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Patterns and drivers of rangeland degradation in Mongolia

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Clarification of contribution

I hereby declare that the ideas behind this research, the writing of the following thesis and the three accompanying papers are my own work, done under the supervision and with assistance of my supervisors, Professor Isabel C. Barrio, Professor Ása L. Aradóttir, Dr. Brandon Bestelmeyer and Dr. Bulgamaa Densambuu.

The contribution of Sumjidmaa Sainnemekh to the papers included in this thesis was as follows:

Paper I: Sumjidmaa Sainnemekh planned the work, together with Isabel C Barrio, and collected all data presented in the review paper. Sainnemekh analyzed and interpreted the data and wrote the manuscript that was revised and approved by all co-authors. Sainnemekh corresponded with the scientific journal.

Paper II: Sumjidmaa Sainnemekh planned the work, together with Brandon Bestelmeyer. The data was collected by technicians working for the national rangeland health monitoring program at the National Agency of Meteorology and Environmental Monitoring (NAMEM) across Mongolia. Sarah McCord and Darren James at Jornada Experimental Range assisted with data management and analyses. Sainnemekh interpreted the data and wrote the manuscript.

Paper III: Sumjidmaa Sainnemekh planned and collected all the data presented in the paper during two field surveys in the Mongolian steppe in 2010-2012 and in 2021. Sainnemekh analyzed and interpreted the data and wrote the manuscript that was revised and approved by all co-authors. Sainnemekh corresponded with the scientific journal.

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Sumjidmaa Sainnemekh

Abstract

Rangelands are currently facing increasing threats from climate change, overgrazing and land conversion and rangeland degradation is a growing concern worldwide. The ability of degraded rangelands to provide the natural resources needed to sustain pastoralists and ensure the persistence of traditional nomadic lifestyles is less than that of healthy rangelands. In Mongolia, serious concerns have emerged in recent decades about the accelerating rate of rangeland degradation. Understanding rangeland degradation and assessing long term trends of vegetation change is thus critical to design sustainable management practices. Mongolian rangelands represent about 2.5% of the world's total grassland area and are considered among the last intact rangelands in the world. Most of the Mongolian territory is covered by rangelands and the livelihoods of nearly half of the Mongolian population are related to livestock grazing on rangelands.

The main objectives of this PhD thesis were (1) to compile previous studies on rangeland degradation in Mongolia and systematically review and synthesize information on how studies identified degradation, the theoretical frameworks used, drivers of degradation and the geographical distribution of studies, (2) to detect trends in vegetation change in Mongolian rangelands using broad scale long-term monitoring data, and (3) to investigate the drivers of change in vegetation over ~10 years in the steppe zone of Mongolia using detailed field data.

Trends in the literature indicated growing concerns about rangeland degradation in Mongolia, especially since the turn of the 21st century when the number of international scientific publications on this topic considerably increased. However, the lack of a common definition of degradation and of standardized ways of measuring it makes it difficult to compare results of different studies. Using a nationwide long-term database of rangeland health in Mongolia, we detected mostly non-significant trends in key indicators of vegetation change across the forest steppe, steppe and desert steppe. However, where significant trends were detected, these were consistent with reported rangeland degradation. For example, we observed noticeable decreasing trends in grasses characteristic of healthy rangelands, including *Stipa* sp. This was the first attempt to use the database of the National Rangeland Monitoring program and the results emphasize the value of this national resource. Using detailed field data, we found that changes in vegetation over a ~10-year period were widespread across the steppe. Plant communities changed from communities dominated by grasses toward communities dominated by annuals and sedges that are characteristic of degraded ecosystem states. However, disentangling the role of different drivers remains difficult. Our results highlight the importance of considering regional differences in the effect of different drivers on grassland vegetation when designing sustainable grazing management strategies. In all, this study shows that we are still far from understanding the complexities of rangeland degradation. Nevertheless, current efforts are promising, and Mongolia provides a good example for the world.

Keywords: rangeland degradation; Mongolia; long-term monitoring; vegetation change; degradation drivers.

Ágrip

Beitilöndum stafar vaxandi hætta frá loftlagsbreytingum og ofbeit. Breytt landnýting ásamt hnignun beitilanda er einnig í auknum mæli áhyggjuefni um heim allan. Hnignuð beitilönd hafa minni getu en óhnignuð til að veita þau náttúrulegu gæði sem þörf er á til að fullnægja þörfum samfélaga hirðingja og tryggja tilveru hefðbundins hirðingjabúskapar. Á undanförnum áratugum komið fram alvarlegar áhyggjur af sívaxandi hnignun beitilanda í Mongólíu. Skilningur á hnignun beitilanda og mat á langtíma þróun gróðurfarsbreytinga er nauðsynleg undirstaða fyrir þróun leiða til sjálfbærrar nýtingar á þeim. Beitilönd í Mongólíu eru um 2,5% af heildarþekju graslendis í heiminum og eru talin vera á meðal síðustu beitilanda heimsins sem eru óröskuð. Þau ná yfir meginhluta Mongólíu og tengist lífsviðurværi nærri helmings mongólsku þjóðarinnar beit búpenings á beitilöndum.

Meginmarkmið þessa doktorsverkefnis voru (1) að taka saman fyrri rannsóknir á hnignun beitilanda í Mongólíu og meta og draga saman með kerfisbundnum hætti upplýsingar um hvernig mismunandi rannsóknir greindu hnignun, á hvaða fræðilega grunni þær byggðu og hverjir voru orsakavaldar hnignunar, ásamt landfræðilegri dreifing þessara rannsókna, (2) að greina leitni gróðurfarsbreytinga í mongólskum beitilöndum með því að nýta langtíma vöktunargögn sem ná yfir stór svæði og (3) að meta orsakir gróðurfarsbreytinga yfir ~10 ára tímabil á gresjum Mongólíu út frá nákvæmum mælingum á gróðurfari.

Samtekt á fyrri rannsóknum um hnignun beitilanda í Mongólíu bendir til þess að áhyggjur af hnignun þeirra fari vaxandi og jókst fjöldi alþjóðlegra vísindagreina um þetta efni verulega upp úr síðustu aldamótum. Skortur á sameiginlegri skilgreiningu á hnignun og á stöðluðum aðferðum við að greina hana gerir það hinsvegar erfitt að bera saman niðurstöður mismunandi rannsókna. Greining á langtímagögnum úr gagnagrunni um ástand beitilanda í allri Mongólíu, *National Rangeland Monitoring program*, leiddi í ljós að leitni í lykilvísum fyrir gróðurfarsbreytingar var yfirleitt ómarktæk, hvort sem um var að ræða skógargresju, gresju eða eyðimerkurgresju. Þar sem leitnin var marktæk var hún hinsvegar í samræmi við birtar heimildir um hnignun beitilanda. Til dæmis kom fram leitni til verulegrar hnignunar grastegunda sem eru einkennandi fyrir óröskuð beitilönd, þar á meðal *Stipa* sp. Þetta var fyrsta tilraunin til að nýta þennan gagnagrunn og niðurstöðurnar sýna ótvírætt gildi hans. Greining á nákvæmum gróðurfarsgögnum leiddi í ljós víðtækar gróðurfarsbreytingar á ~10 ára tímabili yfir alla gresjuna. Gróðursamfélög breyttust frá samfélögum þar sem grös voru ríkjandi yfir í samfélög einærra plantna og stara, sem eru einkennandi fyrir hnignuð vistkerfi. Þáttur mismunandi orsakavalda var hins vegar óljósari og svæðisbundinn. Niðurstöðurnar draga fram taka þarf tillit til svæðisbundins munar á áhrifum mismunandi orsakavalda á gróðurfar graslendis við þróun á leiðum til að nýta það með sjálfbærum hætti. Þessi rannsókn sýnir, þegar allt kemur til alls, að við erum fjarri því að skilja flókin hnignunarferli beitilanda. Þrátt fyrir það lofa nýlegar tilraunir í þá veru góðu og Mongólía er gott dæmi fyrir heimsbyggðina.

Lykilorð: hnignun beitilanda; Mongólía, langtíma vöktun, gróðurfarsbreyting, drifkraftar hnignunar.

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Contents

List of Original Papers

The present thesis is based on the following publications, which will be referred to by their Roman numerals.

I. Sainnemekh, S., I. C. Barrio, B. Densambuu, B. Bestelmeyer, and Á. L. Aradóttir. 2022. Rangeland Degradation in Mongolia: A Systematic Review of the Evidence. *Journal of Arid Environments* 196: 104654. https://doi.org/10.1016/j.jaridenv. 2021.104654 [published]

II. Sainnemekh, S., B. Bestelmeyer, D. James, S. E. McCord, B. Densambuu, E. Baasandai, B. Mendbayar, Á. L. Aradóttir, and I. C. Barrio. 2022. Long-term monitoring data reveal trends in key indicators of rangeland change in Mongolia [manuscript]

III. Sainnemekh, S., I. C. Barrio, B. Bestelmeyer, Á. L. Aradóttir, D. James, and B. Densambuu. 2023. Complex interplay of climate and grazing drives regional differences in vegetation change in the Mongolian steppe. *Rangeland Ecology and Management* [submitted]

List of Figures

Introduction

Rangelands and rangeland degradation worldwide

Rangelands cover 54% of the global terrestrial surface or nearly 80 million square kilometres (ILRI IUCN FAO WWF UNEP & ILC, 2021). Rangelands are broadly defined as land that is grazed or has the potential to be grazed by livestock and wildlife, and include grasslands, shrub lands and tundra (Lund, 2007). Traditional definitions of rangelands have focused on land use alongside physiognomic and ecological characteristics of the ecosystem. However, it is increasingly recognized that rangelands are complex and interconnected ecosystems that include both social and ecological components (Hruska et al., 2017). For instance, about 2 billion people depend on rangelands directly, and at least 1.3 billion people engage in the commercial livestock sector globally (Reynolds et al., 2007; Thornton, 2010). Thus, considering rangelands as complex socio-ecological systems is important to make decisions and formulate policies for sustainable rangeland management (Roche, 2021).

Rangelands provide multiple ecosystem services with important economic value (Sala et al., 2017). For example, rangelands support millions of livestock and wildlife that are the basis of pastoral livelihoods worldwide (Reynolds et al., 2007), playing an important role in global food security (Michalk et al., 2019). In addition, rangelands sustain important sets of regulating and supporting ecosystem services, including carbon storage, water supply, and biodiversity (Bengtsson et al., 2019). Maintaining vegetation cover on rangelands prevents soil erosion by reducing water run-off and protecting soil surface (Molina et al., 2007). Thus, sustainable use of rangeland contributes to several United Nations Sustainable Development Goals, and maintaining rangeland health is critical if we are to achieve the global goals of the 2030 Agenda for Sustainable Development (Niamir-Fuller & Huber-Sannwald, 2020).

Rangelands are facing increasing threats from climate change, overgrazing and land conversion (Boone et al., 2018; Godde et al., 2020), and rangeland degradation is a growing concern worldwide. Rangeland degradation causes loss of ecosystem services and biodiversity and is a primary driver of desertification globally (Bestelmeyer et al., 2015; D'Odorico et al., 2013). These changes in rangelands affect the livelihoods of herders in direct and indirect ways. For instance, rangeland degradation causes fodder shortages for livestock in Central Asian countries (Mirzabaev et al., 2016). Rising demands for livestock products linked to the increasing human population, land conversion and ongoing climate change will, however, put additional pressures on rangelands around the globe (Michalk et al., 2019).

Defining and understanding rangeland degradation

Despite the growing concerns about rangeland degradation worldwide, definitions of degradation, its drivers and consequences remain elusive. The definitions of degradation are often vague and subjective (Engler & von Wehrden, 2018), and different studies use different criteria, or refer to changes in different ways, for example using terms like vegetation change, desertification or rangeland degradation. This lack of consensus on terminology and definitions has led to inconsistencies in the estimates of the global extent and severity of rangeland degradation (Al-Bukhari et al., 2018; Duan et al., 2022; Han et al., 2008; Harris, 2010; Hoppe et al., 2016; Robinson et al., 2003) and creates confusion in the message provided to the public and policy makers (Addison et al., 2012).

Key indicators of rangeland degradation often include shifts in plant species composition, reduced species richness, altered dominance of some plant functional groups within communities and declines in aboveground biomass (Bestelmeyer et al., 2015; D'Odorico et al., 2013). Recently, some studies have emphasized the need to integrate indicators of soil health in studies of rangeland degradation (Byrnes et al., 2018; Jamsranjav et al., 2018). Identifying which indicators to measure is critical, because imprecise assessments of rangeland condition can lead to inadequate recommendations, for example by aiming at regulating livestock numbers where regulations are not needed, or by supporting unproductive management practices that do not combat rangeland degradation.

Understanding the drivers of vegetation change and rangeland degradation is crucial to implementing sustainable rangeland management and developing policies that can sustain herder livelihoods and rangeland health. Climate change, overgrazing and land conversion have often been cited as drivers of rangeland degradation (Boone et al., 2018; Godde et al., 2020), but the drivers of degradation in specific areas are difficult to isolate (Herrick et al., 2019). Several ecological theories and frameworks have been developed to understand rangeland dynamics and vegetation change (**Box 1**). These frameworks include the traditional successional model, non-equilibrium theory, state and transition models and the integrated degradation framework. Some of these frameworks focus on the process of degradation and recognize distinct stages of degradation or ecosystem states, while others, like the non-equilibrium theory, focus on drivers of system dynamics. Such frameworks are a main component of adaptive monitoring programs and long-term ecological research (Lindenmayer & Likens, 2009), and provide a general basis for adaptive management of rangelands.

Box 1. Ecological theories and frameworks to understand rangeland degradation

Traditional successional model. The traditional successional model (or range succession model) derives from the Clementsian approach of plant ecology and was widely used for rangeland management in the USA until the late 1980s. According to this model, the succession of plant communities is a continuum that leads to one permanent climax state. This model is based on an equilibrium system where grazing pressure is assumed to be the major driver of vegetation dynamics. The traditional successional model does not support alternative states or irreversible changes between states. The traditional successional model does not fit to many systems, including arid and semi-arid systems or those with highly variable climate, creating the need for alternative models of rangeland dynamics.
Key references: (Clements, 1916; Dyksterhuis, 1949)

State and transition models. The acknowledgement of the existence of irreversible changes led to the development of a new range management model called State and Transition Model (STMs), that allows for both reversible and irreversible changes in vegetation dynamics. In STMs, reversibility depends on the state of numerous ecosystem processes and current land management regimes. STMs consist of multiple states of rangeland vegetation and transitions among these states that are driven by different triggers. STMs are practical tools for analyzing and interpreting long term monitoring data and provide a theoretical background for planning and implementing resilience-based rangeland management. Applying STMs in rangeland management allows understanding the underlying process of rangeland degradation.
Key references: (Bestelmeyer et al., 2017; Westoby et al., 1989)

Non-equilibrium theory. In arid and semi-arid regions where the coefficient of variation (CV) of precipitation is higher than 33%, rainfall variability plays a main role in rangeland dynamics. The concept of non-equilibrium was proposed in the 1980s and emphasizes the transient nature of vegetation changes in non-equilibrium systems, where rainfall variability has a stronger influence than grazing on vegetation change. In these systems the potential for degradation due to overgrazing is considered to be relatively low and rangeland management needs to be adapted to the highly variable characteristics of these systems and based on current year's rainfall. One of the implications for management at the landscape scale of the non-equilibrium theory is that it allows identifying "key resource areas" and their spatial linkages to more variable surrounding rangelands.
Key references: (Briske et al., 2017; Ellis & Swift, 1988; Illius & O'Connor, 1999; von Wehrden et al., 2012)

Integrated degradation framework. The severity of degradation can be described using process-based frameworks that consist of several steps, each defined by specific indicators of degradation including not only vegetation but also soil variables. The integrated degradation framework combines two frameworks proposed by Milton et al. (1994) and Whisenant et al. (1999) for arid lands. According to this framework, degradation follows five steps. Initially, vegetation changes are reversible fluctuations driven by climate variability. In the second step, the cover of unpalatable plants increases in the community. The third step shows decreased species richness and reduced productivity. Step four is characterized by thinned perennial plant cover, increased bare soil surfaces and soil erosion. In the final step, the rangeland shifts into unproductive barren land, that is useless as a rangeland. It is very challenging to restore rangelands that have reached this final step, so detecting degradation in early stages is urgent.
Key references: (Jamsranjav et al., 2018; Milton et al., 1994; Whisenant, 1999)

Mongolian rangelands

Mongolia provides some clear examples of the challenges faced by global rangelands. Mongolian rangelands represent about 2.5% of the global grassland area (White et al., 2000) and are among the last intact continuous grasslands on Earth (Scholtz & Twidwell, 2022). Rangelands occupy around 80% of the Mongolian territory and almost half of the Mongolian population depends on livestock production (Undarmaa et al., 2018). Mongolia is one of the few countries in the world that has retained its traditional nomadic pastoralism (Nachinshonhor, 2013), which for thousands of years was a widespread and sustainable land use in Mongolia (Fernandez-Gimenez, 1999). The traditional nomadic way of managing the rangelands is based on observation and adaptation to the seasonal, climatic and vegetation fluctuations in time and space (Bruegger et al., 2014; Fernandez-Gimenez, 2000).

The territory of Mongolia, which covers an area of over 1.5 million square kilometers, can be divided into six main ecological zones (**Figure 1**) distinguished by their climate and vegetation (Jigjidsuren & Johnson, 2003): high mountains, mountain taiga, forest steppe, steppe, desert steppe, and desert. Together, the forest steppe, steppe and desert steppe cover about 70% of the country, and the rangelands in these zones represent a key resource for animal husbandry in Mongolia (Angerer et al., 2008). These ecological zones receive intensive human use and are considered the most degraded rangelands (NAMEM & MEGDT, 2015)

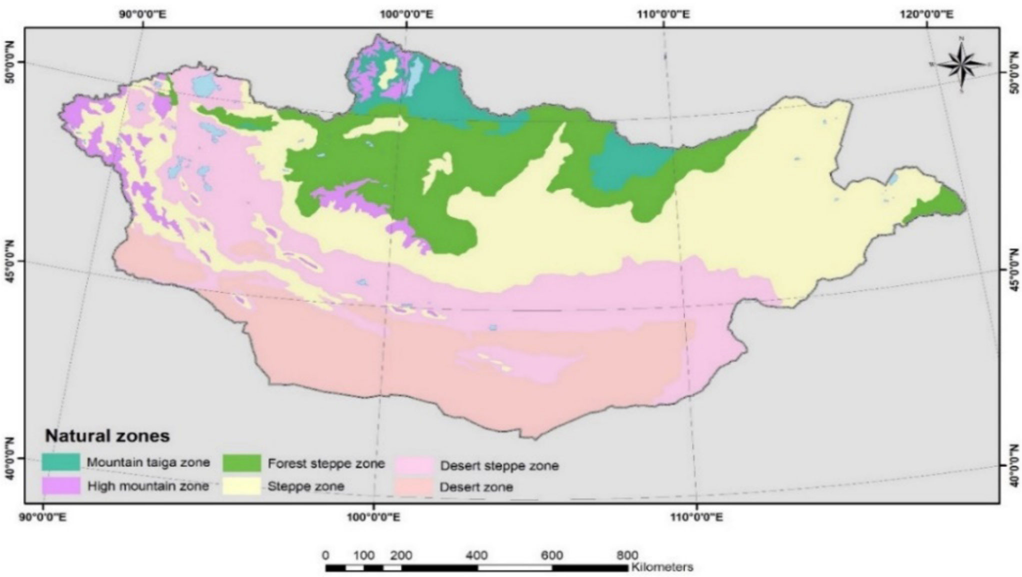

Figure 1. Ecological zones of Mongolia. Source: Green Gold Animal Health project

Similar to many rangeland ecosystems worldwide, Mongolian rangelands are believed to have been degraded considerably, especially within the last thirty years (Bulgan et al., 2013; Jamsranjav et al., 2018; Liu et al., 2013; NAMEM & MEGDT, 2015). Climate change and overgrazing are frequently mentioned as the main causes of land degradation in Mongolia (Batkhishig, 2013), but the predominant role of one or the other is not clear. Since 1940, the mean annual temperature in Mongolia has increased by 2.1°C and temperatures are projected to increase up to 5°C by the end of the 21st century (MARCC, 2009, 2014). In addition, the frequency of extreme weather events in Mongolia has increased over the last thirty years (Du et al., 2018; Fernandez-Gimenez et al., 2012; Sternberg, 2018). For example, the incidence of droughts (Nandintsetseg et al., 2021), the aridity index and the number of extreme warm days have increased and rangeland productivity and soil water availability have decreased, with severe consequences for rangeland health and herders' livelihoods (Du et al., 2018). It has been projected that current moist ecological zones such as the forest steppe will be replaced by dry steppe by the end of the century (Angerer et al., 2008). However, the effects of ongoing climate changes are complicated and often confounded by their interactions with grazing and rainfall (Ahlborn et al., 2020; Spence et al., 2014).

Overgrazing in Mongolia is believed to be the consequence of increasing livestock numbers over the past three decades (Bedunah & Schmidt, 2004; Berger et al., 2008; Luo et al., 2014). In 2021, Mongolia had more than 70 million heads of livestock (National Statistical Office of Mongolia, 2021), more than double than before 1990 (**Figure 2**). One of the reasons for this increase is that with the collapse of the Soviet Union and the transition to democracy in 1990, livestock became private property and their numbers increased exponentially (Berger et al., 2013; Maekawa, 2013). With the social reform and the industrial collapse, many people lost their jobs and shifted to a herder lifestyle which resulted in a doubling of the number of herders (Fernandez-Gimenez, 2001). In addition, livestock numbers were no longer centrally controlled by the government (Addison et al., 2012; Johnson et al., 2006). The continuous increase in livestock numbers that exceed the carrying capacity of the rangelands can lead to shortage of forage supply and uncontrolled rangeland degradation.

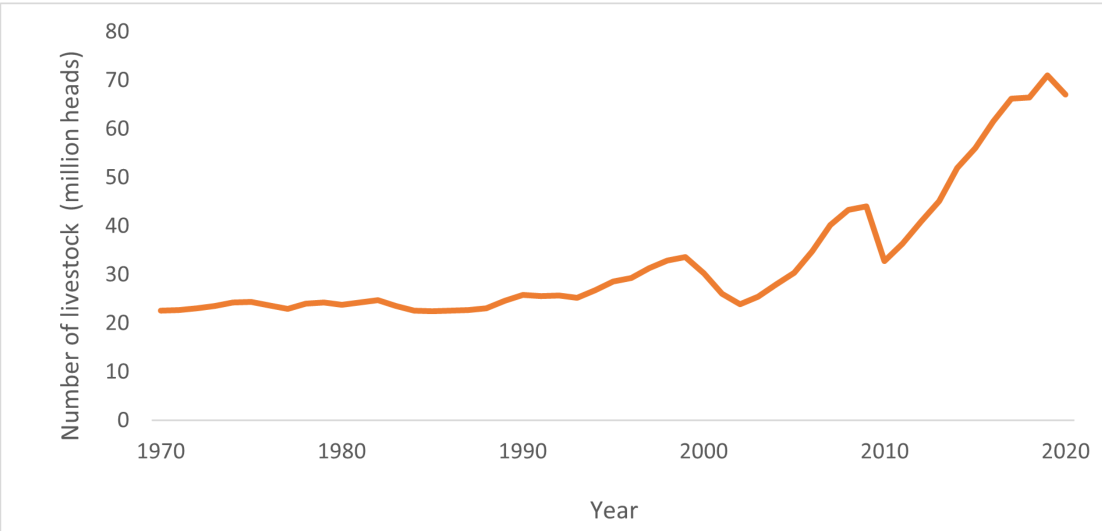

Figure 2. Total number of livestock (million heads) between 1970-2020 in Mongolia. Source: National Statistical Office (2020)

As a consequence of rangeland degradation, livestock productivity is reduced and herders become even more vulnerable to natural disasters such as drought and dzuds (harsh winter) (Nandintsetseg et al., 2021). Rangeland degradation and the socio-economic changes that have taken place in Mongolia in recent decades have accentuated the vulnerability of traditional nomadic practices and led directly or indirectly to increasing rates of rangeland degradation. The environmental conditions in Mongolia, with a harsh, continental climate and the occurrence of periodic extreme events, strongly influence the social and ecosystem dynamics in these systems (Kakinuma et al., 2019). In the face of ongoing climate change, mitigation and adaptation strategies should emphasize the flexibility of mobile herding systems to reduce the vulnerability of Mongolian pastoral systems.

Efforts to monitor rangeland condition in Mongolia

Monitoring allows detection of changes in rangeland states and is the basis for adaptive management. Adaptive long-term monitoring systems allow devising management strategies geared towards maintaining or improving rangeland health. To achieve these goals, it is essential that monitoring programs select reliable indicators of degradation or recovery of rangelands. Choosing a consistent set of standard indicators and methods for rangeland monitoring allows collecting consistent and relevant high-quality data (Karl et al., 2017).

Earlier studies on rangeland degradation in Mongolia provided diverging estimates of the extent and severity of degradation. These inconsistencies were probably due to the lack of long-term data, standardized monitoring methodologies and interpretation tools (Addison et al., 2012; Jamsranjav et al., 2018). To overcome these discrepancies, the National Rangeland Monitoring Program of Mongolia was established in 2011 by the National Agency for Meteorology, Hydrology and Environmental Monitoring (NAMEM). The program was strengthened with the support of the Green Gold Animal Health Project funded by the Swiss Agency for Development and Cooperation, and the program and its standardized protocol for data collection were endorsed by the government. This new standardized methodology and interpretation tool adopted a methodology developed in the US, which included the concept of Ecological Site Descriptions (ESDs) and the development of state and transition models adapted to Mongolian conditions (Herrick et al., 2017). The methodology is repeatable, precise, and user-friendly.

The rangeland monitoring program established 1516 monitoring sites across Mongolia (**Figure 3**), where data on core plant and soil indicators are collected every year. The rangeland monitoring system generates a large amount of high-quality data, and NAMEM publishes bi-annual reports on national rangeland health and interactive maps describing rangeland condition based on STMs for each monitoring site. The maintenance and functioning of this monitoring system is included within nationally approved programs at NAMEM and receives governmental support.

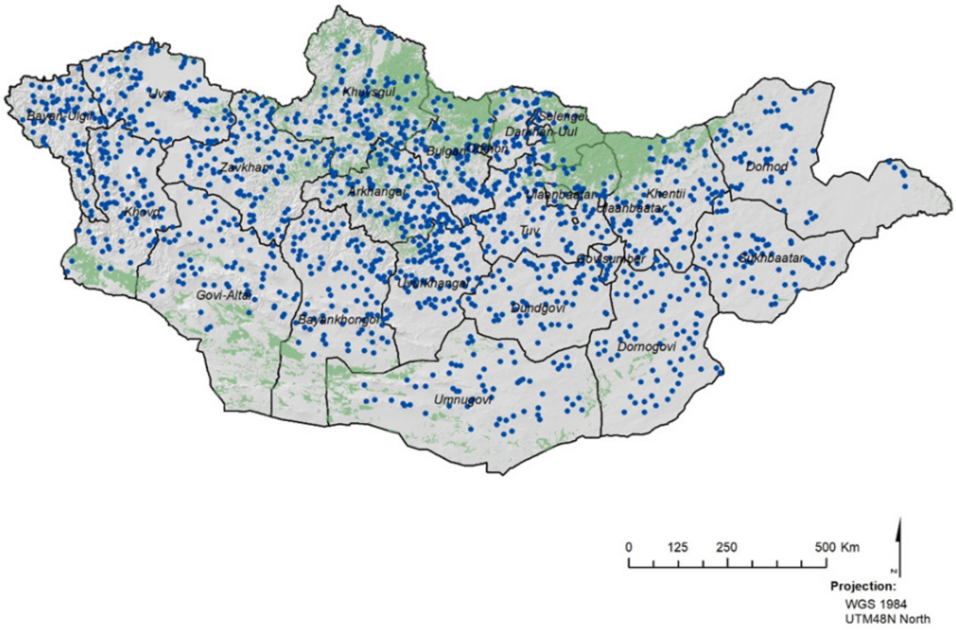

Figure 3. Nationwide long-term rangeland monitoring sites in Mongolia. Source: Green Gold Animal Health Project (2018)

Other large, broad scale rangeland studies in Mongolia include the Mongolian Rangelands and Resilience project (MOR2) funded by US National Science Foundation and the Peri-Urban Rangeland project (PURP) funded by US Millennium Challenge Corporation. MOR2 conducted socio-ecological survey in thirty-six *soums* of ten *aimags* in central and eastern Mongolia between 2011-2013 to assess resilience of Mongolian rangelands. PURP focused on rangeland degradation of peri-urban regions in 2011-2012 and was implemented in two phases. Phase II concentrated on areas surrounding two cities, Choibalsan (38 plots) and Kharkhorin (62 plots). These two projects used the same monitoring methodology (Herrick et al., 2017) and database structure (Courtright & van Zee, 2011) as the National Rangeland Monitoring Program of NAMEM. Although, these projects created their own databases, it has been possible to exchange data between projects. The data from these other two projects spatially complements data from NAMEM's nationwide monitoring.

Objectives of the thesis

The overarching goal of this thesis is to contribute to ongoing efforts to understand the patterns and underlying drivers of rangeland degradation in Mongolia.

The thesis has three specific goals: (1) to systematically review and synthesize information from studies on rangeland degradation in Mongolia to better understand how the issue has been addressed in the past, (2) to detect trends in rangeland vegetation change in different ecological zones of Mongolia using long-term monitoring data, and (3) to use detailed field data to disentangle regional drivers of vegetation change over ~10 years in the steppe zone of Mongolia.

Each goal is addressed in a separate paper.

Summary of investigations

The research has resulted in one published scientific paper, one paper submitted for publication and one manuscript.

The first paper reviewed and synthesized studies on rangeland degradation and vegetation change in Mongolia for the last ~70 years. We compiled 114 documents to understand how different studies defined and quantified rangeland degradation, whether studies mentioned explicitly a theoretical framework for degradation, which drivers of degradation were mentioned, and the distribution of the studies across relevant environmental gradients.

The second paper assessed trends in key indicators of rangeland change over time across three vast ecological zones of Mongolia. We used a quality-controlled subset of 502 locations within the NAMEM database balanced across the three ecological zones, with data on key indicators of rangeland change between 2012-2020.

The third paper analyzed long-term changes in vegetation structure and shifts in plant community composition in the Mongolian steppe. Thirty-one study sites across a 1,000 km gradient from central to eastern Mongolia were revisited after a ~10 year period to collect high-quality field data to disentangle the effects of changes in stocking densities and climate.

Materials and methods

This thesis used different approaches to address rangeland degradation in Mongolia, from synthesis of available literature (paper I) to trend analyses using a long-term nationwide database to assess changes in vegetation across Mongolian rangelands in three main ecological zones (paper II), and detailed analyses of field data to understand the relative contribution of different drivers of vegetation change (paper III).

To understand how previous studies had approached the issue of rangeland degradation in Mongolia, paper I compiled and synthesized the scientific and grey literature using a systematic review. Using a pre-defined list of search terms in international and local databases, the search retrieved 1994 studies published in English, Russian and Mongolian since 1950s. After filtering out studies that were not directly relevant to the synthesis, the review compiled 114 relevant documents spanning a period of 70 years. For each of these documents we extracted data on how studies defined and characterized degradation, whether the studies referred to a specific theoretical framework to describe degradation processes, the drivers of degradation identified by the studies and whether studies attempted at quantifying them, and the geographical distribution of studies.

To assess trends in rangeland vegetation change in different ecological zones of Mongolia, paper II used the nationwide long-term monitoring data on rangeland health of Mongolia collected by NAMEM between 2012-2020. We randomly sampled a balanced number of points (502 monitoring sites in total) located in the forest steppe, steppe and desert steppe zones of Mongolia, to compare their responses to well documented changes in climate and grazing pressures in Mongolia in the last decade. At each of these sites, vegetation and soil parameters were measured annually following a standardized methodology featuring two parallel 50 m transects, 25 m apart (**Figure 4**). Foliar and basal cover were estimated each year for each plant species, using the Line Point Intercept (LPI) method, with one point every 25 cm along the transects, for a total of 400 points per plot. Total aboveground biomass was clipped to ground level in five replicate 1 x 1 m quadrats per site.

Trends in the cover of plant functional groups and species, and structural characteristics of vegetation including overall biomass, were calculated using Thiel-Sen regression and Kendall's Tau was used to evaluate statistical significance ($P < 0.05$). The consistency of trends for each indicator at each ecological zone was estimated as the percentage of monitoring sites that showed a significant trend (positive or negative).

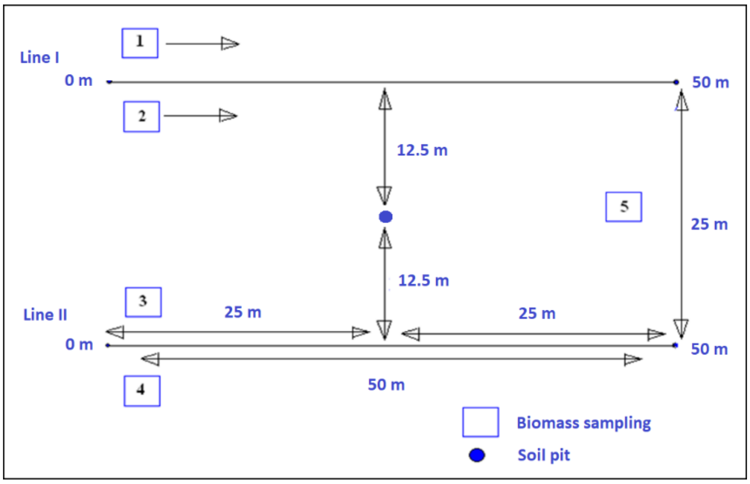

Figure 4. The diagram of the NAMEM monitoring sites. Two parallel line transects, 50 m long (Line I and II) are surveyed with the Line Point Intercept method with points every 25 cm. Aboveground plant biomass is sampled in five 1x1 m quadrats per site. A soil pit was excavated in the centre of the monitoring site when the site was established.

To investigate the drivers of vegetation change over ~10 years in the steppe zone of Mongolia, paper III used repeated field surveys of vegetation in 31 sites in the Mongolian steppe. The survey sites belonged to three large rangeland monitoring programs in Mongolia and spanned a 1,000 km gradient across the steppe zone. Twenty-one of these sites were located in the central steppe and 10 in the eastern steppe. Vegetation sampling and data collection was conducted in 2010-2012 and ~10 years later, in 2021, following the standardized methodology of the National Rangeland Monitoring Program of Mongolia (Herrick et al., 2017; NAMEM, 2011). Changes in structural and compositional characteristics of vegetation were related to changes in climate (monthly average temperature, monthly precipitation data) and stocking rates over the same period. Changes in community composition were assessed using Principal Component Analyses, and the direct and indirect effects of drivers on changes in foliar cover and aboveground plant biomass were assessed using piecewise Structural Equation Models.

Throughout the thesis, data summaries and analyses were conducted in the statistical software R, version 4.0.1 (R Core Team, 2020), using specific libraries for different analyses. For ecample, we used the *piecewiseSEM* package to build piecewise Structural Equation Models (Lefcheck, 2016) and the *emmeans* package (Lenth, 2022) to calculate least squares means and standard errors in paper III, and the *wql* package (Jassby & Cloern, 2017) to run the Mann-Kendall trend tests in paper II. The statistical software Canoco Version 5 (ter Braak & Smilauer, 2012) was used to run the multivariate analyses to investigate compositional shifts in vegetation presented in paper III.

Main findings

Concerns about vegetation change and rangeland degradation in Mongolia have increased substantially since the 1950s (paper I). Our systematic review found 114 documents related to rangeland degradation. Only six of these studies were published before 1990, while the number of documents increased drastically in the 2000s with a notable increase in the number of documents published in English in international scientific journals. These trends in the literature support an increased recognition of rangeland degradation as a main environmental concern in Mongolia, as also reflected in public media.

The majority of published studies assessing rangeland degradation in Mongolia used single response indicators, mostly including plant or plant community variables, followed by studies assessing changes in land cover and soil properties to detect changes in rangelands (paper I). Understanding Mongolian rangeland dynamics and detecting changes in ecosystem structure and function is important to prevent severe rangeland degradation and to guide the design of sustainable rangeland management strategies. For this reason, identifying a core set of indicators of rangeland health is an essential step to harmonizing data collection efforts. The National Rangeland Monitoring Program of Mongolia established in 2011 by the National Agency for Meteorology, Hydrology and Environmental Monitoring (NAMEM) aims at addressing this gap. Data on key indicators are collected annually at a large number of monitoring sites across Mongolia. NAMEM publishes interactive maps describing rangeland condition and presents summaries on national rangeland health in bi-annual reports, but the large NAMEM dataset remains a precious, untapped resource. This thesis represents one of the first attempts to use long-term data (9 years) throughout Mongolian rangelands to detect trends in vegetation change. Using this dataset (paper II) and additional analyses using high-quality field data at a subset of points within the steppe zone (paper III), our results confirm the occurrence of widespread changes across the Mongolian territory over the last decade.

In the scientific literature on rangeland degradation in Mongolia (paper I), we found that the use of conceptual frameworks was relatively limited (about one fourth of all studies). The most frequently mentioned theoretical framework until relatively recent times was the traditional successional model (Tuvshintogtokh, 2014). It was not until 2008 that new frameworks were introduced to rangeland degradation studies in Mongolia, including state and transition models and the integrated degradation framework (**Box 1**). Nowadays, the state and transition model framework is the main underpinning of the national rangeland monitoring program run by NAMEM.

The common belief is that overgrazing and climate change are the main drivers of degradation in Mongolia (paper I). All rangeland studies included in paper I mentioned at least one driver of degradation, but the quantification of the effects of these drivers was insufficient. Approximately

60 percent of studies mentioned livestock grazing as the only driver of degradation, particularly in the ecological zones that are used for agricultural purposes, i.e., the steppe, forest steppe and desert steppe. Quantifying the relative importance of degradation drivers in the different ecological zones is crucial for adaptive management. Our work showed that indeed, climate and stocking rates influence vegetation dynamics across the steppe zone of Mongolia (paper III), but the relative importance of these drivers varies regionally. Grazing had a stronger effect in the eastern steppe, while in the central steppe precipitation was the main driver of vegetation change, through its effects on the cover of grasses.

Understanding what drives rangeland dynamics is crucial for developing sustainable management practices, especially in Mongolia where equilibrium and non-equilibrium systems coexist and are mixed in the vast territory (papers II and III). Rangeland degradation studies covered all ecological zones in Mongolia, but the distribution was not even. The largest number of studies was recorded in the steppe and forest steppe, followed closely by the desert steppe (paper I). When taking a closer look at vegetation trends in these main ecological zones over the last decade (paper II) we found that trends in key indicators of rangeland change differed. Contrary to our expectations based on the non-equilibrium theory, whereby the forest steppe being an equilibrium system would be more prone to degradation, we found that the steppe zone showed stronger and more consistent changes across monitoring sites, consistent with degradation trends. Further, within the steppe zone, we found that the relative importance of climate and stocking rates varied regionally depending on environmental conditions (paper III). Our results showed that the Mongolian steppe responds to climate and grazing in complex ways that show marked regional variation. These results highlight the need to consider spatial variation in the importance of climate change and grazing effects when designing regional rangeland management strategies.

Discussion

How have previous studies approached the issue of rangeland degradation in Mongolia?

The number of scientific publications on rangeland degradation in Mongolia notably increased after the mid-1990s and progressively more of these studies were published in international fora (**Figure 2** in paper I). The studies published before the 1990s reported on impacts of grazing by wild and domestic herbivores in Mongolian rangelands, but overgrazing was not mentioned as a common concern. The observed changes in vegetation were thought to be related to the arid conditions prevailing in the country (Yunatov, 1950). This view is consistent with general models of rangeland dynamics proposed in the late 1980s, where the role of abiotic conditions and productivity were proposed as key moderators of the effects of grazing on plant communities (Milchunas et al., 1988). However, concerns about rangeland degradation issues in Mongolia became more prominent in the literature in the early 2000s (paper I), as also found by Johnson et al. (2006). Our review included all possible studies about rangeland status and vegetation condition in Mongolia with a special focus on the grey literature. Many studies in Mongolia have been only published as internal reports, and in the best case only brief summaries of these studies have been included in review papers published in international journals, so a wealth of information on rangeland degradation remains hidden to the international scientific community (Addison et al., 2012; Jamsranjav et al., 2018).

All the studies mentioned rangeland degradation in the paper I but the specific definition and the methodology used to describe rangeland degradation is not clear and differed among studies. Defining degradation is often problematic and frequently involves a subjective component (Engler & von Wehrden, 2018) but it is a key step if we want to coordinate research efforts. Such differences in definitions and methodology used in the assessment of rangeland degradation have been acknowledged by other studies (Jamsranjav et al., 2018; Li et al., 2013) and make comparisons across studies difficult. For example, we found large discrepancies in the extent of rangeland degradation in Mongolia, varying from 22 to 95% of the total territory (**Table 1** in paper I). Such differences in the results obtained by scientific studies contribute to muddling the message that is conveyed to the public and policy makers (Addison et al., 2012). Thus, the use of standardized methodologies should be a priority, so that estimates provided by different studies are comparable.

Most studies on rangeland degradation did not explicitly mention a conceptual framework to understand rangeland degradation. Among the studies that mentioned a theoretical framework, most referred to the traditional rangeland model, which has been used in Mongolia until recent times (Tuvshintogtokh, 2014). However, this framework has been dismissed as outdated in the international literature as it is not applicable to most arid and semiarid rangelands. State and transition models (STMs) were developed in the late 1980s (Bestelmeyer et al., 2017; Westoby et al., 1989) to accommodate nonlinear and irreversible system dynamics, but were not applied to rangeland studies in Mongolia until 2008 (Sasaki et al., 2008). STMs are currently applied to national monitoring programs (NAMEM & MEGDT, 2015) and help guide rangeland research in Mongolia. More recently, some studies have incorporated the integrated degradation framework (Jamsranjav et al., 2018; Khishigbayar et al., 2015), which recognizes different degradation steps and emphasizes the need to integrate vegetation and soil indicators. The application of these conceptual models based on robust frameworks in rangeland monitoring and assessments is essential to understand rangeland degradation in Mongolia and to develop adaptive management plans.

What are the trends in rangeland vegetation in different ecological zones of Mongolia?

Using the database of the National Rangeland Monitoring Program of Mongolia, trends in key indicators across the three main ecological zones of Mongolia were explored for the first time in paper II. Prior to that, only remote sensing studies had provided information on long-term and broad-scale changes in Mongolian rangelands (Hilker et al., 2014; Liu et al., 2013). Remotely-sensed vegetation indices cannot, however, fully capture plant compositional changes (Hiernaux et al., 2009; Miehe et al., 2010). Ground-based studies in contrast, represent a snapshot of one or two years and are generally more limited in spatial coverage. The large database of the National Rangeland Monitoring Program of Mongolia collected by NAMEM provides a unique opportunity to detect vegetation changes in Mongolian rangelands, with its extensive network of sites where data has been collected annually since 2012 using a standardized methodology.

Our analyses showed non-significant trends for key vegetation and plant indicators between 2012-2020 for most of the monitoring sites (paper II). This result could be attributed to a conservative statistical approach for defining trends to detect change in rangelands. The observed lack of clear degradation trends at most monitoring points could also reflect efforts to improve grazing management and to prevent further rangeland degradation. For the sites where significant trends were detected, on the other hand, these were consistent with described degradation pathways. Some key indicators like the habitat forming grass species *Stipa* sp showed decreasing trends in 21.2% of the sites in the steppe (**Figure 3** in paper II), while *Artemisia adamsii* a well-known indicator of rangeland degradation, showed increasing trends in 4.3% of the monitoring sites. These results align with other studies conducted in the steppe zone in which dominant grass species are replaced by *Carex duriuscula, Artemisia frigida* and *Allium polyrrhizum* in moderately degraded grasslands (Na et al., 2018; Okayasu et al., 2012). In turn, in heavily degraded sites unpalatable subshrubs like *Artemisia adamsii* and *Artemisia frigida* become dominant and create a patchy vegetation pattern (Na et al., 2018; Okayasu et al., 2012). We also found that total biomass showed decreasing trends in all three ecological zones. This result is also supported by previous studies. For example, Sternberg et al (2011) found that aboveground biomass in central Mongolian steppe decreased by 16% between 1998 and 2006 based on both remotely-sensed NDVI data and field observations. Similarly, Liu et al. (2013) detected declines in biomass between 1988 and 2008 throughout the steppe zone of Mongolia. Overall, these changes are also reflected in the state and transition models for Mongolian rangelands (Densambuu et al., 2018) which provide a useful tool to interpret rangeland trends.

Interestingly, the observed trends were clustered in certain areas and could be related to different pressures specific to those regions. For example, our results (paper II) are consistent with the steppe being a hotspot for ongoing degradation, particularly the central steppe which has higher stocking rates than the eastern part. In addition, in 2010-2012 most sites in eastern Mongolia were in good condition (closer to reference state), whereas sites in central Mongolia were in moderate or heavily degraded states (paper III; (Densambuu et al., 2018)).

Following the predictions of the non-equilibrium theory, we expected to find more evidence of changes in key vegetation parameters in the forest steppe zone rather than in the steppe (paper II). However, we found more consistent significant trends in the steppe. The non-equilibrium model has been tested by Fernandez-Gimenez and Allen-Diaz (1999) in Mongolian rangelands including the mountain steppe, steppe and desert steppe zones. They found that the steppe zone conformed to the traditional successional model, with declines in the cover of grasses and increases in the cover of forbs and annuals in response to increased grazing pressure (Fernandez-Gimenez & Allen-Diaz, 1999). They concluded that the responses of rangeland ecosystems to climate and grazing are complex, and rangeland dynamics are difficult to interpret. Along the same lines, we found that even within the steppe zone, regional differences can determine that the system behaves more like a non-equilibrium (i.e. climate-driven) or an equilibrium (i.e. grazing-driven) system (paper III). These results agree with studies that concluded it is crucial that rangeland dynamics is continuum between equilibrium and non-equilibrium (Boone & Wang, 2007; Derry & Boone, 2010). Our results support the notion that rangeland dynamics are not black or white, and it might not be possible to apply a clear-cut categorization of rangelands into equilibrium or non-equilibrium systems, especially in highly variable ecosystems like Mongolia.

What are the main drivers of vegetation change over ~10 years in the steppe zone of Mongolia?

The responses of the Mongolian steppe ecosystem to climate and grazing have been the focus of many studies (paper I). This is not surprising, given that this region is one of the most populated and intensively used for animal husbandry in Mongolia (Angerer et al., 2008). How these systems will respond to ongoing changes in climate and land use remains a question and disentangling the effect of different drivers is essential to determine proper rangeland management strategies in the steppe. Using high-quality field data collected ~10 years after the initial surveys, we found widespread changes in the structure and composition of vegetation in the Mongolian steppe (paper III). These changes are consistent with those found by other studies (Bazha et al., 2015; Jamiyansharav et al., 2018; Khishigbayar et al., 2015; Na et al., 2018; Tuvshintogtokh & Ariungerel, 2013). However, even within an ecologically defined zone, we observed regional differences in the responses to drivers. The observed shifts in community composition in the eastern steppe were towards communities typical of the arid central steppe communities that had been observed in the baseline survey, while changes in the central steppe diverged depending on grazing pressure. In the central steppe, sites associated with higher stocking densities shifted to communities dominated by sedges and annuals. Comparable changes have been also reported by Yang et al (2022) who found that grazing increased C4 annuals like *Salsola collina* in Mongolian grasslands. In contrast, sites with a relatively low grazing pressure shifted to grass-dominated communities (**Figure 6** in paper III). These changes are in line with other studies that show that the abundance of grazing tolerant grasses and xerophytic shrubs, subshrubs and sedges increased in response to grazing in central and eastern Mongolian steppe (Bazha et al., 2015; Danzhalova, 2008; Gunin et al., 2012; Tuvshintogtokh & Ariungerel, 2013).

Grazing was recognized as the main driver of rangeland degradation by most studies (**Figure 4** in paper I), followed by precipitation and temperature. However, the relative importance of these drivers seems to differ (paper II) between ecological zones (Dangal et al., 2016; Hilker et al., 2014; Narantsetseg et al., 2015), and even within ecological zones as the contribution of different drivers varied regionally within the steppe zone (**Figure 7** in paper III). Grazing had a stronger effect in the eastern steppe, while precipitation was the main driver of vegetation change in the central steppe, through its effects on the cover of grasses. Our results highlight the importance of considering regional differences in the effects of drivers on grassland vegetation when designing sustainable grazing management strategies (Munkhzul et al., 2021). It is important to conduct long-term studies that allow detecting vegetation dynamics using standardized key indicators and to quantify drivers of change at the ecoregional level. Such studies should be complemented with experimental studies like exclosures to understand the mechanisms behind rangeland degradation processes.

Conclusions

Increasing concerns about rangeland degradation in Mongolia emphasize the urgent need to understand rangeland dynamics, the drivers of degradation and their regional variation. This thesis assessed the current state of knowledge of rangeland and vegetation change in Mongolia by synthesizing a large amount of information compiled through a systematic literature review, including grey literature in Mongolian, as well as through new analyses of long-term monitoring data. Our synthesis and analyses identified several issues that needed to be considered in this field and that have been addressed in this thesis:

(1) Standardized methodologies and approaches are needed so that results of different studies are comparable, and the message conveyed to the public and policy makers is less ambiguous. Based on this observation, we used data collected using a standardized methodology to detect trends in vegetation change and to describe their drivers in papers II and III.

(2) The use of theoretical frameworks can help in understanding the processes of rangeland degradation, but their application to vegetation studies in Mongolia has been limited. The results of papers II and III contributed to the global debate of non-equilibrium theory by demonstrating that the application of a clear-cut division between equilibrium and non-equilibrium systems is difficult because most systems, especially in the Mongolian steppe, show intermediate behaviour.

(3) Grazing and climate are frequently mentioned as the main drivers of degradation, but they have not been adequately quantified (paper I). Investigation of the main drivers of vegetation change in the steppe zone (paper III) revealed that interactions between these drivers are complex and vary regionally. The Mongolian territory covers a vast area and includes a wide range of environmental conditions and rangeland types with different ecological potential. Given this variability, the response of rangelands to abiotic and biotic disturbances differs markedly even within ecological zones. Considering such regional differences is important to design sustainable rangeland management in Mongolia.

(4) Previous studies and existing monitoring sites within the National Rangeland Monitoring Program of Mongolia cover well the three main ecological zones (forest steppe, steppe and desert steppe), but monitoring sites in high mountain and desert are scarce. Given the predictions of stronger climate change in high mountain areas and desert, there is a need to expand monitoring sites in these regions.

In sum, this thesis advances our knowledge on rangeland degradation in Mongolia, by synthesizing available knowledge (paper I), detecting trends and patterns of vegetation change (paper II), and disentangling the drivers of change in the steppe zone (paper III). This thesis also contributes to testing global theoretical models of rangeland science, and emphasizes that, despite our best efforts, we are still far from understanding the complexities of rangeland degradation. Nevertheless, current efforts to monitor rangeland health in Mongolia that use standardized methodologies for long-term data collection and are based on robust theoretical frameworks hold promise for the design of policies and strategies for sustainable land use and can provide a model example for other countries facing similar issues.

Future work

This thesis has consolidated previous knowledge on rangeland degradation in Mongolia and has contributed new understanding of the trends in vegetation dynamics and its drivers across Mongolia. In doing so, the thesis has also identified important knowledge gaps and several avenues for future research. Priorities for future research should include:

- Clarifying definitions of degradation and using standardized methods specific to different ecological zones to measure rangeland degradation appropriately and consistently.
- Defining suitable indicators of rangeland dynamics, including both vegetation and soil indicators based on the ecological potential of different rangelands in Mongolia.
- Quantifying the relative importance of different drivers not only within each ecological zone, but at an ecoregional level.
- Understanding the complex interplay of climate and grazing on rangeland vegetation dynamics. Experimental studies are needed to better understand the mechanisms behind the influence of different drivers and complement existing observational studies conducted at larger spatial and temporal scales.
- Using available nationwide long-term rangeland monitoring data to its full potential, to better understand rangeland trends and their regional variation.
- Strengthening appropriate theoretical frameworks to understand rangeland dynamics and support their application. In this respect, State and Transition Models have shown promise and have been implemented within national programs. Further refinement of the models is, however, needed.
- Better understanding the role of rangelands in food security and the future challenges posed by ongoing environmental changes.

References

Addison, J., Friedel, M., Brown, C., Davies, J., & Waldron, S. (2012). A critical review of degradation assumptions applied to Mongolia's Gobi Desert. *The Rangeland Journal*, *34*(2), 125-137. https://doi.org/http://dx.doi.org/10.1071/RJ11013

Ahlborn, J., von Wehrden, H., Lang, B., Römermann, C., Oyunbileg, M., Oyuntsetseg, B., & Wesche, K. (2020). Climate–grazing interactions in Mongolian rangelands: Effects of grazing change along a large-scale environmental gradient. *Journal of Arid Environments*, *173*, 104043.

Al-Bukhari, A., Hallett, S., & Brewer, T. (2018). A review of potential methods for monitoring rangeland degradation in Libya. *Pastoralism*, *8*(1), 1-14.

Angerer, J., Han, G., Fujisaki, I., & Havstad, K. (2008). Climate change and ecosystems of Asia with emphasis on Inner Mongolia and Mongolia. *Rangelands*, *30*(3), 46-51.

Batkhishig, O. (2013). Human impact and land degradation in Mongolia. In *Dryland East Asia: Land Dynamics amid Social and Climate Change*. The Higher Education Press.

Bazha, S. N., Gunin, P. D., Danzhalova, E. V., Drobyshev, Y. I., Kazantseva, T. I., Ariunbold, E., . . . Tserenkhand, G. (2015). Invasive Successions as the Indicator of Desertification of Dry Steppe by Way of Example of Central Mongolia. *Russian Journal of Biological Invasions*, *6*(4), 223-237. https://doi.org/10.1134/S2075111715040025

Bedunah, D. J., & Schmidt, S. M. (2004). Pastoralism and Protected Area Management in Mongolia's Gobi Gurvansaikhan National Park. *Development and Change*, *35*(1), 167-191. https://doi.org/10.1111/j.1467-7660.2004.00347.x

Bengtsson, J., Bullock, J. M., Egoh, B., Everson, C., Everson, T., O'Connor, T., . . . Lindborg, R. (2019). Grasslands—more important for ecosystem services than you might think. *Ecosphere*, *10*(2), e02582.

Berger, J., Buuveibaatar, B., & Mishra, C. (2013). Globalization of the Cashmere Market and the Decline of Large Mammals in Central Asia. *Conservation Biology*, *27*(4), 679-689. https://doi.org/10.1111/cobi.12100

Berger, J., Young, J. K., & Berger, K. M. (2008). Protecting migration corridors: challenges and optimism for Mongolian saiga. *PLoS Biology*, *6*(7), e165.

Bestelmeyer, B. T., Ash, A., Brown, J. R., Densambuu, B., Fernández-Giménez, M., Johanson, J., . . . Shaver, P. (2017). State and transition models: theory, applications, and challenges. In D. D. Briske (Ed.), *Rangeland Systems* (pp. 303-345). Springer, Cham.

Bestelmeyer, B. T., Okin, G. S., Duniway, M. C., Archer, S. R., Sayre, N. F., Williamson, J. C., & Herrick, J. E. (2015). Desertification, land use, and the transformation of global drylands. *Frontiers in Ecology and the Environment*, *13*(1), 28-36.

Boone, R. B., Conant, R. T., Sircely, J., Thornton, P. K., & Herrero, M. (2018). Climate change impacts on selected global rangeland ecosystem services. *Global Change Biology*, *24*(3), 1382-1393.

Boone, R. B., & Wang, G. (2007). Cattle dynamics in African grazing systems under variable climates. *Journal of Arid Environments*, *70*(3), 495-513.

Briske, D. D., Illius, A. W., & Anderies, J. M. (2017). Nonequilibrium ecology and resilience theory. In *Rangeland Systems* (pp. 197-227). Springer, Cham.

Bruegger, R. A., Jigjsuren, O., & Fernandez-Gimenez, M. E. (2014). Herder Observations of Rangeland Change in Mongolia: Indicators, Causes, and Application to Community-Based Management. *Rangeland Ecology & Management*, *67*(2), 119-131. https://doi.org/10.2111/rem-d-13-00124.1

Bulgan, D., Mandakh, N., Odbayar, M., Otgontugs, J., Tsogtbaatar, J., Elbegjargal, N., . . . Erdenetuya, M. (2013). Desertification atlas of Mongolia. In M. A. o. S. Institute of Geoecology (Ed.). Ulaanbaatar, Mongolia.

Byrnes, R. C., Eastburn, D. J., Tate, K. W., & Roche, L. M. (2018). A global meta-analysis of grazing impacts on soil health indicators. *Journal of Environmental Quality*, *47*(4), 758-765.

Clements, F. E. (1916). *Plant succession: an analysis of the development of vegetation*. Carnegie Institution of Washington.

Courtright, E. M., & van Zee, J. W. (2011). The Database for Inventory, Monitoring, and Assessment (DIMA). *Rangelands*, *33*(4), 21-26. https://doi.org/10.2111/1551-501X-33.4.21

Dangal, S. R. S., Tian, H., Lu, C., Pan, S., Pederson, N., & Hessl, A. (2016). Synergistic effects of climate change and grazing on net primary production of Mongolian grasslands. *Ecosphere*, *7*(5), e01274.

Danzhalova, E. V. (2008). *Rangeland degradation of steppe ecosystem in Central Mongolia* [Doctoral dissertation, Buryat State University]. Moscow, Russia.

Densambuu, B., Indree, T., Battur, A., & Sainnemekh, S. (2018). State and transition models of Mongolian rangelands. (4th ed.). TEPE publishing, Ulaanbaatar, Mongolia.

Derry, J. F., & Boone, R. B. (2010). Grazing systems are a result of equilibrium and non-equilibrium dynamics. *Journal of Arid Environments*, *74*(2), 307-309.

Du, C., Shinoda, M., Tachiiri, K., Nandintsetseg, B., Komiyama, H., & Matsushita, S. (2018). Mongolian herders' vulnerability to dzud: a study of record livestock mortality levels during the severe 2009/2010 winter. *Natural Hazards*, *92*(1), 3-17.

Duan, C., Shi, P., Zong, N., Zhang, X., & Yu, C. (2022). Assessing Rangeland Sensitivity to Degradation in North Tibet. *Rangeland Ecology & Management*, *84*, 86-97.

Dyksterhuis, E. J. (1949). Condition and management of range land based on quantitative ecology. *Rangeland Ecology & Management/Journal of Range Management Archives*, *2*(3), 104-115.

D'Odorico, P., Bhattachan, A., Davis, K. F., Ravi, S., & Runyan, C. W. (2013). Global desertification: drivers and feedbacks. *Advances in Water Resources*, *51*, 326-344.

Ellis, J. E., & Swift, D. M. (1988). Stability of African pastoral ecosystems: alternate paradigms and implications for development. *Rangeland Ecology & Management/Journal of Range Management Archives*, *41*(6), 450-459.

Engler, J.-O., & von Wehrden, H. (2018). Global assessment of the non-equilibrium theory of rangelands: Revisited and refined. *Land Use Policy*, *70*, 479-484.

Fernandez-Gimenez, M. E. (1999). Sustaining The Steppes: A Geographical History of Pastoral Land Use in Mongolia. *Geographical Review*, *89*(3), 315-342. https://doi.org/10.1111/j.1931-0846.1999.tb00222.x

Fernandez-Gimenez, M. E. (2000). The Role of Mongolian Nomadic Pastoralists' Ecological Knowledge in Rangeland Management. *Ecological Applications*, *10*, 1318-1326.

Fernandez-Gimenez, M. E. (2001). The effects of livestock privatization on pastoral land use and land tenure in post-socialist Mongolia. *Nomadic Peoples*, *5*(2), 49-66.

Fernandez-Gimenez, M. E., Batkhishig, B., & Batbuyan, B. (2012). Cross-boundary and cross-level dynamics increase vulnerability to severe winter disasters (dzud) in Mongolia [Article]. *Global Environmental Change-Human and Policy Dimensions*, *22*(4), 836-851. https://doi.org/10.1016/j.gloenvcha.2012.07.001

Fernandez-Gimenez, M. E., & Allen-Diaz, B. (1999). Testing a non-equilibrium model of rangeland vegetation dynamics in Mongolia. *Journal of Applied Ecology*, *36*(6), 871-885.

Godde, C. M., Boone, R. B., Ash, A. J., Waha, K., Sloat, L. L., Thornton, P. K., & Herrero, M. (2020). Global rangeland production systems and livelihoods at threat under climate change and variability. *Environmental Research Letters*, *15*(4), 044021. https://doi.org/10.1088/1748-9326/ab7395

Gunin, P. D., Bazha, S. N., Danzhalova, E. V., Dmitriev, I. A., Drobyshev, Y. I., Kazantseva, T. I., . . . Titova, S. V. (2012). Expansion of Ephedra sinica Stapf. in the arid steppe ecosystems of Eastern and Central Mongolia. *Arid Ecosystems*, *2*(1), 18-33.

Han, J. G., Zhang, Y. J., Wang, C. J., Bai, W. M., Wang, Y. R., Han, G. D., & Li, L. H. (2008). Rangeland degradation and restoration management in China. *The Rangeland Journal*, *30*(2), 233-239.

Harris, R. B. (2010). Rangeland degradation on the Qinghai-Tibetan plateau: a review of the evidence of its magnitude and causes. *Journal of Arid Environments*, *74*(1), 1-12.

Herrick, J. E., Shaver, P., Pyke, D. A., Pellant, M., Toledo, D., & Lepak, N. (2019). A strategy for defining the reference for land health and degradation assessments. *Ecological Indicators*, *97*, 225-230.

Herrick, J. E., van Zee, J. W., McCord, S. E., Courtright, E. M., Karl, J. W., & Burkett, L. M. (2017). Monitoring manual for grassland, shrubland and savanna ecosystems, 2nd edn.. Volume, I: Las Cruces, New Mexico: Core Methods. USDA-ARS Jornada Experimental Range. In.

Hiernaux, P., Mougin, E., Diarra, L., Soumaguel, N., Lavenu, F., Tracol, Y., & Diawara, M. (2009). Sahelian rangeland response to changes in rainfall over two decades in the Gourma region, Mali. *Journal of Hydrology*, *375*(1-2), 114-127.

Hilker, T., Natsagdorj, E., Waring, R. H., Lyapustin, A., & Wang, Y. (2014). Satellite observed widespread decline in Mongolian grasslands largely due to overgrazing. *Global Change Biology*, *20*(2), 418-428. https://doi.org/10.1111/gcb.12365

Hoppe, F., Zhusui Kyzy, T., Usupbaev, A., & Schickhoff, U. (2016). Rangeland degradation assessment in Kyrgyzstan: vegetation and soils as indicators of grazing pressure in Naryn Oblast. *Journal of Mountain Science*, *13*(9), 1567-1583.

Hruska, T., Huntsinger, L., Brunson, M., Li, W., Marshall, N., Oviedo, J. L., & Whitcomb, H. (2017). Rangelands as social–ecological systems. In *Rangeland Systems* (pp. 263-302). Springer, Cham.

Illius, A. W., & O'Connor, T. G. (1999). On the relevance of nonequilibrium concepts to arid and semiarid grazing systems. *Ecological Applications*, *9*(3), 798-813.

ILRI IUCN FAO WWF UNEP, & ILC. (2021). Rangelands Atlas. In. Nairobi Kenya: ILRI.

Jamiyansharav, K., Fernández-Giménez, M. E., Angerer, J. P., Yadamsuren, B., & Dash, Z. (2018). Plant community change in three Mongolian steppe ecosystems 1994–2013: applications to state-and-transition models. *Ecosphere*, *9*(3), e02145.

Jamsranjav, C., Reid, R. S., Fernández-Giménez, M. E., Tsevlee, A., Yadamsuren, B., & Heiner, M. (2018). Applying a dryland degradation framework for rangelands: the case of Mongolia. *Ecological Applications*, *28*(3), 622-642.

Jassby, A. D., & Cloern, J. E. (2017). Some tools for exploring water quality monitoring data. R package 729 version 0.4. 9. In.

Jigjidsuren, S., & Johnson, D. A. (2003). *Forage plants of Mongolia*. Admon publishing, Ulaanbaatar, Mongolia.

Johnson, D. A., Sheehy, D. P., Miller, D., & Damiran, D. (2006). Mongolian rangelands in transition. *Secheresse*, *17*(1/2), 133-141.

Kakinuma, K., Yanagawa, A., Sasaki, T., Rao, M. P., & Kanae, S. (2019). Socio-ecological interactions in a changing climate: a review of the Mongolian pastoral system. *Sustainability*, *11*(21), 5883.

Karl, J. W., Herrick, J. E., & Pyke, D. A. (2017). Monitoring protocols: options, approaches, implementation, benefits. In *Rangeland Systems* (pp. 527-567). Springer, Cham.

Khishigbayar, J., Fernández-Giménez, M. E., Angerer, J. P., Reid, R. S., Chantsallkham, J., Baasandorj, Y., & Zumberelmaa, D. (2015). Mongolian rangelands at a tipping point? Biomass and cover are stable but composition shifts and richness declines after 20 years of grazing and increasing temperatures. *Journal of Arid Environments*, *115*, 100-112.

Lefcheck, J. S. (2016). piecewiseSEM: Piecewise structural equation modelling in R for ecology, evolution, and systematics. *Methods in Ecology and Evolution*, *7*(5), 573-579.

Lenth, R. (2022). *emmeans: estimated marginal means, aka least-squares means. R package version 1.4. 7. 2020*. In

Li, X. L., Gao, J., Brierley, G., Qiao, Y. M., Zhang, J., & Yang, Y. W. (2013). Rangeland degradation on the Qinghai-Tibet plateau: Implications for rehabilitation. *Land degradation & development*, *24*(1), 72-80.

Lindenmayer, D. B., & Likens, G. E. (2009). Adaptive monitoring: a new paradigm for long-term research and monitoring. *Trends in Ecology & Evolution*, *24*(9), 482-486.

Liu, Y. Y., Evans, J. P., McCabe, M. F., de Jeu, R. A. M., van Dijk, A. I. J. M., Dolman, A. J., & Saizen, I. (2013). Changing climate and overgrazing are decimating Mongolian steppes. *Plos One*, *8*(2), e57599.

Lund, H. G. (2007). Accounting for the world's rangelands. *Rangelands*, *29*(1), 3-10.

Luo, Z., Liu, B., Liu, S., Jiang, Z., & Halbrook, R. S. (2014). Influences of human and livestock density on winter habitat selection of Mongolian gazelle (Procapra gutturosa). *Zoological Science*, *31*(1), 20-30.

Maekawa, A. (2013). The cash in cashmere: Herders' incentives and strategies to increase the goat population in post-socialist Mongolia. In *The Mongolian Ecosystem Network* (pp. 233-245). Springer.

MARCC. (2009). *Mongolia: Assessment Report on Climate Change 2009*.

MARCC. (2014). *Mongolia: Second Assessment Report on Climate Change*.

Michalk, D. L., Kemp, D. R., Badgery, W. B., Wu, J., Zhang, Y., & Thomassin, P. J. (2019). Sustainability and future food security—a global perspective for livestock production. *Land Degradation & Development*, *30*(5), 561-573.

Miehe, S., Kluge, J., Von Wehrden, H., & Retzer, V. (2010). Long-term degradation of Sahelian rangeland detected by 27 years of field study in Senegal. *Journal of Applied Ecology*, *47*(3), 692-700.

Milchunas, D. G., Sala, O. E., & Lauenroth, W. K. (1988). A generalized model of the effects of grazing by large herbivores on grassland community structure. *The American Naturalist*, *132*(1), 87-106.

Milton, S. J., du Plessis, M. A., & Siegfried, W. R. (1994). A conceptual model of arid rangeland degradation. *BioScience*, *44*(2), 70-76.

Mirzabaev, A., Ahmed, M., Werner, J., Pender, J., & Louhaichi, M. (2016). Rangelands of Central Asia: challenges and opportunities. *Journal of Arid Land*, *8*(1), 93-108.

Molina, A., Govers, G., Vanacker, V., Poesen, J., Zeelmaekers, E., & Cisneros, F. (2007). Runoff generation in a degraded Andean ecosystem: Interaction of vegetation cover and land use. *Catena*, *71*(2), 357-370.

Munkhzul, O., Oyundelger, K., Narantuya, N., Tuvshintogtokh, I., Oyuntsetseg, B., Wesche, K., & Jaeschke, Y. (2021). Grazing Effects on Mongolian Steppe Vegetation—A Systematic Review of Local Literature. *Frontiers in Ecology and Evolution*, *9*, 703220.

Na, Y., Li, J., Hoshino, B., Bao, S., Qin, F., & Myagmartseren, P. (2018). Effects of different grazing systems on aboveground biomass and plant species dominance in typical Chinese and Mongolian steppes [Article]. *Sustainability (Switzerland)*, *10*(12), Article 4753. https://doi.org/10.3390/su10124753

Nachinshonhor, U. (2013). Use of Steppe Vegetation by Nomadic Pastoralists in Mongolia. In N. Yamamura, N. Fujita, & A. Maekawa (Eds.), *The Mongolian Ecosystem Network* (pp. 145-156). Springer Japan. https://doi.org/10.1007/978-4-431-54052-6_12

NAMEM. (2011). *Monitoring manual for Hydrology, Meteorology and Environment: Agrometeorology*. National Agency for Meteorology, Hydrology and Environmental Monitoring. Ulaanbaatar, Mongolia.

NAMEM, & MEGDT. (2015). *National report on the rangeland health of Mongolia*. National Agency for Meteorology and Environmental Monitoring and Ministry of Environment, Green Development and Tourism. TEPE publishing, Ulaanbaatar, Mongolia

Nandintsetseg, B., Boldgiv, B., Chang, J. F., Ciais, P., Davaanyam, E., Batbold, A., . . . Stenseth, N. C. (2021). Risk and vulnerability of Mongolian grasslands under climate change. *Environmental Research Letters*, *16*(3), Article 034035. https://doi.org/10.1088/1748-9326/abdb5b

Narantsetseg, A., Kang, S., Lkhamsuren, B.-E., Jang, K., & Ko, D. W. (2015). Assessment of biotic and abiotic factors controlling herbaceous biodiversity in Mongolian steppes. *Ecological Informatics*, *29*, 221-229.

National Statistical Office of Mongolia. (2021). *Livestock census*

Niamir-Fuller, M., & Huber-Sannwald, E. (2020). Pastoralism and achievement of the 2030 agenda for sustainable development: A missing piece of the global puzzle. In *Stewardship of Future Drylands and Climate Change in the Global South* (pp. 41-55). Springer.

Okayasu, T., Okuro, T., Jamsran, U., & Takeuchi, K. (2012). Degraded rangeland dominated by unpalatable forbs exhibits large-scale spatial heterogeneity. *Plant Ecology*, *213*(4), 625-635. https://doi.org/10.1007/s11258-012-0027-3

R Core Team. (2020). *R: A language and environment for statistical computing*. In R Foundation for Statistical Computing.

Reynolds, J. F., Smith, D. M. S., Lambin, E. F., Turner, B. L., Mortimore, M., Batterbury, S. P. J., . . . Herrick, J. E. (2007). Global desertification: building a science for dryland development. *Science*, *316*(5826), 847-851.

Robinson, S., Milner-Gulland, E. J., & Alimaev, I. (2003). Rangeland degradation in Kazakhstan during the Soviet era: re-examining the evidence. *Journal of Arid Environments*, *53*(3), 419-439.

Roche, L. M. (2021). Grand challenges and transformative solutions for rangeland social-ecological systems–emphasizing the human dimensions. *Rangelands*, *43*(4), 151-158.

Sala, O. E., Yahdjian, L., Havstad, K., & Aguiar, M. R. (2017). Rangeland ecosystem services: nature's supply and humans' demand. In *Rangeland Systems* (pp. 467-489). Springer, Cham.

Sasaki, T., Okayasu, T., Jamsran, U., & Takeuchi, K. (2008). Threshold changes in vegetation along a grazing gradient in Mongolian rangelands. *Journal of Ecology*, *96*(1), 145-154. https://doi.org/10.1111/j.1365-2745.2007.01315.x

Scholtz, R., & Twidwell, D. (2022). The last continuous grasslands on Earth: Identification and conservation importance. *Conservation Science and Practice*, e626.

Spence, L. A., Liancourt, P., Boldgiv, B., Petraitis, P. S., & Casper, B. B. (2014). Climate change and grazing interact to alter flowering patterns in the Mongolian steppe. *Oecologia*, 1-10.

Sternberg, T. (2018). Investigating the presumed causal links between drought and dzud in Mongolia. *Natural Hazards*, *92*(1), 27-43.

Sternberg, T., Tsolmon, R., Middleton, N., & Thomas, D. (2011). Tracking desertification on the Mongolian steppe through NDVI and field-survey data [Article]. *International Journal of Digital Earth*, *4*(1), 50-64, Article Pii 919642499. https://doi.org/10.1080/17538940903506006

ter Braak, C. J. F., & Smilauer, P. (2012). *Canoco reference manual and user's guide: software for ordination, version 5.0*. Microcomputer Power.

Thornton, P. K. (2010). Livestock production: recent trends, future prospects. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1554), 2853-2867.

Tuvshintogtokh, I. (2014). *The steppe vegetation of Mongolia*. Bembi San, Ulaanbaatar, Mongolia.

Tuvshintogtokh, I., & Ariungerel, D. (2013). Degradation of Mongolian Grassland Vegetation Under Overgrazing by Livestock and Its Recovery by Protection from Livestock Grazing. In *The Mongolian Ecosystem Network* (pp. 115-130). Springer.

Undarmaa, J., Tamura, K., Natsagdorj, L., & Yamanaka, N. (2018). *Rangeland ecosystems of Mongolia*. Munkhiin useg.

von Wehrden, H., Hanspach, J., Kaczensky, P., Fischer, J., & Wesche, K. (2012). Global assessment of the non-equilibrium concept in rangelands. *Ecological Applications*, *22*(2), 393-399.

Westoby, M., Walker, B., & Noy-Meir, I. (1989). Opportunistic management for rangelands not at equilibrium. *Journal of Range Management*, *42*(4), 266-274.

Whisenant, S. (1999). *Repairing damaged wildlands: a process-orientated, landscape-scale approach* (Vol. 1). Cambridge University Press.

White, R., Siobhan, M., & Mark, R. (2000). Pilot analysis of global ecosystems: Grasslands ecosystems. *World Resources Institute, Washington, USA*.

Yang, H., Auerswald, K., Gong, X., Schnyder, H., & Bai, Y. (2022). Climate and anthropogenic drivers of changes in abundance of C4 annuals and perennials in grasslands on the Mongolian Plateau. *Grassland Research*, *1*(2), 131-141.

Yunatov, A. A. (1950). *The main features of the vegetation cover of the Mongolian People's republic*. Akad. Nauk SSSR.

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