contrasting perceptions of "overstocking." We sought to establish a unified method that was (1) acceptable to land managers and herders and (2) tailored to different ecological regions and seasonal pasture types (Appendix S2). While the concept of carrying capacity is controversial (Sayre, 2008), and seasonal and interannual flexibility is paramount, we defined a sustainable or resilient livestock carrying capacity as the maximum stocking rate that should maintain or improve vegetation or related resources (Holechek et al., 1995). Carrying capacities serve as a reference point for stocking decisions, rather than a prescription. Calculation of a sustainable carrying capacity (used for general grazing guidelines) and location- and time-specific stocking rates (used for season-to-season grazing adjustments) should account for (1) forage utilization levels that leave sufficient biomass to maintain desired plant communities; (2) adjustments to utilization levels and the timing of grazing or rest needed to promote the recovery of key plant species; and (3) realistic estimates of actual utilization that account for forage loss to trampling, decomposition, and other herbivores. Harvest efficiency, the percentage of total plant production that is ingested by the animal, is a core criterion for sustainable carrying capacities and stocking rates (Smart et al., 2010). We initially proposed the use of a 30% harvest efficiency to achieve a utilization level (50%–60%) that is broadly recommended to maintain rangeland health (USDA Natural Resources Conservation Service, 2003) and specifically recommended for steppes in Inner Mongolia, China (Liang et al., 2002; Wang et al., 2011). This proposal was not widely accepted for a variety of reasons, including the belief that livestock directly consume ca. 50%–55% of available forage biomass and that harvest efficiency is very high in Mongolia. Consequently, a working group of government agencies adopted a set of ecological region and season-specific utilization coefficients (Appendix S2: Table S1) that may or may not be sustainable yet provide a critical benchmark against which to develop broadly accepted evaluations of forage balance needed to guide management. Importantly, forage demand in many areas often exceeded these generous forage allocations (Fernández-Giménez et al., 2017; National Agency for Meteorology and Environmental Monitoring and Ministry of Environment, 2015).

Land classification, STMs, and recovery classes

Land classification and STMs were developed as tools to interpret monitoring data and define operational thresholds indicating that shifts in management approaches are needed (Biggs & Rogers, 2003). Multi-temporal and grazing gradient sampling clearly indicate that Mongolian rangelands can undergo significant state transitions in vegetation (Jamiyansharav et al., 2018; Jamsranjav et al., 2018; Khishigbayar et al., 2015; Sasaki et al., 2011). STMs use a combination of narrative descriptions, quantitative vegetation cover estimates, and diagrams to describe alternative vegetation states, thresholds and transitions, and proactive and restorative management responses considering possible transitions (Bestelmeyer et al., 2017). STMs are developed for land areas featuring uniform potential production, known as "ecological sites" or groups of ecological sites that have similar management characteristics called "ecological site groups" (Bestelmeyer et al., 2016). Ecological sites/groups are nested within areas of uniform climate (i.e., eco-zones in Mongolia) and are distinguished based on landforms, soil profile characteristics, and potential vegetation.

Ecological site groups and STMs were developed using a combination of interviews with experienced herders, environmental and animal production technicians, botanists, and academics alongside literature review and vegetation-soil sampling across Mongolia. A catalog of 22 STMs was developed for all land areas of Mongolia (Densambuu, Indree, et al., 2018), including quantitative criteria to distinguish states, estimated forage biomass production for each state (based on the biomass sampling described above), and estimated livestock carrying capacity based on calculations described earlier (Figure 1). In general, STMs posit that rangeland degradation in Mongolia involves a sequence involving (1) reduction of perennial grasses (most often *Stipa*, *Poa*, and *Festuca*) associated with reduced productivity; (2) increasing relative dominance by upland sedges (*Carex*), subshrubs (*Artemisia*), or annual plants, often associated with sparse overall vegetation cover; (3) persistent transitions indicated by the near absence of formerly dominant grass species and extreme dominance by *Carex* and *Artemisia*; and (4) on vulnerable soils, severe soil erosion and dramatic loss of plant productivity (Jamsranjav et al., 2018).

The ecological state of each STM was categorized to a "recovery class" (Box 1). The recovery class hypothesizes timelines to recovery of a healthy "reference" state based on current vegetation cover/composition and assuming a change in grazing management that is STM-specific. Recovery class designations were based largely on expert knowledge and existing research studies when available. Our goal in defining rangeland condition in this way was to focus on positive actions to restore rangelands rather than the pejorative "degradation." For example, while low perennial grass cover may indicate that vegetation degradation has occurred, the presence of remnant perennial grasses suggests that recovery can occur in several years with grazing management. The recovery classes allow standardized interpretations of monitoring data across multiple STMs to facilitate reporting and visualization of rangeland restoration needs (Figure 2). In other words, the vegetation cover criteria for defining what is recovery class I (reference conditions) differ between a meadow steppe and a desert grassland site, but the *interpretations* of monitoring data can be combined into a single map to simplify communication. Grazing management strategies are linked to each recovery class, which serve as starting points for community grazing management decisions at the soum and PUG levels. We recognize that there are simply not enough site-specific, long-term data to confidently predict plant community responses to changes in grazing management, but the recovery classes offer initial hypotheses that can be tested and revised via adaptive management (Rumpff et al., 2011).

GOVERNANCE AND MANAGEMENT

Organizations and policies

Community-based natural resource management (CBNRM) can be effective in promoting adaptive capacity in the face of extreme weather events and in promoting the use of information and innovative rangeland management practices (Fernández-Giménez et al., 2015; Ulambayar & Fernández-Giménez, 2019). The resilience-based management system centers on a form of CBNRM involving PUGs and local governments (Figure 3). PUGs consist of multiple herder families that have traditionally used a particular territory and that have been allocated the exclusive right to manage their rangeland, at least under nonemergency weather conditions (Dorligsuren et al., 2012; Fernández-Giménez et al., 2012). PUGs are nested within soums that develop participatory annual rangeland use plans with multiple PUGs. Representatives of national government agencies work at the soum level to provide PUGs and local governments with monitoring information, estimates of vegetation biomass as a basis for stocking rate adjustments, maps, and support of assessment and management

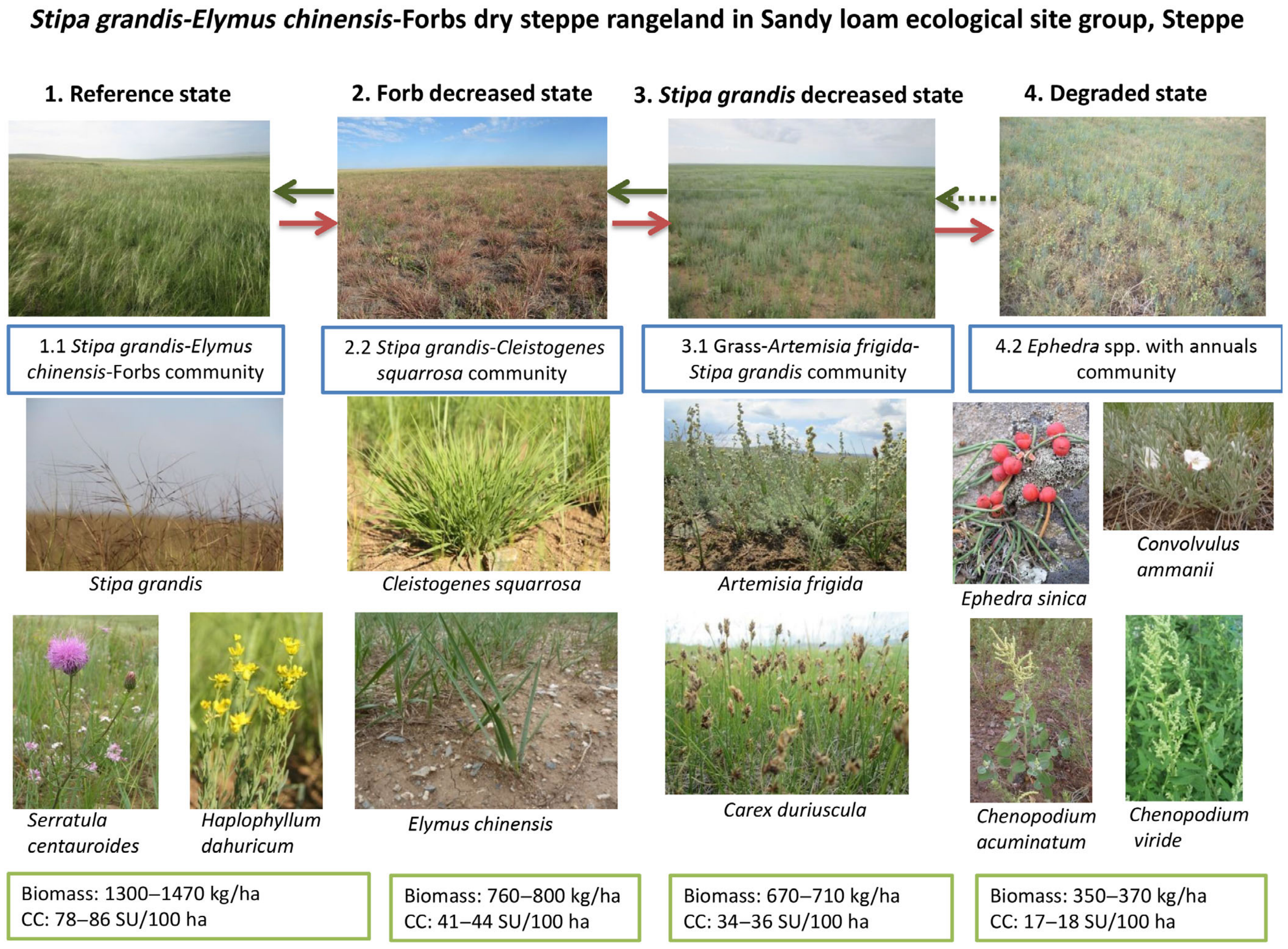

FIGURE 1 An example of a state-and-transition model for sandy loam alluvial fan soils in the dry steppe of central-eastern Mongolia, from Densambuu, Indree, et al. (2018). Red arrows represent undesired transitions and dark green arrows indicate restoration; the dashed arrow indicates restoration from the degraded state may be limited. Key plant species are shown for each state. At bottom, estimated aboveground plant biomass yield and resilient carrying capacity (CC; the number of Mongolian sheep units [SU] that can be grazed to maintain or improve plant community composition) are displayed. Tables associated with these diagrams contain more information about each state and transitions.

strategies via STMs and consensus about rangeland conditions.

The primary policy tool for rangeland restoration is the voluntary "rangeland use agreement" (RUA) between local government and PUGs. The RUA creates a platform on which herders and local government negotiate and agree on seasonal grazing boundaries, livestock stocking rates, and herd age structure and composition based on the ecological state of an area and current herd structure. The RUA is the basis for developing annual grazing and herd management plans, establishing the roles and responsibilities of herders and local government, as well as enforcement mechanisms. RUAs are being established at two levels. First-level agreements are between PUGs and local government that regulate seasonal grazing movements of PUG members. Second-level agreements are between small herder groups within PUGs and local government that regulate stocking rates and herd management needed to attain rangeland health goals. Experience indicates that smaller herder groups are better able to reach agreement on and enforce stocking rate adjustments than the larger PUGs. Second-level agreements are developed after first-level agreements are mature and enforced.

Over time, RUAs are expected to reduce stocking rates and alter herd age structure via the offtake of old and unproductive animals. Where possible, RUAs have encouraged diversification of herd composition by increasing cattle to develop meat export markets (e.g., in Dornod, Sukhbaatar, and Khentii aimags of the eastern region of Mongolia). In addition to long-term improvements to rangelands and income streams, some RUAs

BOX 1 Current working definitions of recovery classes used by the Mongolian government

Class I: The plant community is at or near reference conditions or requires 1–3 growing seasons for recovery from minor changes; match stocking rate to forage supply and use temporary seasonal deferment as needed.

Class II: The plant community is altered and may be rapidly recovered (3–5 growing seasons) with favorable climatic conditions or a change in management (e.g., stocking rate reduction, seasonal deferment, and rotation). The nature of alteration is not regarded as a significant long-term threat to the provision of forage and other ecosystem services.

Class III: The plant community is altered and may take 5–10 growing seasons to recover with changed management (stocking rate reduction, seasonal deferment, and long-term rest). Alteration represents a significant loss of important ecosystem services (and are clearly related to anthropogenic drivers), but recovery is possible in time.

Class IV: The plant community is altered due to the local loss of key plant species, invasion of noxious plant species, or alteration of hydrology that is unlikely to be recovered for over a decade to many decades without intensive interventions such as species removal, seeding, or manipulations to recover historical hydrological function (i.e., an ecological threshold was crossed). Previous ecosystem services have been lost and are usually costly to recover.

Class V: The plant community is altered due to extensive soil loss, accelerated erosion rates, or salinization. Altered plant–soil feedbacks or permanent changes in the soil profile maintain the degraded state. Previous ecosystem services have been lost and it is usually impractical to recover them (often regarded as true desertification).

include access to rangeland risk fund. A small voluntary grazing fee, 300 Mongolian Tugrik (MNT; 0.09 USD) per sheep unit, is matched by local government and invested in rangeland management or disaster relief, which provides a strong incentive to herders for participation in agreements. In addition, as of this writing, proposed amendments to the Land Law governing land possession and use in Mongolia (Ulambayar & Fernández-Giménez, 2019) would provide legal recognition of the user rights of PUGs alongside responsibilities to maintain rangeland health in contracted lands. RUAs are being considered as a vehicle for defining these responsibilities.

As of this writing, 1575 PUGs have been established in 184 soums (representing 56% of total soums) and 18 aimags (equivalent to provinces), involving 91,900 herders. RUAs signed with the soum governor have been processed for 1262 PUGs, involving 51.2 million ha of rangeland. Notably, 153 soums and 24,425 households participate in the rangeland risk fund, which is valued at 2.3 billion MNT. The success of PUGs and RUAs in catalyzing changes in grazing management has been variable for a several reasons, including (1) logistical feasibility to change management based on factors such as availability of water sources and spatial arrangement of pastures; (2) the importance of trespass grazing by animals from neighboring areas; (3) levels of community participation and enforcement; and (4) the levels of financing available to support PUGs (Borsy et al., 2021; Joly et al., 2013; Ulambayar & Fernández-Giménez, 2019). We estimate that about 60% of PUGs with RUAs have successfully implemented management that is informed by monitoring data. An independent audit conducted in 2021 indicated that rangeland improvements are localized to this point (Borsy et al., 2021). For example, in the Bayan Uul PUG (Tsahir soum, Arkhangai aimag), community leaders consulted with several herder families that were grazing a fall/winter pasture out of season to rest the pasture over the summer growing season by moving their livestock to more suitable grazing areas. Monitoring data were consistent with improving vegetation conditions in the rested pasture (Densambuu, Sainnemekh, et al., 2018). While some PUGs are considered to be self-sustaining, other PUGs and higher level PUG support organizations at the aimag and national level will require new donor support and, ideally, stable government support to produce durable ecological and societal benefits (Borsy et al., 2021).

Rangeland monitoring and interpretation as a basis for decision-making

Stocking rate and management recommendations developed as part of RUAs begin with rangeland condition assessments. National government technicians and PUGs use STMs to evaluate pasture areas within each PUG (step 1; Figure 3). Longer term monitoring trends are also considered in this step, via monitoring sites across the

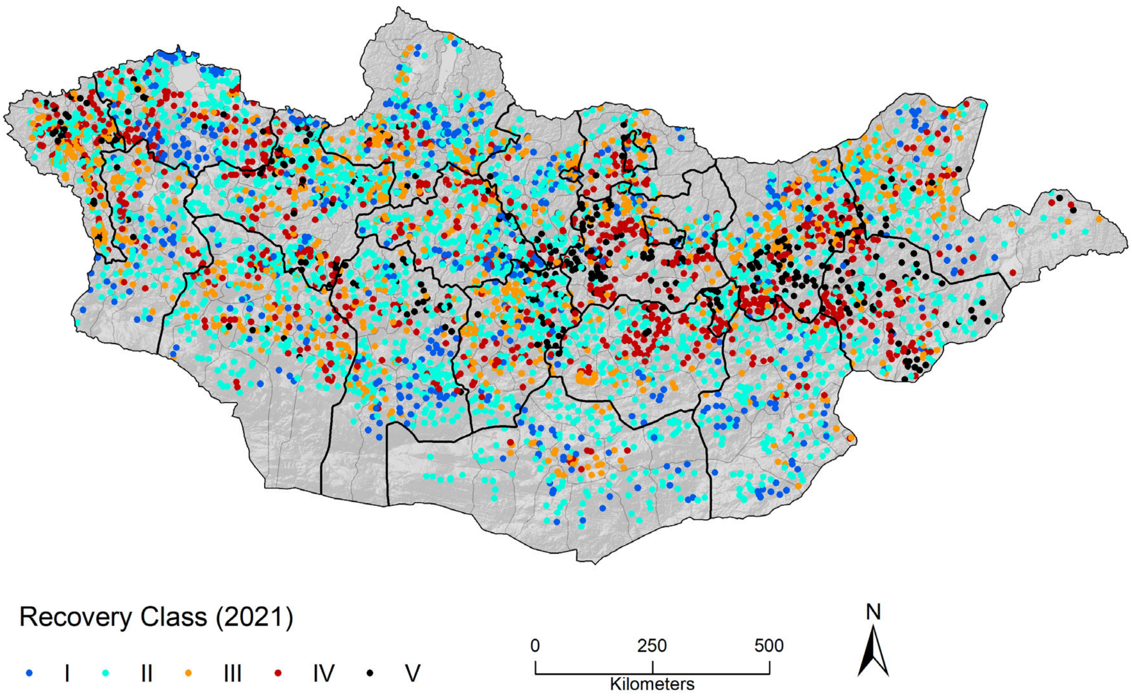

FIGURE 2 An example of low-intensity photopoint rangeland monitoring dataset used in annual rangeland decisions from 2021 collected by the land management officers of the Agency for Land Management, Geodesy and Cartography (5921 points). Cover data are interpreted to recovery classes (Box 1) via the national state-and-transition model catalog. The percentage of points in each recovery class was as follows: I, 11.9; II, 44.4; III, 18.3; IV, 17.8; and V, 7.6. Thus, 2021's ecological state interpretations indicate that while most areas (I–III) could recover within several years to a decade, some areas may be difficult to restore even with changes in management.

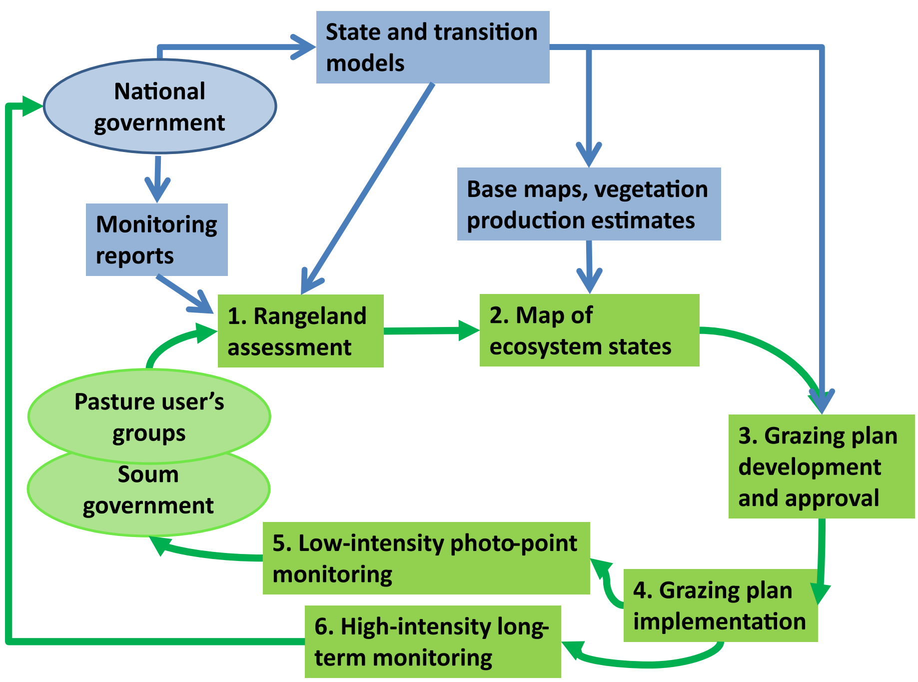

FIGURE 3 Steps in the resilience-based management approach. Green boxes and arrows indicate activities occurring at the local level (soum and Pasture Users' Group, green ovals) and blue boxes/arrows indicate support from the national government.

country. Based on the assessment, government technicians work with PUGs to produce of a map of ecological states that provides a spatially explicit representation of management needs (step 2) (Steele et al., 2012). STMs are included as annexes to the RUAs to describe the present baseline of contracted rangelands and general management recommendations. Using the map, STMs (Figure 4), and monitoring data, initial grazing plans were developed by PUGs and local government, including stocking rates, seasonal use schedules for herder families, and other restoration actions (step 3). Plans are implemented over each grazing year (step 4). Short-term impacts of management (e.g., bare ground cover and forage utilization) are monitored using photopoints and observations of pasture use by national government staff located in soums that work with herders to interpret data and to adjust or enforce management plans adaptively (step 5 and loop). Discussion of monitoring data in development of annual management plans occurs in meetings at the PUG and bag levels in fall of each year, in which herders and government staff evaluate progress. Long-term monitoring data are delivered to national offices and trends are reported to soum government and the national public (step 6). New information about ecosystem change is used to update STMs periodically.

The monitoring and interpretation systems in place provide an unprecedented ability to understand rangeland state transitions and are used for numerous applications. Nonetheless, there are concerns that the density and frequency of monitoring observations (one time per year) are not sufficient to detect abrupt and patchy changes. A logical next step is to use the wealth of long-term ground observations to train machine learning models that use remote sensing and other gridded spatial variables to estimate fractional cover and production of plant functional groups, as has been done in the United States (Allred et al., 2022).

FIGURE 4 Presentation of locally applicable state-and-transition models with herders of a Pasture Users' Group as part of discussions on a Rangeland Use Agreement. Photo credit: Mongolian National Federation of Pasture Users' Groups.

Product traceability system

Green labeling (or sustainability certification/eco-certification) can promote "informational governance" of natural resources by providing consumers and industry a means to associate products with sustainable management practices (Bailey et al., 2016; Mol & Oosterveer, 2015). Price premiums and access to better markets associated with certified products can thereby incentivize sustainable management. The Green Gold Project and the Mongolian National Federation of PUGs (MNFPUG) sought to leverage the potential benefits of traceability through the development of the Responsible Nomads Standard (RNS) and associated livestock Raw Material Traceability System (RMTS). The RNS provides criteria for screening and certification and the MNFPUG recently obtained the right from the Mongolian government to certify cooperatives via this standard. The Responsible Nomads Application (RNA) is a digital tool that allows consumers to identify the source of raw materials and provides all information related to traceability and quality of the product. Using the Quick Response (QR) code on the product packaging (Figure 5) that is linked to a database containing certificates and indicators, consumers can evaluate the origin, quality, safety, and sustainability of the products they purchase and obtain information including the condition of the pastures, animal welfare, animal health, and environmental stewardship via linkages to rangeland health monitoring and assessment databases and documentation of RUAs (Appendix S3). Partners are also exploring the potential of blockchain technology to document sustainability indicators across the supply chain (Kouhizadeh et al., 2021). The Mongolian Wool and Cashmere Association and Mongolian Leather Association are facilitating the cooperation of domestic processors with the green labeling effort. The traceability system aims to communicate diverse elements of livestock production, including rangeland ecological state, animal health and welfare, product quality, and herder gate price (i.e., herder income per unit of raw materials). The linkage to animal health is critical for building both domestic and export markets for certified products and provides a ready platform for traceability of other production system attributes (cf. the "One Health" concept; Destoumieux-Garzón et al., 2018). For example, export markets require assurance that meat products are free from foot and mouth

FIGURE 5 A graphic example of the Responsible Nomads traceability mobile application. Photo credit: Mongolian National Federation of Pasture Users' Groups. QR, Quick Response.

disease that is endemic to Mongolia (Narmandakh & Sakurai, 2021). Furthermore, domestic consumers may respond primarily to certification that products are free from communicable diseases and residual veterinary drugs, thereby indirectly supporting environmental stewardship and animal welfare. As sustainability-based markets develop, the Responsible Nomads system has the potential to create new marketing opportunities that reward herders for participation in resilience-based management. At present, the Responsible Nomads certification has been piloted on products including yak down, goat cashmere, milk and leather. Accelerated, coordinated use across supply chains and international recognition will be needed for the Responsible Nomads brand to be recognized alongside other existing certifications for animal fibers (e.g., Mongolian Noble Fibers). Responsible Nomads, however, has the advantage of being linked to field monitoring and assessment data.

DISCUSSION

Great strides have been made in implementing the resilience-based management system across Mongolian rangelands, as evidenced by the number of PUGs and RUAs established and the existence and use of a new rangeland monitoring and interpretation system in national and local governments. There is independent evidence that community-based rangeland management (including PUGs) can have positive effects on community outcomes, depending on local contexts (Ulambayar & Fernández-Giménez, 2019). However, considering that changes in rangeland management (stocking rate adjustments, changes in timing and location of grazing) and subsequent rangeland restoration is a gradual process, the ultimate effectiveness of the resilience-based management approach will require long-term data to assess. Furthermore, community participation varies in space and time depending on environmental conditions, evaluation of tradeoffs, mobility preferences, training and support, and levels of enforcement in local communities (Addison et al., 2013; Kasymov et al., 2023; Ulambayar et al., 2017). Nonetheless, our experiences in the initial establishment of resilience-based management systems across Mongolia highlight several general strategies that may be useful in other nations where rangelands are common.

First, we found that collaboratively developed STMs are invaluable tools for the clear specification of environmental problems and their solutions at local to national levels. They are essential for communication about environmental quality criteria between rangeland users and the government. In addition, STMs are being used to identify environmental quality targets by herders, governments, and businesses, including standards for sustainability certification (Tseelei, 2009). Collaborative development of models and linked information, especially carrying capacity, was essential to acceptance of the models by herders and officials (Knapp et al., 2011). For example, even if the estimates of carrying capacity ultimately prove to be too high to allow for vegetation restoration, more conservative estimates would have led to rejection of the model-based management process altogether. Although the benchmarks for defining contrasting ecological states, management recommendations, and restoration timelines for different land classes are inherently imprecise and may be wrong, they provide an informed basis for coordinated action that can (and must) be tested with subsequent monitoring.

Second, systematic monitoring methods have been instrumental in creating unambiguous connections between expectations and on-the-ground conditions. Disagreement about rangeland measurements within the Mongolian government, and what constituted "health" or "degradation" (Addison et al., 2012; Sainnemekh et al., 2022), was a primary motivation for the Green Gold project at its inception. Without common monitoring methods and interpretations, multi-institutional coordination of management needs and evaluation of progress would be impossible. Alongside STMs, monitoring methods also facilitate a precise linkage between national-scale trends and local management responses. Nonetheless, the spatial extent, frequency, and impact of monitoring could be improved by increasing direct involvement of herders via herder-led data collection, for example, via mobile applications, and reinforcing the alignment of traditional indicators used by local herders with indicators derived from agency monitoring programs (Jamsranjav et al., 2019). Furthermore, maintaining agency expertise in field monitoring and data processing through staff support and training is a challenge that requires continuous investment by national government and donor organizations.

Third, clearly defined roles for and collaboration between local cooperatives and local to national government facilitate governance (e.g., via enforcement and incentives behind RUAs) and support key activities, such as monitoring, that would otherwise not be sustainable. Furthermore, without local involvement in government-led monitoring, the resulting data would likely not be meaningful for management. A similar role for national government can be found in other successful natural resource management cooperatives, such as the Malpai Borderlands Group in the United States (Sayre, 2005). The presence of government representatives in local communities can be viewed as a positive legacy of the former socialist system in Mongolia, and this legacy might be exploited to support resilience-based management in other former socialist states of central Asia. In other countries without such legacies, additional support will be required for coordination of local and national governments and to build local expertise in organizing pastoralist communities, monitoring, rangeland management, and animal care and breeding.

Finally, our experience highlights the critical role of "boundary-spanning institutions" and individuals (Cash et al., 2003) that can communicate with herders, scientists, government officials, and politicians. In our case, boundary spanners were staff employed by the Green Gold Project. Without significant and sustained (>10 years) donor support of boundary-spanning activities, it is unlikely that international scientific expertise, government agency workflows and policy, and herder's organizations would have been linked effectively. Coordination of donor support is important, especially considering how duplicative and competing donor-supported efforts can sow confusion and waste limited resources (Harbour et al., 2021). The availability of effective boundary spanners is also promoted by the small population size and rapid pace of societal change in Mongolia. It is not uncommon for a Mongolian scientists or development professionals to have been raised in a herding community, or to have been educated alongside current government officials and politicians.

The success or failure of resilience-based management in sustaining productive rangeland social-ecological systems will depend on several interacting factors at the nexus of ecology and society—what Biggs et al. (2012) refer to as the "complex adaptive systems" perspective. The ability of grazing management and stocking rate reductions to initiate vegetation recovery, interactions of management with climate change, the short-term costs of stocking rate reductions to herders and safety nets, the adoption of national policies to incentivize management, the ability or willingness of local governments and PUGs to monitor compliance and enforce RUAs, and market demands may either promote or detract from sustainability. Research on previous efforts to improve rangeland conditions via PUGs suggests that it may be difficult to initiate or detect social and ecosystem change considering these complexities (Addison et al., 2013; Diefenderfer et al., 2021; Kasymov et al., 2023; Ulambayar et al., 2017). Iterative scenario development could be an important tool for evaluating the prospects for resilience-based management tools to have a significant impact on social-ecological system trajectories in the context of ongoing ecological, social, and policy changes (Allington et al., 2018). Long-term monitoring of social-ecological system attributes and the sustained implementation of monitoring, planning, and enforcement in multiple settings will ultimately demonstrate whether the resilience-based management approach now in place will be successful in navigating the effects of global change in the decades ahead.

AUTHOR CONTRIBUTIONS

Burmaa Dashbal contributed to the conceptualization; project administration; and writing—original draft (co-first author). Brandon T. Bestelmeyer contributed to the conceptualization; methodology; writing—original draft; and writing—review and editing (co-first author). Bulgamaa Densambuu and Enkh-Amgalan Tseelei contributed to the conceptualization; methodology; and writing—original draft. Budbaatar Ulambayar developed the methodology and performed investigation and data curation. Sumjidmaa Sainnemekh, Justin Van Zee, Jeb Williamson, and Ankhtsetseg Battur developed the methodology and performed investigation.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data supporting this research are sensitive and not available publicly. The photopoint data interpreted to recovery classes (2021) used to illustrate the data used in land management decisions are available to qualified researchers either directly from the Agency for Land Administration and Management, Geodesy and Cartography, Government of Mongolia, by contacting A. Enkhmanlai via info@gazar.gov.mn or Government Building XII, Barilgachidiin Square, Chingeltei District, 4th Khoroo, Ulaanbaatar, Mongolia; or via the senior author Burmaa Dashbal, Mongolian National Federation of Pasture Users' Groups, Tokyo residence 6-606, Olympic Street 12, Bayanzurkh District 13381, Ulaanbaatar Mongolia, Ulaanbaatar, Bayanzurkh District, Ulaanbaatar, Mongolia, d.burmaa.1@gmail.com.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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