LETTER

Using an integrated social-ecological analysis to detect effects of household herding practices on indicators of rangeland resilience in Mongolia

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Abstract

Temperate grasslands, including those of northern Eurasia, are among the most imperiled ecosystems on Earth. Eighty percent of Mongolia’s land area is rangeland, where interacting climate, land-use and changes in governance threaten the sustainability of Mongolia’s rangelands and pastoral culture. Particularly concerning are the potential ecological impacts of changing pastoral grazing practices—namely declining use of grazing reserves and pastoral mobility. However, like other grazing practices globally, there have been no empirical studies to evaluate the effects of specific Mongolian grazing practices on ecological function at a management scale. We collected data on the grazing practices of 130 pastoral households across four ecological zones and sampled ecological conditions in their winter pastures. We used a novel social-ecological analysis process to (1) develop integrated, holistic indicators of ecological function using exploratory and confirmatory factor analysis, and (2) assess the effects of individual grazing practices on these indicators using statistical matching to control for confounding management and contextual factors. We identified two latent factors related to ecological and pastoral resilience: Factor 1 represents resource retention and soil stability and Factor 2 represents species richness and functional diversity. Using these two factors as response variables, we found that the values of both resilience factors were higher in pastures where households made fall or winter otor migrations or set aside grazing reserves. This study provides the first management-scale empirical test of the ecological response to specific grazing practices in Mongolia, using an approach that can be applied in other rangeland systems. Our findings highlight the importance to ecological and pastoral resilience of supporting traditional pastoral practices of mobility and grazing reserves, while also controlling stocking densities, increasing rangeland monitoring, and ensuring equitable access to state-designated emergency grazing reserves at local, regional, and national levels.

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Introduction

Globally, interacting climate, land-use, political and economic changes threaten the sustainability of rangelands, the pastoral cultures they support, and ecosystem services they provide [1]. Temperate grasslands, like those of northern Eurasia, are among the most imperiled ecosystems on Earth [2, 3]. In Mongolia, where 80% of the land area is grassland, the combined impacts of these threats have altered rangeland governance, livestock markets, and ultimately pastoral land use patterns and livelihoods, undermining the future sustainability of Mongolia’s rangelands and pastoral culture. At the household level, these changes are reflected in declining herd mobility, increasing year-round grazing of seasonal pastures [4, 5], changing herd composition, and rising poverty and income inequality [6, 7], even as the national herd size continues to grow [8]. Like many rangelands globally [1], the condition of Mongolia’s rangelands is widely debated [9, 10], but the synergistic impacts of climate warming, growing livestock populations, and decline in traditional nomadic grazing practices appear to be pushing this system towards potentially irreversible ecological [11] and cultural thresholds [8].

Recent work on sustainability and adaptation in pastoral systems suggests that herd mobility and grazing reserves are among several adaptive strategies that have enabled pastoralists to use grazing animals to support livelihoods by harvesting primary production and converting it to food, fiber, transportation and other goods and services without damaging the long-term productive potential or biodiversity of rangeland ecosystems [12, 13]. However, the effectiveness of such practices in maintaining or improving rangeland conditions has not been empirically tested in Mongolia. In other rangelands globally, grazing practices that ecological theory and pastoralist knowledge predict should lead to improved ecological conditions often do not actually result in superior measured ecological outcomes [14, 15].

There are two potential explanations for the inconsistency between expected and empirically assessed outcomes. First, until very recently [16, 17], few studies evaluated the ecological outcomes of actual management decisions at a management-relevant scale—the ranch or pastoral grazing territory. Second, existing studies conducted at a management scale do not isolate the effects of specific practices [18, 19], but rather evaluate the aggregate effects of the whole suite of practices implemented on a particular ranch on multiple indicators (e.g. production, species composition, soil quality).

On the Mongolian Plateau, grazing research has largely focused on (1) observational studies of ecological conditions at a pasture scale (e.g. along livestock use gradients), but which lack information on specific management practices [20–24]; (2) broad-scale correlation analyses [25–27] and modelling studies [28, 29] that use remote sensing, human and livestock population data, but lack local context or analysis of grazing management or herd movements; and (3) small-scale, controlled experiments (e.g. [30, 31]) that do not represent how practices are applied by pastoralists across a landscape.

Here, we address these limitations by generating quasi-experimental estimates of the effects of specific grazing practices of individual pastoral households on the ecological conditions of pastures at the scale of a seasonal pasture area, accounting for ecological and institutional contexts. Our approach provides a tractable method of isolating the key factors of system resilience that are often the theme of research in rangelands worldwide, but are difficult to assess directly.

Measuring ecological and pastoral resilience

Measuring and managing for resilience is a major theoretical and practical concern in the study and stewardship of social-ecological systems [32–34]. Here we use resilience in its broadest sense, encompassing both resistance to change and the ability of a system to recover following disturbance [35]. Ultimately, system resilience must be measured over time [36]. However, key attributes of resilient systems are often assessed at single points in time, and we need ways to use these data effectively.

The first objective of our analysis was to develop an integrated ecological indicator that we could apply across Mongolia’s diverse rangeland types. Rangeland ecosystem resilience to grazing and drought is associated with a system’s capacity to capture, store, and release energy, nutrients and water [37], to retain functional and structural diversity at multiple levels of organization [38–40], and to regenerate following episodic heavy grazing and prolonged drought, sometimes in combination [36]. Converting these broad concepts into measurable indicators presents several challenges. First, many remote sensing and some field studies in pastoral systems rely on productivity and/or total vegetation cover (or NDVI/EVI proxies) as the sole indicator of ecological condition [25, 27]. But greenness, total biomass and cover do not incorporate species or functional type composition or richness, plant spatial arrangement, or soil stability, all of which contribute to rangeland resilience. Conversely, using many indicators (i.e. separate measurements of each functional type, soil characteristic, and species) can lead to intractable analyses, inflated Type I error rates, or simply difficulty interpreting results across multiple dependent variables. We need more holistic and integrated indicators that combine many individual measures into meaningful ecological constructs that reflect the structure and processes of rangeland systems so that they can be used to assess ecological condition. We initially hypothesized that two latent ecological factors could be used to represent the dynamics captured
in the field measurements; one that represented system attributes associated with ecological functions that promote resilience, and another that represented attributes associated with loss of resilience, or high levels of disturbance.

In pastoral social-ecological systems, pastoralists use local knowledge, social networks and other information sources to monitor rangeland, livestock, weather conditions and markets, and adapt to variable environments using five key strategies: mobility, grazing reserves, diversity, reciprocity/exchange, and flexibility [12, 13]. In the Mongolian context, household practices related to herd mobility and grazing reserves are most likely to have a direct and measurable impact on ecological and pastoral resilience, as explained below.

Mongolian herders, like pastoralists around the world [13], use grazing reserves to ensure sufficient forage to carry herds through the dormant season, when they rely on standing dead forage to feed their animals. Herders typically set aside specific areas for winter and spring use, and sometimes emergency reserves, and refrain from grazing them during the summer and fall growing seasons. Grazing reserves contribute to ecological resilience by returning nutrients and carbon to the soil via litter, enhancing water infiltration, and retaining soil. They support pastoral resilience by providing forage for winter, and emergency reserves for winter disasters and drought.

Although specific movement patterns vary widely across Mongolia and over time [41, 42], herders customarily move four times per year among distinct seasonal pasture areas, exploiting the diversity of natural habitats and avoiding continuous grazing in any one area [43]. Most animals are gathered near the herder’s ger (portable dwelling) each night, and are herded to more distant pastures during the day, creating a pattern of concentrated impacts around campsites that attenuate with distance from camps. This heterogeneous pattern of grazing impacts has been well-studied across Mongolia [21, 22, 44], and is similar to grazing orbits found in pastoral systems elsewhere, where livestock use generates grazing ‘hot spots’ that enhance plant and animal diversity [45–48] and contribute to landscape heterogeneity. Some households make additional movements, called otor, to fatten animals on distant pastures in the fall, or to escape harsh winter weather (dzud) or prolonged drought. Herd mobility in these landscapes thus both exploits plant species and community diversity across the landscape, and contributes to this diversity via heterogeneous grazing patterns.

Based on this understanding of Mongolian pastoral systems and grazing practices, we predicted that the pastures of households who reported going on fall or winter otor or reserving winter, spring, or emergency pastures would have higher ecological resilience indicator values than pastures of otherwise similar households that did not use these practices. Conversely, we predicted that pastures of households that reported grazing reserve pastures out of season would have lower values for these indicators.

Methods

Study design

We sampled in 36 districts located in ten provinces, across four Mongolian ecological zones—mountain and forest steppe, steppe, eastern steppe, and desert steppe (figure 1). We selected districts based on adjacency of pairs of districts within the same ecological zone with and without formal community-based rangeland management (CBRM) organizations (see [49]). Within each district, we randomly selected an average of five community groups sharing common grazing areas and water sources, surveyed five households representing each group using a structured household questionnaire, conducted community-level focus groups and interviews, and collected ecological samples on the winter pasture area used by one surveyed household in each group. Here, we include data only from households whose winter pastures were sampled (N = 130), as our objective is to test whether the behaviors of specific households are associated with detectable differences in ecological conditions of their pastures. We sampled winter pastures because these areas are ungrazed during the summer sampling period, facilitating plant identification and biomass estimation, and because they are a key resource for pastoral households—without winter forage livestock cannot survive or reproduce. We collected social data in April 2011–May 2012 and sampled pastures in summers 2011 and 2012, following social surveys.

Social data collection

We surveyed households using quantitative questionnaires measuring household attributes including herd and grazing management practices. This article focuses on a subset of the management practices conventionally believed to affect rangeland ecological conditions directly: herd size; average and total distance moved per year; winter and fall otor; reserving winter, spring and emergency pastures; and grazing reserve pastures out of season (i.e. grazing winter pastures during summer). We also include as covariates whether each household was a CBRM member, because past studies showed CBRM members are more likely to use certain practices, and whether other households grazed their reserved pastures (‘trespassing’). Household questionnaire design was based on prior studies in Mongolia [4, 5]. Questionnaires were pre-tested and revised before implementation. Data from community-level focus groups and interviews were coded and entered into an organizational profile database. Here we use data on community-level rules about grazing as a covariate in our analysis.
Table 1. Summary statistics of the ecological variables: minimum and maximum, mean and standard deviation are provided for all continuous measures of cover. Vegetation cover, bare ground and species richness are the average of the 500 m and 1000 m distance samples. Soil resource categorical values are the 500 m distance samples.

| Variable                        | Plot min/max | mean  | sd   |
|---------------------------------|--------------|-------|------|
| Perennial grass cover (%)       | 0–94.8       | 25.73 | 23.2 |
| Perennial forb cover (%)        | 0–33.6       | 10.92 | 9.2  |
| Sedge cover (%)                 | 0–55.6       | 7.05  | 9.9  |
| Shrub cover (%)                 | 0–34.8       | 5.08  | 5.3  |
| Litter cover (%)                | 0–74.6       | 28.37 | 20.4 |
| Bare ground (%)                 | 0–74.6       | 28.37 | 20.4 |
| Species richness                | 0–61.5       | 29.23 | 12.9 |
| Resource retention class (RRC)  | isolated/fragmented/connected |       |      |
| Soil redistribution class (SRC) | high/med/low erosion |       |      |

Ecological data collection

At each surveyed household’s winter pasture, we established three plots at increasing distances from the winter campsite and livestock corral: 100 m, 500 m, and 1000 m. Here we use only data from 500 m and 1000 m plots because we expect they better represent livestock use levels that reflect differences in grazing practices among households, whereas 100 m plots are highly disturbed by livestock and human activities across all households regardless of management, so we would not expect to see any differences. At each distance we collected data on plant cover by functional group and species. To estimate key properties associated with ecological function and resilience, we rated each site using the categorical classes for resource retention class (RRC) and soil redistribution class (SRC) [50, 51], which describe the spatial distribution of perennial plant patches (RRC) and the extent of soil movement and deposition (SRC). For each household, plot-level cover and species richness measures are averaged across the 500 and 1000 m plots, and SRC and RRC were assigned the value from 500 m plots. The variables used here are listed in Table 1.

Remote sensing data

We used several variables derived from remote sensing data as covariates, to account for ecological context for grazing practices in the sampling year. Specifically, we derived district-level estimates of mean forage availability (kg ha\(^{-1}\)) from 2000–2011 (average across all pixels in a district for each year), precipitation mean and standard deviation (mm year\(^{-1}\)) from 1979–2011, and stocking density (sfu ha\(^{-1}\)) from 1981–2011. Sheep forage units (sfu) are a livestock equivalency unit that converts livestock populations of each species to a common unit (sfu; see supplemental methods available at stacks.iop.org/ERL/13/075010/mmedia). Forage data were derived from MODIS Terra sensors (250 m pixels), precipitation data are drawn from the Climate Prediction Sensor’s Unified Precipitation Data [52] and stocking density was derived from livestock population data from the National Statistical Office of Mongolia [53]. Full details on data processing in supplementary materials.

Data analysis

There were two stages to our analysis. First, we reduced the suite of measured ecological variables to two latent factors. We then used those values as outcome variables to assess the impacts of household management practices on rangeland condition. Our overall workflow is outlined in figure 2, and additional details are in the supplemental methods.
Development of integrated ecological indicators

We used exploratory factor analysis to assess patterns of association among variables, prior to testing a hypothesized measurement model. We examined the loadings of all of the variables across two factors first, based on our initial hypothesis of two inversely related latent factors, but also assessed variable loadings across hypothetical three and four factor structures to look for consistencies in patterns among variables. Exploratory factor analysis indicated a strong association between species richness and the second factor, and both soil resource classifications tended to associate together, and not with the variables for forb and sedge cover. This led us to revise our hypothesized measurement model such that the two latent factors represented two complementary but distinct dimensions of ecological function and resilience (rather than negatively correlated factors) (figure 2). We expected the first factor to explain variables associated with production and site stability, such as perennial grass and litter cover, RRC and SRC, and the second factor to be associated with indicators of moderate disturbance, such as species richness and perennial forb cover.

We used confirmatory factor analysis (CFA) to evaluate our hypothesis that the field measurements adequately explain or represent the underlying (latent) ecological condition of sampled pastures, and that this condition could best be represented with a model with two latent variables. Table S2 shows the correlation matrix of variables used in the measurement model (supplementary methods).

Then, we used the validated CFA model to predict values for the latent variables for each sample unit (household’s winter pasture), resulting in 130 predicted values for each factor. These values were rescaled from 0–1, exported, and aligned by household with the
Results

The measurement model with two latent factors was the best fit to the covariance structure of the data. Model fit statistics indicated close model-data fit (CFI = 0.91; RMSEA = 0.08; SSRMR = 0.06). Standardized parameter estimates are presented in figure 3, unstandardized estimates and the squared multiple correlation estimates are in table 2. We interpret the two factors in our model as representing two distinct latent variables related to ecological resilience as explained below. We use both to evaluate effects of different management practices because they represent distinct and complementary dimensions of ecosystem function that might be expected to respond differently to different practices.

The Resource Retention Factor (F1ResRet) is important for ecological resilience because it represents capacity to capture energy (e.g. total grass cover), return carbon and nutrients to the soil (e.g. total litter cover), and to intercept and store water (RRC) and retain soil (SRC). F1ResRet supports pastoral resilience because perennial grass is the main source of energy for livestock. Litter indicates leftover, unconsumed forage from the previous winter; an effective forage reserve and buffer for a drought or dzud year.

The Functional Diversity Factor (F2FunctDiv) is important to ecological resilience because diversity at multiple scales is associated with ecosystem functionality [56, 57], and diversity and redundancy are important to reorganization and recovery following disturbance [39, 58]. Some constituent variables for F2FunctDiv are indicators of heavy grazing (e.g. Sedge species Carex duriuscula). However, in systems such as Mongolian grasslands, which evolved with grazing from large herbivores, diversity is typically maximized at intermediate levels of disturbance [59], especially in the more mesic mountain and forest steppe [20]. F2FunctDiv is important to pastoral resilience because forbs provide nutritional quality for livestock [9], and overall species richness contributes to diet diversity for a range of livestock species [60]. Species richness may also indicate presence of plants pastoralists use for food and medicine.

Shrubs were associated with both F1ResRet and F2FunctDiv, and are important components of many Mongolian steppe ecosystems, their presence driven largely by climate and soil texture [61], although some species, such as Caragana microphylla, are associated with heavy grazing [62–64]. Many species of shrubs and sub-shrubs are important to pastoral production as protein-rich forage for browsing species (goats, camels) and as fuel for pastoral households. Some valued forage species, like Artemisia frigida, increase with moderately high grazing and decrease with very high grazing [61].

Matching significantly improved the balance between the treatment and control groups for all of the practices that we assessed (figure S1, table S3–S8).

Table 2. Standardized and unstandardized parameter estimates from the measurement model and relative fit statistics.

| Loadings                  | Unstd  | Std     | R-sq  |
|--------------------------|--------|---------|-------|
| Factor 1: resource capture and retention |         |         |       |
| Perennial grass          | 0.80   | 0.75    | 0.56  |
| Litter                   | 0.94   | 0.68    | 0.47  |
| RRC                      | 0.79   | 0.79    | 0.63  |
| SRC                      | 0.77   | 0.77    | 0.59  |
| Bare ground              | 1.15   | 0.91    | 0.83  |
| Shrubs                   | 0.22   | 0.29    | 0.22  |
| Factor 2: species and functional diversity |         |         |       |
| Perennial forbs          | 0.49   | 0.52    | 0.28  |
| Sedges                   | 0.91   | 0.77    | 0.59  |
| Species richness         | 12.02  | 0.94    | 0.88  |
| Shrubs                   | 0.18   | 0.23    |       |
| Fit statistics:          |        |         |       |
| CFI                      | 0.91   |         |       |
| RMSEA                    | 0.08   |         |       |
| SRMR                     | 0.07   |         |       |

Under this approach are: fall and winter otor movements; retaining winter, spring and emergency pastures; and grazing reserved pastures out of season.

We assessed covariate balance before and after matching with the standardized mean difference for each covariate and the propensity score [53–54] (supplementary methods; figure S1, tables S3–S8).

household survey data for use as a response variable in subsequent analyses of treatment effects.

Effects of specific household practices

We assessed the impact of household-level management practices on the ecological outcome variables using a statistical matching approach to estimate a treatment effect for each practice [54, 55]. Statistical matching is a non-parametric approach to preprocessing data to ensure that samples from treated (subject to a practice) and control (not subject to a practice) groups are similar to each other with respect to key confounding variables. This preprocessing improves the validity of the causal inference drawn from subsequent analyses. We use optimal full matching because it maximizes the final sample size by allowing for one-to-many and many-to-one matches between treatment and controls; samples outside the range of support are discarded (tables S3–S8 show final sample sizes in each treatment). The practices we consider as ‘treatments’ under this approach are: fall and winter otor movements; retaining winter, spring and emergency pastures; and grazing reserved winter pastures out of season.

We considered several different potentially confounding variables for each individual practice based on covariates that could affect whether a household chose to undertake that practice, or affect the outcome variables themselves. These included: CBRM membership, ecological zone, ecological context (e.g. recent and long-term trends in climate and forage availability) and whether the household had undertaken other practices (table 3). We assessed covariate balance before and after matching with the standardized mean difference for each covariate and the propensity score [53–54] (supplementary methods; figure S1, tables S3–S8).
higher in the treatment compared to control groups for all practices (table 4; figure S2). A test of differences in distributions indicated that the treatment groups were significantly different than control groups across all practices except for grazing out of season. Mean values of latent factors were not significantly different between the treatment and control across all comparisons.

**Discussion**

Our objectives were (1) to develop holistic, integrated indicators of rangeland ecological condition and resilience that would enable us to (2) evaluate the impacts of specific management practices. Our modeling supports the presence of two latent ecological factors that represent two distinct and complementary aspects of rangeland resilience: resource capture and retention (F1ResRet), and species and functional diversity (F2FunctDiv). Each is important for supporting the resilience of the ecological and pastoral production aspects of rangeland systems.

**Table 3.** Covariates used in the matching procedures.

| Matching variables:          | Otor movements | Reserve seasonal pastures | Graze out of season |
|------------------------------|----------------|--------------------------|---------------------|
|                              | Fall Winter    | Winter Spring Dzud       |                     |
| CBRM                         | X X            | X X X X X               | X                   |
| Ecological zone              | X X            | X X X X X               | X                   |
| Trespassing by another ail (household) | X X           | X X X X X               |                     |
| Herd size                    | X X            | X X X                   |                     |
| Avg distance migrated        | X X            | X X                     |                     |
| Total distance migrated      | X X            | X                       |                     |
| Rules on timing of grazing   | X X            | X                       | X                   |
| Fall otor                    | X X            | X X                     |                     |
| Winter otor                  | X X            | X X X                   |                     |
| Reserve winter pastures      | X X            | X X X                   |                     |
| Reserve spring pastures      | X X            | X X                     |                     |
| Dzud pastures                | X X            | X X                     |                     |
| Precip mean/sd               | X X            | X X                     |                     |
| Stocking density             | X X            | X X                     |                     |
| Available forage             | X X            | X X X                   |                     |

**Table 4.** Median values for the two latent ecological factors, post-matching, and the average treatment effect on the treated (TE), for each of the individual practices, CBRM and grazing out of season.

| Practices                   | Factor 1 | TE | Factor 2 | TE |
|-----------------------------|----------|----|----------|----|
|                             | Ctrl     | Trt| Ctrl     | Trt| |
| Fall otor                   | 0.17     | 0.64* 0.47 0.13 0.38* 0.25 |
| Winter otor                 | 0.29     | 0.60* 0.31 0.21 0.37* 0.16 |
| ResSpringPasture            | 0.30     | 0.52* 0.22 0.17 0.36* 0.19 |
| ResWinterPasture            | 0.25     | 0.65* 0.40 0.17 0.37* 0.20 |
| ResDzudPasture              | 0.32     | 0.67* 0.35 0.25 0.44* 0.19 |
| GrizOutSeason               | 0.45     | 0.67 0.22 0.28 0.39 0.11 |

* Significantly different, as determined through Kolmogorov-Smirnov test of distribution.

We hypothesized that the winter pastures of households who reported fall and winter otor movements, and set aside winter, spring or emergency grazing reserves, would have higher values for F1ResRet and F2FunctDiv compared to pastures of households that did not do these practices. All hypothesized beneficial practices were associated with higher median values of both factors in pastures that received these ‘treatments.’ We also expected that pastures of households that
grazed their winter pastures out of season would have lower values of both factors. Pastures with and without out-of-season grazing did not differ in either factor, suggesting that out-of-season grazing does not damage winter pasture ecological function. This could be because pastoralists only graze winter pastures out of season if there is sufficient excess forage or because grazing occurs early in the growing season, leaving ample time for pastures to regrow before winter.

The practices associated with the greatest effect sizes for F1ResRet were reserving winter pasture and fall otor (table 4). Winter and emergency reserves and fall otor had the greatest effect sizes for F2FunctDiv, but overall the effects of the practices on F2FunctDiv were weaker than for F1ResRet. Stronger effects on F1ResRet may be because households that do fall otor are less likely to move to their winter campsites early. Grazing reserves and fall otor contribute to accumulation of biomass (indicated by perennial grass and litter cover), and resulting retention of soil and water resources. Both grazing reserves and fall otor movements were associated with reduced vulnerability in the 2009–2010 winter disaster [65]. Our study focused on resilience attributes of winter pastures, a key pastoral resource in Mongolia. More work is needed to understand how and whether specific grazing practices affect the conditions of other seasonal pastures, especially those used during the growing season. Further, we do not claim that these practices alone are sufficient to ensure pastoral system resilience, which will likely require innovation as well as reliance on traditional adaptive strategies.

Our findings have practical and policy implications for rangeland and pastoral resilience in Mongolia. In the absence of strong government or local community control on stocking rates, or effective market incentives [65], winter disasters (dzud) are the main limiting factor on livestock populations in Mongolia [66, 67] and have devastating impacts on herder livelihoods and well-being [65]. Here, we show that otor and grazing reserves are associated with indicators of rangeland and pastoral resilience in winter pastures, providing the first direct empirical evidence of the effectiveness of these household-level practices in maintaining desirable ecological conditions. Our results build on past work, which showed that households that did fall otor and had grazing reserves suffered fewer livestock losses in a dzud the following winter [65], by providing evidence of an ecological mechanism linking these practices and reduced dzud impact. These findings provide scientific evidence to support local government and CBRM policies to encourage fall otor and to designate and protect reserve pastures.

Our results also highlight the need for national-level policies in Mongolia, including the proposed Pastureland Law, to support herd mobility and equitable allocation of and access to grazing reserves for all herders, in order to promote resilient rangelands and pastoral production systems. Because previous work has shown that unregulated and uncoordinated winter otor during disasters undermines the effectiveness of grazing reserves [65] and can lead to inequitable access [68], it is important that policies balance movement flexibility, equitable access, and protection of grazing reserves through careful coordination and transparent rules of access. One way to achieve this is to reinvigorate and enforce existing policies requiring designated grazing (otor) reserves at the district, province and national levels, to complement household-level reserves and ensure that the mobility of one household in a disaster does not compromise the reserves of another. In addition, support for mobility and reserves must be combined with rangeland monitoring [50] and controls on overall stocking densities [8, 69] to avoid crossing irreversible degradation thresholds that could undermine both ecosystem and pastoral resilience. Finally, pastoral resilience in Mongolia, as elsewhere, will likely require new innovations in addition to maintaining effective existing adaptive strategies [70, 71].

Our study makes two main methodological contributions to rangeland science and the study of coupled natural-human pastoral systems that can be used to assess resilience in other rangeland contexts. First, we used latent variable modeling to develop indicators that represent meaningful and complementary dimensions of ecological and pastoral resilience. While the predicted values of these indicators are specific to our dataset, our method demonstrates an approach that researchers can use to reduce measured attributes into response variables that are important to both ecological function and pastoral production. The indicators incorporate multiple constituent variables in each factor rather than relying on a single unidimensional indicator such as total vegetation cover, biomass or greenness. Our findings also could inform the priorities for field sampling if data on only a limited number of variables can be collected. For example, this work suggests that species richness and functional group cover combined with qualitative soil surface classifications (RRC and SRC) are sufficient to capture major dimensions of ecological resilience in Mongolian winter rangelands. Such dimension reduction can be applied to streamline sampling and interpretation in other regions as well.

The second methodological contribution is the use of statistical matching to overcome the challenges to analyzing the impacts of specific grazing practices at a management-relevant scale under actual management conditions. While the matching approach has been used within the conservation field for impact assessments of protected areas and community forest management (e.g. [72–74]), here we apply the approach to assess individual herding management strategies. We are able to control for multiple potentially confounding social and ecological factors, and isolate the effects of practices on ecological outcomes. This provides robust evidence on the effectiveness (or lack thereof) of specific practices for achieving specific ecological outcomes in a management context. While this method requires
a relatively large sample size of both households and their associated grazing areas, which may sometimes be logistically or financially prohibitive, this methodology could inform the design of future landscape-scale grazing management research. Our study benefited from a larger sample size than is typically possible for ranch-scale coupled social-ecological sampling, but, like many studies, is a ‘snapshot’ in time sample. Studies that follow the trajectories of pastoral households/ranches over time with both social surveys and field monitoring are ideal. Ultimately, to assess ecological or pastoral resilience to actual shocks, repeat samples are required.

There is currently no consensus on the fate of global rangeland and pastoral systems in the face of changing climate [75, 76]. Rangelands could be well poised to withstand current changes given inherent resilience and pastoral management flexibility, or they could be increasingly vulnerable due to accumulated loss of ecological resilience and increased social vulnerability. Conflicting evidence on the state of global rangelands suggests we need approaches that enable us to synthesize diverse existing data across different dry-land contexts. But in order to assess resilience more broadly, we first need new approaches for synthesizing data at single landscapes and ways to isolate ability of specific practices to confer resilience.

This study provides the first empirical test of the effect of specific grazing practices on latency resilience parameters at a scale that is relevant for resource managers and policy-makers. While our findings are framed within the Mongolia context, there is great potential for this approach to be applied to other rangeland management contexts. For example, in the US Great Plains, the inability to control for confounding variables at management relevant scales has led protracted debates about the value of particular grazing practices [18] and hindered development of science-based decision-making partnerships to address broader issues facing livestock producers and rangeland systems in the region. In Kenya, where a growing movement of community conservancies [77] parallels the growth of CBRM in Mongolia [49], our methods could be adapted to identify robust synthetic indicators and evaluate the effectiveness of conservancies in maintaining rangeland and pastoral resilience. As the conservation movement adopts more rigorous standards of evidence-based practice [73, 78], the methods applied here, when adapted for other contexts, provide encouraging avenues for evaluating conservation effectiveness in rangelands globally.

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