

THESIS

HERDER OBSERVATIONS OF PASTURE AND HYDRO-CLIMATIC CHANGES IN
MONGOLIA

Submitted by

Darya Lilie

Department of Ecosystem Science and Sustainability

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2024

Master's Committee

Advisor: Steven Fassnacht

David Barnard
Sunshine Swetnam

Copyright by Darya Alexandra Lilie 2024

All Rights Reserved

ABSTRACT

HERDER OBSERVATIONS OF PASTURE AND HYDRO-CLIMATIC CHANGES IN MONGOLIA

Mongolia's climate is extreme and changing with long, cold winters, and dry, hot summers. Mongolia has many sunny days, and precipitation tends to be low. Climate change has altered Mongolian rangelands over the years, from declining water sources and forage production, to shifting boundaries of the ecological zones. With increasing temperatures and extreme precipitation events, climate change is expected to continue to alter rangeland conditions. In addition to climate change, overgrazing contributes to land degradation, leading to desertification in some areas of Mongolia. To combat land degradation community-based rangeland management (CBRM) programs were implemented in some *soums* (counties) in Mongolia, however they can only be successful if they incorporate the existing institutions that coordinate pastoralist mobility. In this thesis, herder interviews were combined with station and remote sensing data to assess changes in pasture and climate over ecozones in Mongolia, considering the impact of CBRM initiatives.

This study focused on interviewing herders from community managed and non-managed *soums* to use their traditional ecological knowledge (TEK) to assess change. Herder surveys answered both close-ended questions on a 5-point Likert scale about changes observed in climate, snow, rivers, lakes, springs, and rangeland conditions, and open-ended questions on causes, impacts, and adaptations to climate and rangeland conditions across three ecozones (forest steppe, steppe, and desert steppe) for a pair of *soums* in each ecozone, one with

community-based managed and the other without (3 ecozones x 2 *soums*). Using the different datasets, we compared the remote sensing data on rangeland conditions variability and station data on temperature and precipitation variability versus the herder responses to close-ended questions across the ecozone-management pairs, evaluated herder responses from open-ended questions on the causes, impacts, and adaptations to changes in climate and rangeland conditions in comparison to the herder responses to open-ended questions by *soum* and ecozones, and combined the sensor variability versus the degree of consensus (complete agreement) among herder closed-ended responses to explain herder responses to causes, impacts, and adaptations.

Herder observations and remote sensing data were in agreement for changes in the pasture conditions and precipitation. Herder responses and station data were less in agreement for temperature trends, depending on the season. The open-ended questions about causes, impact, and adaptation of pasture change corresponded to the overall climatic and pasture changes observed by station–remote sensing data and from the closed-ended questions. Key reasons for change were rain and water, *dzud* (Mongolian winter extreme weather), wind, sand, dust, and desertification, and livestock. These heavily impact livestock, quality of life, and money. Adaptation to change were to prepare the livestock better through making and purchasing hay in the north, and more movement to follow vegetation and water in the south.

ACKNOWLEDGEMENTS

First, I would like to thank my advisor, Dr. Steven Fassnacht. This research would not have been possible without his help and support. Even during the rough times, his consistent encouragement, guidance, and dedication have tremendously helped me get this research across the finish line. I would also like to thank my committee members, Dr. Sunshine Swetnam, and Dr. David Barnard for guidance and support. I would like to thank all the scientists that worked on the collection and processing of the data used in my research.

Finally, I would like to thank my significant other for encouraging and supporting me during this process, as well as my friends and family for continuous support and enthusiasm for my research.

TABLE OF CONTENTS

ABSTRACT.....	ii
ACKNOWLEDGEMENTS.....	iv
CHAPTER 1. INTRODUCTION.....	1
1.1 Mongolian Climate and Climate Change.....	1
1.2 Rangeland Management.....	2
1.3 Objectives	3
CHAPTER 2. STUDY SITES	5
CHAPTER 3. DATA AND METHODOLOGY	8
3.1 Spatial and Station Data	8
3.1.1 Meteorological Data	8
3.1.2 Rangeland Condition Data	9
3.2 Herder Data.....	10
3.3 Data Analysis.....	11
CHAPTER 4. RESULTS	14
4.1 Station and Remote Sensing Observations	14
4.1.1 Pasture Conditions	14
4.1.2 Precipitation	14
4.1.3 Temperature	15
4.2 Close-ended Questions on Herder Observations	16
4.2.1 Herder Responses on Pasture Production	16
4.2.2 Herder Responses on Precipitation	18
4.2.3 Herder Responses on Temperature	21
4.3 Combined Station, Remote Sensing, and Herder Observations	22
4.4 Open-ended Questions on Causes, Impacts, and Adaptations to Changes.....	25
4.4.1 Herder Responses on Causes	25
4.4.2 Herder Responses on Impacts.....	27
4.4.3 Herder Responses on Adaptations	29
CHAPTER 5. DISCUSSION.....	31
5.1 Pasture Conditions.....	31

5.2 Precipitation.....	33
5.3 Temperature.....	35
5.4 Causes, Impacts, and Adaptations	37
5.5 Community-Based Rangeland Management (CBRM) versus Non-CBRM.....	38
5.6 Limitations and Future Work	39
CHAPTER 6. CONCLUSIONS	42
REFERENCES	44
APPENDIX A. Computation of the Mann-Kendall Test and the Theil-Sen’s Slope Test	51
APPENDIX B. Computation of the Potential for Conflict Index 2 (PCI ₂)	54
APPENDIX C. Herder Survey	55
APPENDIX D. Herder Snow Responses	60

CHAPTER 1. INTRODUCTION

1.1 Mongolian Climate and Climate Change

Mongolia, which sits between China and Russia, contains many ecozones at different elevations where climate is both inconsistent and extreme (Tumenjargal et al., 2020). Winters in Mongolia are long and cold, while summers are dry and hot (Fassnacht et al., 2011). Mongolia sees large fluctuations in temperature as also seen in other arid/semi-arid regions of the world (Fassnacht et al., 2011). Between 1940 and 2000 the extreme maximum temperature of 43.1 °C was recorded in July, and extreme minimum temperature of -52.9 °C recorded in January (Ma et al., 2003; Batima, 2006). Mongolia also has a larger number of sunny days, averaging at around 260 days per year (Fassnacht et al., 2011). Precipitation tends to be low, ranging between 50 and 100 mm in the southern desert steppe, between 250 and 300 mm in the forest steppe, and between 300 and 400 mm in the northern mountains (Batima and Dagvadorj, 2000; Venable et al., 2015; Tumenjargal et al., 2020). A majority of the precipitation falls between April and September, with 50% to 60% falling in July and August (e.g., Marin, 2010; Tumenjargal et al., 2020).

Climate change has altered Mongolian rangeland drastically over the years. Its effect is seen in the declining water sources, forage production, and the shifting of the boundaries of the ecological zones in Mongolia (Batima et al. 2005; Angerer et al. 2008; Fassnacht et al. 2011; Venable et al. 2012; Hilker et al. 2014; Liu et al. 2013, Bruegger et al. 2014). With the increasing temperatures at all locations in Mongolia, the permafrost layer degradation has also accelerated in the last 15 years (Sharkhuu et al., 2007). Temperature increase has been observed to be much

greater than changes in the precipitation extremes (Nandintsetseg et al., 2007; Fassnacht et al., 2011; Tumenjargal et al., 2020).

Climate changes are expected to alter the rangeland conditions. Conditions such as increasing temperature and changes in precipitation contribute to increase in evaporation and therefore creating less moisture for plant growth (Nandintsetseg and Shinoda, 2013). These conditions significantly contribute to droughts, harsh winters (*dzuds*), dust storms, and desertification (IPCC 2022; Mandakh et al. 2007; Nandintsetseg et al. 2007; Kurosaki et al. 2011; Gombolhuudev 2011; Sternberg et al 2011).

1.2 Rangeland Management

Overgrazing contributes to land degradation along with climate change leading to desertification. More than 22% of Mongolian rangeland has been heavily or entirely degraded (Densambuu et al., 2018). To combat desertification, Mongolian policymakers have implemented new pasture use and conservation policies at the community level which include community-based management, land tenure, assessment and monitoring of pastures, and resource use planning (Kasymov and Ring, 2023). These systems, however, can only be successful if they incorporate the existing institutions that coordinate pastoralist mobility (Kasymov and Ring, 2023). Traditionally herders in Mongolia move their livestock from one area to another (called *otor* in Mongolian), when there is either scarcity or a decrease in quality of a pasture to help with regeneration. In addition, not only do herders use pastures seasonally but they also switch their livestock between warmer desert/semi desert habitats and cooler steppe habitats to develop stronger animals (Kasimov and Ring, 2023). Increasing competition and conflict on access to pastures and water resources as well as fear of losing their pasture to others guide the herder

decisions on where to move their herd, therefore the movement of herds has been drastically reduced from five to six times a year to one to two times or no movement at all (Kasimov and Ring, 2023). This practice in combination with climate change eventually degrades rangeland.

Mongolian herder observations of climate change have started to be integrated into scientific research through conversations and surveys with herders (Fernandez-Gimenez, 2000; Marin, 2010; Bruegger, et al., 2014; Fernandez-Gimenez, et al., 2015; Goulden, et al., 2016). Incorporating herders' strategic choices and quantitatively measuring the critical mass levels that are needed to support different institutional pasture use and conservation policies would help in preventing pastoral mobility decline in Mongolia (Kasimov and Ring, 2023). To address these issues some *soums* (equivalent to counties) in Mongolia have established community-based rangeland management (CBRM) herder organizations with support from donor organizations (Bruegger et al., 2014; Mau and Chantsalkham, 2006). In this research scientists focused on interviewing herders from community managed and non-managed *soums* to incorporate traditional ecological knowledge (TEK) into rangeland management policies and management institutions and to compare the difference in responses to questions from herders in both community managed and non-managed *soums*.

1.3 Objectives

In addition to climate change, herders have noted that land management policies are not always in favor of pastoral movement (*otor*) (Kasymov and Ring, 2023), making it difficult for herders to practice traditional regenerative herding lifestyle that is beneficial not only for the rangeland, but also for the livestock and herders. This research uses the spatial sensor data and

herder survey responses to investigate climate changes and their implications on rangeland conditions for Mongolian herders. The surveys used both close-ended questions on a 5-point Likert scale about changes observed in climate, snow, rivers, lakes, springs, and rangeland conditions, and open-ended questions on causes, impacts, and adaptations to climate and rangeland conditions across three ecozones (forest steppe, steppe, and desert steppe) for a pair of *soums* in each ecozone, one with community-based managed and the other without (3 ecozones x 2 *soums*). Using the different datasets, three objectives were defined for this research as follows:

1. compare the sensor-based variability versus the herder responses to close-ended questions across the ecozone-management pairs,
2. evaluate herder responses from open-ended questions on the causes, impacts, and adaptations to changes in climate and rangeland conditions in comparison to the herder responses to open-ended questions by *soum* and ecozones, and
3. combine the sensor variability versus the degree of consensus among herder closed-ended responses to explain herder responses to causes, impacts, and adaptations.

CHAPTER 2. STUDY SITES

This research focused on remote sensing, meteorological, and herder data from three ecozones in Mongolia (Table 2-1 and Figure 2-1) (Ayan Travel, 2024; Mongolian Guide, 2024). The forest-steppe is the most northerly and gets the most precipitation (250-350 mm per year); the desert-steppe is the most southerly and gets the least precipitation (100-150 mm per year); and the steppe is in between the other two and gets an average amount of precipitation (150-250 mm per year) (Batima and Dagvadorj, 2000; Nandintsetseg et al., 2007; Venable et al., 2015; Tumenjargal et al., 2020). Based on previous research on rangeland conditions it was observed that the most unstable ecological systems are in the forest steppe and steppe ecozones, while the desert steppe ecozones are not as easily influenced by the rangeland use (Densambuu et al., 2015). Forest steppe and steppe are highly influenced by rangeland use and with the changes in precipitation affecting soil moisture in these two ecozones the plant growth is greatly affected in comparison to the desert steppe where plants are adapted to low moisture in the sediment (Densambuu et al., 2015). The desert-steppe, steppe, and forest-steppe zones are at the highest risk for degradation due to climate change and herders not adjusting herd size based on forage availability (Gao et al., 2015).

Table 2-1. Description of the three study *aimags* with six *soums*. Three community-based rangeland managed (CBRM) *soums*, and three non-managed *soums*, one in each *aimag*.

<i>Aimags</i>	Selenge	Tuv	Dundgobi
Location in Mongolia	Northern	Central	Middle to Southern, in Gobi-Desert.
Ecozone	Forest Steppe	Steppe	Desert Steppe
Known for	Many lakes, rivers, orchards, and pastures. 47% pasture land. Named after Selenge River.	Springs and lakes. Mainly located in rolling steppe, but also incorporates some valleys and mountains.	Steppe in the north, and desert in the middle and southern parts of <i>aimag</i> . The northern part has many lakes and streams, and the southern part gradually turns into desert.
CBRM <i>soum</i>	Bayangol	Undurshireet	Ulziit
Non-CBRM <i>soum</i>	Saikhan	Erdenesant	Undurshil

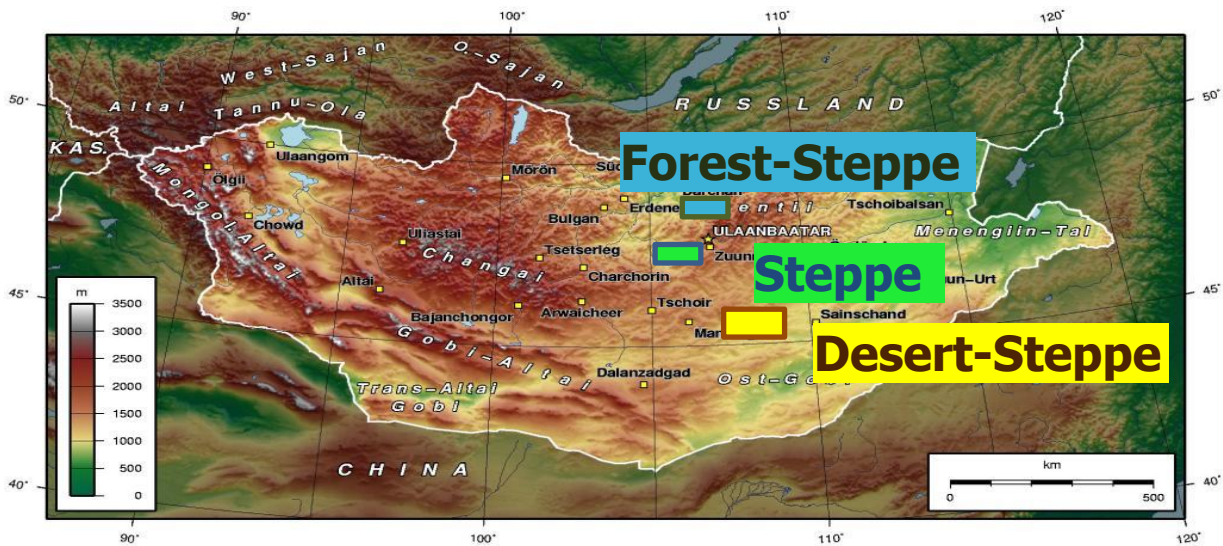
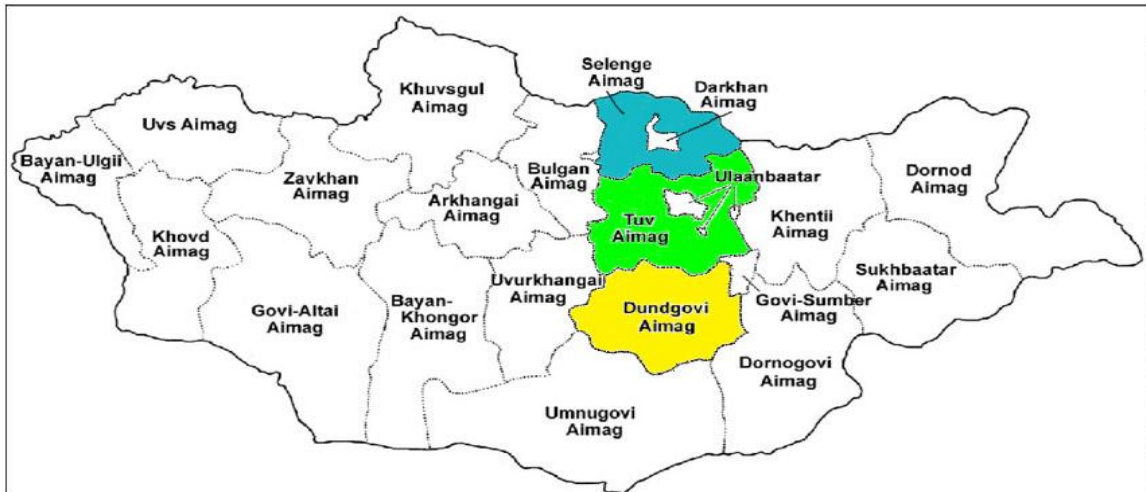


Figure 2-1. Administrative Map of Mongolia showing all *aimags*, including the three study *aimags*, and elevation map of Mongolia illustrating the three study ecozones (Forest-Steppe, Steppe, and Desert-Steppe).

CHAPTER 3. DATA AND METHODOLOGY

3.1 Spatial and Station Data

3.1.1 Meteorological Data

Mongolia has about 120 operational hydro-meteorological stations (Dagvadorj et al., 2009) across its 1.6 million square kilometer area. Scientists mostly use the data from these stations collected by the Mongolian Institute of Meteorology, Hydrology, and Environment (Tumenjargal et al., 2020). These stations are rather dispersed across the country (Shiklomanov et al., 2002; Venable et al., 2015), and their time series are more often discontinuous and inconsistent (Klein et al., 2014; Venable, 2016). In addition, the data recorded at these stations may not represent the areas in between stations (Meromy et al., 2013; Fassnacht et al., 2018), even in areas where the climate is considered homogeneous the stations record different climate trends (Pielke et al., 2002; Fassnacht et al., 2016).

Global spatial datasets were used to assess climate conditions. Here, we used the data from the Mongolian Research and Information Institute of Meteorology, Hydrology, and Environment (RIIME), and additional station data is from the United States National Oceanic and Atmospheric Administration National Climatic Data Center (NOAA NCDC) for temperature (Venable et al., 2020) and the Climate Prediction Center (CPC) Unified Precipitation dataset for precipitation (Chen et al., 2008; Fernandez-Gimenez et al., 2015; Venable et al., 2020). These datasets are both at 0.5 x 0.5 degrees latitude-longitude resolution (~55 km x 55 km). We used 1993-2013 for temperature and 1993-2012 for precipitation in our analysis (Fernandez-Gimenez et al., 2015). For precipitation we calculated a 5-year moving average. Then we used GIS to

calculate average values for each pixel in the grid by year, and after that we calculated *soum* and ecozone averages for temperature and precipitation (Fernandez-Gimenez et al., 2015).

3.1.2 Rangeland Condition Data

Remote sensing data were used to assess rangeland conditions. The Normalized Difference Vegetation Index (NDVI) was used to represent rangeland production. NDVI quantifies vegetation greenness to understand vegetation density and evaluate changes in plant health. NDVI measures the difference between near-infrared light (NIR) which vegetation reflects and red light and which vegetation adsorbs (Remote Sensing Phenology, 2018). Below is the formula for measuring NDVI:

$$\text{NDVI} = \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})} \quad (3-1),$$

with values between -1 and +1 (Remote Sensing Phenology, 2018). If the image has low red values or low reflectance and high NIR values or high reflectance this will give you high NDVI values, which indicates healthier vegetation, and if there is high reflectance in red values and low reflectance in NIR values the output will give you low NDVI values, which indicates less or no vegetation (GISGeography, 2024). For Mongolia, we used the Advanced Very High Resolution Radiometer (AVHRR) NDVI (Pinzon and Tucker, 2014, Fernandez-Gimenez et al., 2015) data from 1993 to 2009 as our proxy for rangeland production (Tucker et al., 1985; Fernandez-Gimenez et al., 2015). These data are at an 8-km resolution. TIMESAT software (Eklundh and Jansson, 2009) was used to extract the time series variables, which included NDVI small integral (pasture condition), start of season (green-up), and end of season (brown-down) (Fernandez-Gimenez et al., 2015).

3.2 Herder Data

Herder observations added information to interpret climate and rangeland changes across the study areas in Mongolia (Fernandez-Gimenez et al., 2020). Survey data were collected in Mongolian and then translated into English. To verify that the translation is correct, the English version was then translated back into Mongolian and compared to the original data. Herders from the six *soums* across the three ecozones were asked close-ended and open-ended questions from June 22 through July 28, 2013, with a maximum of four days of data collection at each *soum*. A total of 109 herders completed the survey interview of which 62 were male and 47 were female. They ranged in age from 29 to 87 years old and had lived in their area from 10 to 87 years.

Herders were asked 26 close-ended questions on a 5-point Likert scale about changes observed in climate, snow, rivers, lakes, springs, and rangeland conditions (Appendix C); nine on rangeland condition were used here (Table 3-1). The target was 20 herder participants from each *soum* or 40 from each *aimag* to complete the survey. Herders were asked to reflect back to 20 to 30 years on the climate changes, hydrological changes, and rangeland changes over that time and respond to the close-ended questions by selecting the most appropriate response from a total of 6 possible responses (Table 3-1). Rangeland conditions included pasture growth, green-up timing, and brown-down timing. Climate variables included rainfall characteristics, snowfall characteristics, and seasonal temperatures. Open-ended questions asked herders about 1) the causes of their observed changes in climate and rangeland conditions, 2) the impacts of observed changes on their lives and livelihoods, and 3) their adaptation to these changes (Table 3-2), enabling the herders to discuss the changes that they had seen and expand on the closed-ended questions. Further, for the open-ended question on causes of change, they were asked to rank the causes by importance.

3.3 Data Analysis

A statistical analysis was performed to evaluate trends of the spatial climate data and the NDVI-based rangeland condition data. We used the non-parametric Mann-Kendall test (Mann, 1945; Kendall and Gibbons, 1990) to evaluate the significance of trends over time. The Theil-Sen's slope was used to estimate the rate of change (Theil, 1950; Sen, 1968; Gilbert, 1987).

Herder responses to close-ended questions were rescaled from a range of 1 to 5 to a range of +2 to -2 with 0 as no change. The initial code of 6, no response, was coded as "no data." To assess the level of consensus in herder observations within and between communities and ecozones, we used the Potential for Conflict Index (PCI₂) (Vaske et al., 2010). A PCI₂ of 1 represents the lowest amount of consensus and the greatest variability among herder observations while a PCI₂ of 0 reflects a complete consensus among herders or a distribution with 100% at one point on the response scale (Vaske et al., 2010). These results were used to graphically represent the PCI₂ herder responses with the station data for each of the six soums in three ecozones. The PCI₂ test also provides a net score, which is the mean of the rescaled responses across each six soums in three ecozones for each question.

We recoded the three open-ended questions (Table 3-2) to a series of common words (e.g., poor rain or sand storm). For each question (causes, impacts and adaptations), specific common words or phrases were selected from the responses to the recoding used one identified words or phrases. There were 30, 61, and 40 specific words or phrases identified for the causes, impacts, and adaptations questions, respectively. From here, more general themes were identified; 10, 7 and 7 for the causes, impacts, and adaptations questions, respectively. Then the frequencies of categorical responses were computed. To increase our understanding of diverse

perceptions of causes, impacts, and adaptations to rangeland conditions and climate, we compared the most frequent themes by *soum* and ecozones.

Table 3-1. The nine closed-ended questions asked of herder for them to thinking about their area over the previous 20 years. The sixth response was” Don’t know/Not applicable.”

Climate Variable	Perceived Amount of Change				
1. The amount of pasture growth	1. Much lower	2. Lower	3. No change	4. Greater	5. Much greater
2. The timing of when the grass turns green is	1. Much earlier	2. Earlier	3. No change	4. Later	5. Much later
3. The timing of when the grass turns brown is	1. Much earlier	2. Earlier	3. No change	4. Later	5. Much later
4. The amount of rainfall has	1. Decreased a lot	2. Decreased a little	3. Not changed	4. Increased a little	5. Increased a lot
5. The number of days between rainfall events has become	1. Much shorter	2. Shorter	3. No change	4. Longer	5. Much longer
6. Average spring temperatures are	1. Much cooler	2. Cooler	3. No change	4. Warmer	5. Much warmer
7. Average summer temperatures are	1. Much cooler	2. Cooler	3. No change	4. Warmer	5. Much warmer
8. Average fall temperatures are	1. Much cooler	2. Cooler	3. No change	4. Warmer	5. Much warmer
9. Average winter temperatures are	1. Much cooler	2. Cooler	3. No change	4. Warmer	5. Much warmer

Table 3-2. The three open-ended questions

A. Thinking about all the changes in pasture conditions you have mentioned so far (remind them of the changes mentioned). Please tell me why (what causes) explain these changes? (list) [causes]
B. How are changes in climate and pasture affecting your life and livelihood? [impacts]
C. What measures are you taking to adapt to these changes? [adaptations]

CHAPTER 4. RESULTS

4.1 Station and Remote Sensing Observations

4.1.1 Pasture Conditions

Both steppe soums saw a significant decrease in pasture growth (Figure 4-1a). Undurshil in the desert-steppe saw a significant increase in the pasture growth, while Ulziit did not see any change in pasture growth. Both forest steppe soums did not see any change in pasture growth. There is no statistically significant change in green up. Green up was later in both steppe *soums* (between 0.5 to 1.1 days per year), but earlier in the other *soums*. In one desert steppe *soum* (Undurshil), green up was 2.7 days per year earlier, while it was about a half day per year earlier in the other *soums*. Brown-down was significantly earlier in one steppe *soum* (Erdenesant) (0.7 days per year), while it was much earlier in the other steppe *soum* (Undershireet at 3.6 days per year), however this increase was not significant. Brown-down was about 1.3 days later in the Ulziit desert steppe *soum*, while there was minimal change in the other *soums* (Figure 4-1a).

4.1.2 Precipitation

Annual rain (not including snow) declined for all *soums* in all three ecozones, and it declined significantly in the steppe and desert steppe *soums* (Figure 4-1a). In the forest-steppe ecozone a decline of 1.5 mm and 2.1 mm per year was observed; in the steppe, rain declined by 2.2 and 2.7 mm per year, while in the desert-steppe rain declined by 4.5 and 5.4 mm per year. The number of days between rainfall events significantly increased in the forest steppe and steppe *soums*, between 1.3 and 1.8 days per year. In the desert steppe, Ulziit saw fewer days

between rainfall events while Undurshil saw a slight increase in the number of days; neither trend in the desert steppe was significant (Figure 4-1a).

4.1.3 Temperature

Meteorological observations for spring temperatures showed that for the forest steppe and steppe *soums* temperature cooled slightly (between 0.01 and 0.02°C per year), while the desert *soums* warmed by 0.02 and 0.03°C per year from 1993 to 2013 (Figure 4-1a); no changes were significant. All summer temperatures warmed, with significant warming in both steppe *soums* and one desert steppe *soum* (Undurshil) (about 0.085°C per year). For the others *soums*, summer warming was between 0.03 and 0.05°C per year. Fall temperatures warmed in all *soums*, but not significantly, with the least warming in the desert steppe *soums* (0.03 and 0.05 °C per year) and between 0.08 and 0.11°C per year in the four northern *soums*. Winter temperatures cooled significantly from 0.17 and 0.27°C per year for the forest steppe and steppe *soums*, however winter temperatures cooling was not significant and less in the desert *soums* (-0.08 and -0.09°C per year) (Figure 4-1a).

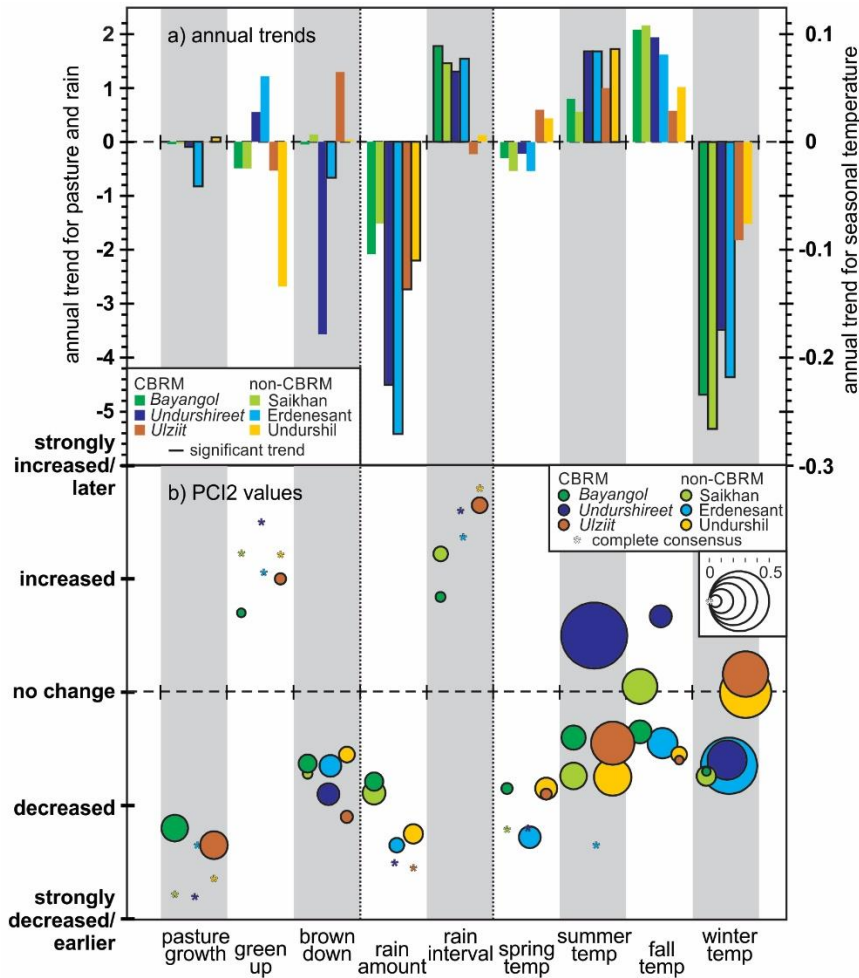


Figure 4-1: Pasture (growth, green up, brown down) and climate (rain amount and interval, seasonal temperatures) observation in the forest steppe (green), steppe (blue), and desert steppe (brown-yellow) ecozones. The darker shade (left) represents the CBRM *soum*. The dark outline around the bars represents significance. a) Rate of change from instrument data in pasture based on greenness (NDVI from remote sensing data with no units), precipitation (mm per year and days per year), and temperature (degrees Celsius per year using scale on the right axis). b) The PCI_2 results reflect the amount of consensus, with a small bubble representing high consensus and a large bubble representing low consensus. Bubble centers represent the mean response.

4.2 Closed-ended Questions on Herder Observations

4.2.1 Herder Responses on Pasture Production

Many of the herders observed somewhat lower to much lower pasture production in both the 5-year (50 to 80% of the herders) and the 20-year (80 to 100% of the herders) time periods

(Figure 4-2). Over the last 5 years, up to 30% of herders in all *soums* except in Undershireet saw increased pasture production (Figure 4-2a), while only herders in Bayangol and Ulziit (~10%) saw increased pasture production for 20-year period (Figure 4-2b). The observed decreases in pasture production over the last five years were mostly in the “somewhat lower” category (40-80% of responses) while over the last 20 years, the majority were in the "much lower" category (30 to 80% of responses) (Figure 4-2b).

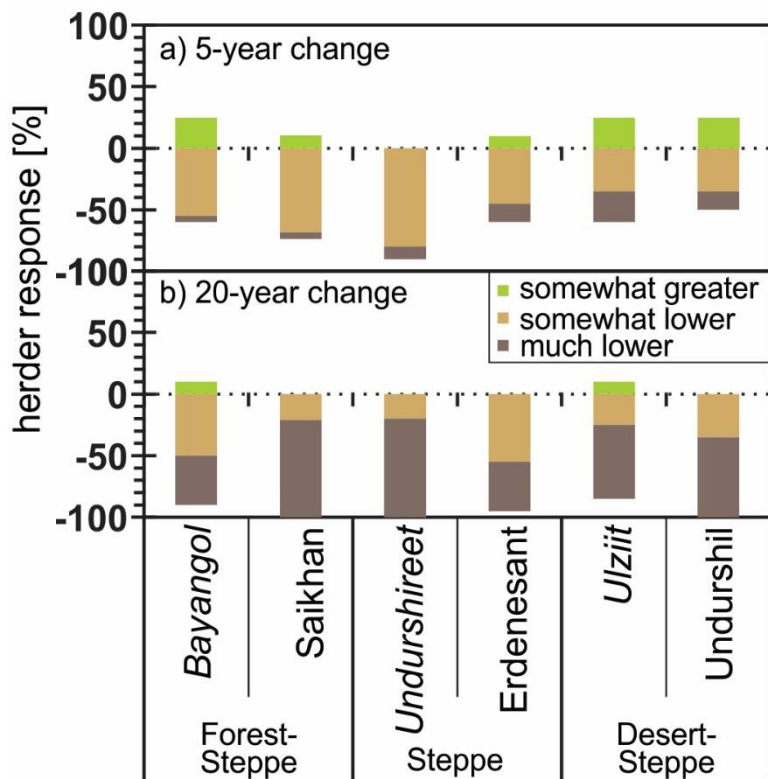


Figure 4-2: Herder observed pasture production in the last a) 5 and b) 20 years in Mongolia in managed (in italics) and non-managed *soums* within three ecozones. Brown colors represent decreased and green colors represent increases.

Most herders (65 to 100% of respondents) observed a later or much later green-up in the season (Figure 4-3a). Bayangol and Ulziit were the only *soums* where a few herders (~5%) had observed an earlier green-up (Figure 4-3a). Sixty to 80 percent of herders observed earlier to much earlier brown-down in the season (Figure 4-3b). Fewer herders saw a much earlier brown-

down (5-40%; Figure 4-3a) compared to the number that saw a much later green-up (10-50%; Figure 4-3a). Five to 10% of herders in all *soums* saw a later brown-down with some in Erdenesant seeing a much later brown-down (Figure 4-3b).

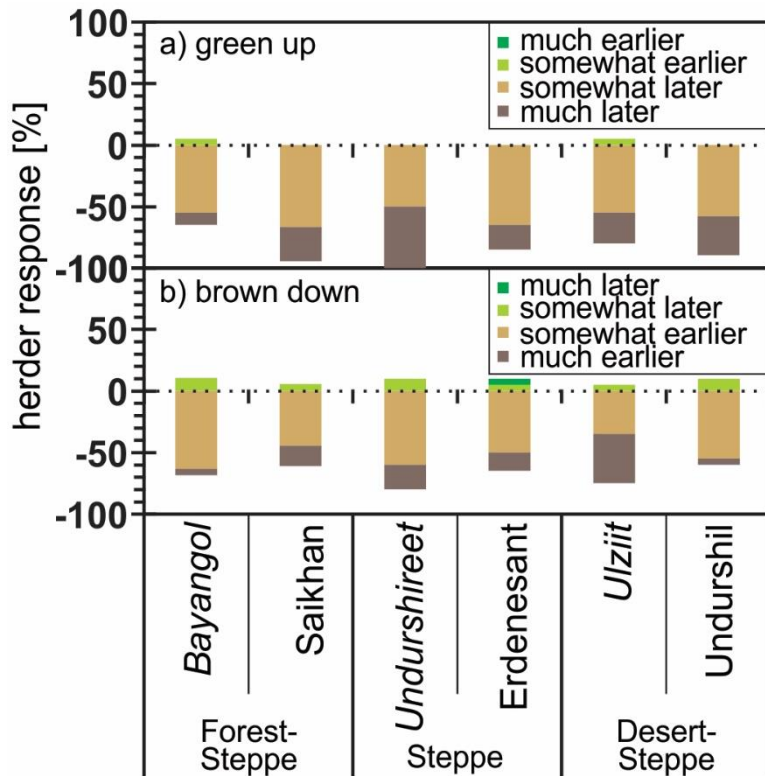


Figure 4-3: Mongolian herder observed a) green up and b) brown down in managed (in italics) and non-managed *soums* within three ecozones. For green-up (a), brown colors represent later, and green colors represent earlier start, while for brown-down (b) the colors are reversed, i.e., brown is an earlier brown-down and green is later.

4.2.2 Herder Responses on Precipitation

Many of herders (50 to 100%) from all *soums* responded selecting decreased in the amount of rainfall (Figure 4-4a), with 20 to 50% saying that rainfall amounts decreased a lot. Some herders in three *soums* (both forest steppe and Erdenesant) said rainfall increase a little. Only in Undushil did a few herders say that rain amounts increase a lot (Figure 4-4a). Most of herders (70 to 100%) from all *soums* stated that the duration of rainfall was somewhat lower to

much lower (Figure 4-4b). Thirty to 80% (Ulziit) said that the duration was much lower. Except Ulziit, about half the herders saw a somewhat lower duration of rain (Figure 4-4b).

A small percentage (5%) of herders responded with shorter days between rainfall events in Bayangol, Saikhan, and Ulziit *soums* (Figure 4-4c). Between 60 to 100% of herders responded stating that there is a somewhat longer to much longer time between rain events. Herders in Desert Steppe ecozone stated that there is a much longer time between rain events versus somewhat longer in comparison to the other two ecozones where slightly more herders responded with somewhat longer time between events versus much longer. The exception is Undushil where herders responded more with much longer time between rain events (Figure 4-4c).

About 70 to 100% of herders from all provinces also responded selecting somewhat greater to much greater intensity of rainfall over the previous 20 years (Figure 4-4d). Between 5 and 20% of herders selected that the intensity of rainfall was somewhat lower in all provinces except for Undushil. Both *soums* in the forest steppe received the greatest number of responses to the intensity of rain being somewhat lower (20% of herders) in comparison to other ecozones. For the steppe ecozone, 5 to 10% of herders stated that the intensity of rainfall was somewhat lower, and for Ulziit in the desert steppe ecozone, 5% responded with rain intensity being somewhat lower (Figure 4-4d).

Overall, herders are observing that the rain amount, duration, and days in between rainfall events are decreasing while the intensity of the rainfall events are increasing (Figure 4-4). The responses were similar across the rain questions for each *soum* (Figure 4-4a versus, 4-4b, 4-4c, and 4-4d). While most herders saw a negative change in rain, i.e., a decrease in rain (less amount, less duration, more time between events) or increase in intensity (Figure 4-4), herder

observations in the forest steppe were the least negative with some positive responses (expect duration at Bayangol). Similarly, there tended to be more negative responses (decreased a lot, much lower, much longer, much greater) for the steppe and desert steppe compared to the forest steppe (Figure 4-4).

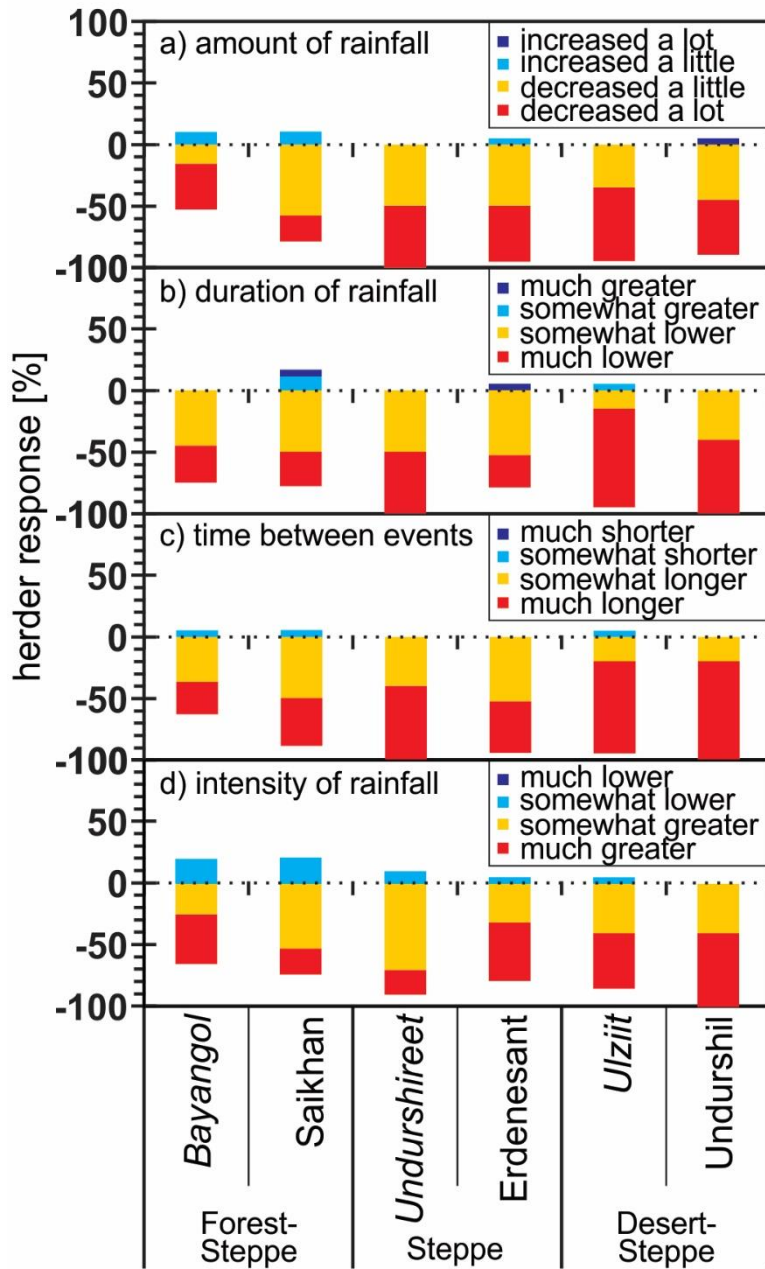


Figure 4-4: Mongolian herder observed rainfall in managed (in italics) and non-managed *soums* within three ecozones. Red and orange colors denote less rain amount, less duration of rain, longer time between events and less intensity. Blue colors denote more and longer.

4.2.3 Herder Responses on Temperature

Responses from Mongolian herders to temperature changes for all four seasons are mostly that temperatures are cooler (Figure 4-5), with some responses being much cooler. The spring saw the most consistent responses across all *soums* with almost all herders (80 to 100%) responded that temperatures were cooling (Figure 4-5a), of which 5-40% observed much cooler springs. Undurshireet *soum* was the outlier in the summer and fall with 80% seeing warming (20% much warmer in the summer; Figure 4-5b). Summer was a dichotomy of extremes; a few herders said that the summer was much warmer, except Erdenesant, while others said summer had become much cooler (40% in Erdenesant; Figure 4-5b). The fall had the least extreme responses as it was mostly warmer (5-70%) or cooler (10-60%) with only a few (5%) saying that the fall was getting much cooler (Figure 4-5c). The distribution of responses was similar for the pair of *soums* in each ecozone in the winter, but different between ecozones (Figure 4-5d). In the forest steppe, 60% of herders saw winter temperatures cool and about 10% saw them warm; in the steppe these numbers were 50% saw cooling while 20% saw warming, and in the desert steppe 30% saw cooling while 50% saw warming (Figure 4-5d).

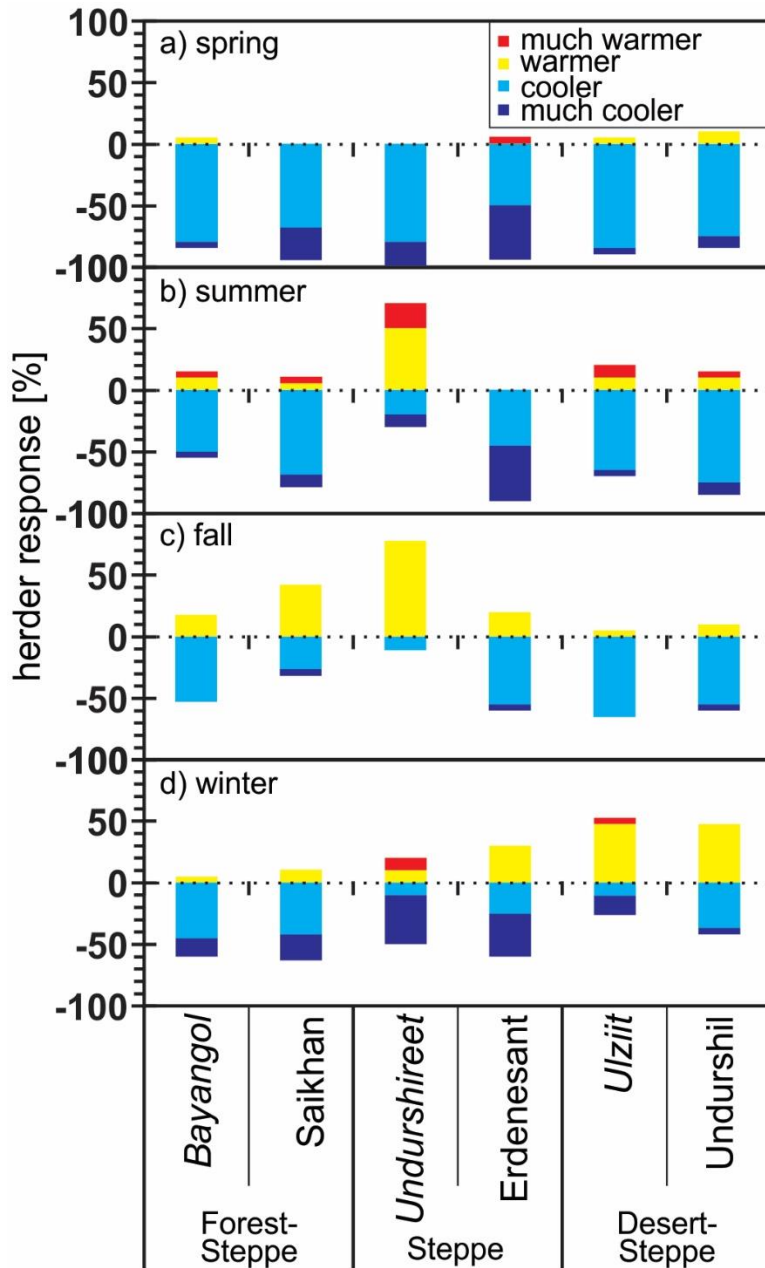


Figure 4-5: Mongolian herder observed seasonal temperatures in managed (in italics) and non-managed *soums* within three ecozones. Yellow and red colors represent warming, while blue colors represent cooling.

4.3 Combined Station and Remote Sensing and Herder Observations

Both steppe soums saw a significant decrease in pasture growth (Figure 4-1a). Undurshil in the desert-steppe saw a significant increase in the pasture growth, while Ulziit did not see any

change in pasture growth. Both forest steppe soums did not see any change in pasture growth (Figure 4-1a). The herder responses paint a different picture. Herder responses show that there is a decrease in pasture growth with four out of the six soums showing a high consensus, and two soums (Bayangol and Ulziit) showing moderate consensus (Figure 4-1b). Green up was later in both steppe *soums*, but earlier in the other *soums* (Figure 4-1a). Although there were no statistically significant changes in spring green-up times, the direction of the trends differed among zones, with a trend towards earlier green-up in the forest steppe and desert steppe and later green-up in the steppe (Figure 4-1a). Herder responses to green up questions illustrate a high consensus on increased and strongly increased or a later green up for all the ecozones (Figure 4-1b). Brown-down was significantly earlier in one steppe *soum* (Erdenesant), while it was much earlier in the other steppe *soum* (Undershireet) however this increase was not significant (Figure 4-1a). Ulziit desert steppe *soum* saw later brown-down, while there was minimal change in the other *soums* (Figure 4-1a). Herder responses show a higher consensus on the decreased or slightly earlier brown down, which agrees with the remote sensing data from steppe ecozone, but not with the other two ecozones (Figure 4-1b).

Annual rain declined for all *soums* in all three ecozones, however it significantly declined in the steppe and desert steppe *soums* (Figure 4-1a). The herder observations in all *soums* are in agreement with high consensus that the rain amount has been decreasing (Figure 4-1b). The number of days between rainfall events significantly increased in the forest steppe and steppe *soums* (Figure 4-1a). In the desert steppe the trends were not statistically significant. Ulziit saw fewer days between rainfall events while Undurshil saw a slight increase in the number of days (Figure 4-1a). Data from herder responses shows that herders from all *soums* agree that the number of days between rainfall has increased or strongly increased with higher and high

consensus (Figure 4-1b). The herder responses differ in comparison with the remote sensing data in the desert steppe *soum* with the remote sensing data showing closer to no change or decrease meanwhile herder data illustrates a strong increase in the number of days between rainfall events (Figure 4-1b).

Meteorological observations for spring temperatures showed that for the forest steppe and steppe *soums* temperature cooled slightly, while the desert *soums* warmed (Figure 4-1b); no changes were significant. Herder responses to spring temperatures show a general consensus that the spring temperatures cooled with mostly higher to high consensus (Figure 4-1b). All summer temperatures warmed, with significant warming in both steppe *soums* and one desert steppe *soum* (Undurshil) (Figure 4-1a). Herder responses show that majority of the herders in *soums* responded with summer temperatures cooling, except for herders in Undurshireet *soum* where herders selected that the summer temperature warmed, but we can observe that there is low consensus on the summer temperature warming (Figure 4-1b). In addition, there is moderate consensus from herders in the desert steppe ecozone on the summer temperatures cooling. Fall temperatures warmed in all *soums*, but not significantly (Figure 4-1a). Herders in most *soums* agreed that the fall temperatures are slightly cooling, with herders in Saikhan selecting no change with moderate consensus (Figure 4-1b). Undurshireet *soum* shows that the temperatures are warming with a higher consensus from the herders in this *soum*. Winter temperatures cooled significantly for the forest steppe and steppe *soums*; however, winter temperatures cooling was not significant and less in the desert *soums* (Figure 4-1a). For winter temperatures herders mostly responded with either no change or a cooler temperature, however there is lower consensus in the herder responses in the steppe and desert steppe ecozones in comparison to forest steppe ecozone which shows a high consensus on winter temperatures cooling (Figure 4-1b).

4.4 Open-ended Questions on Causes, Impacts, and Adaptations to Change

4.4.1 Herder Responses on Causes

While there are at least 10 general causes of changes (Figure 4-6), the biggest causes for changes that the herders observed are related to rain and water with 40 to 95% of herders (Figure 4-6c) stating that water, rain, rain at wrong time, poor/less rain, drought, rain shot (cloud seeding/dispersal), and heavy snow are the main causes of the changes (Figure 4-7). The rain-water responses were lowest in the forest steppe ecozone (40 to 70%), and similar for the steppe and desert steppe *soums* (80 and 95%). Many of the herders (38 to 90 percent) responded that rain was the main cause of change, followed by drought (5 to 40 percent) (Figure 4-7). There were other rain and water responses, but these were mentioned less often (Figure 4-7).

Livestock (Figure 4-6h), overgrazing, and specific types of livestock were the largest cause of change in the forest steppe, followed by human activity (Figure 4-6j) and movement (Figure 4-6i). The change was caused by livestock for about 50% of herders in the steppe and 30% of the desert steppe herders (Figure 4-6h). Human activity such as mining, transportation, lack of restoration, cutting of trees, to name few herder responses, caused change for 25 to 40% of herders in the steppe and desert steppe (Figure 4-6j). Except for Bayangol *soum*, 40 to 60% of herders said that weather-based events, such as *dzud* (Mongolian winter extreme weather), wind, sand, dust, and desertification caused change (Figure 4-6f). Climate change (Figure 4-6a) and sun (Figure 4-6e) were mentioned as a cause for change by 5 to 30% of herders in all *soums*, except Ulziit. Other causes such as mining, people, transportation, agriculture, cutting trees, no reforestation, no pasture, and construction were also mentioned, but only by a few herders in each *soum*.

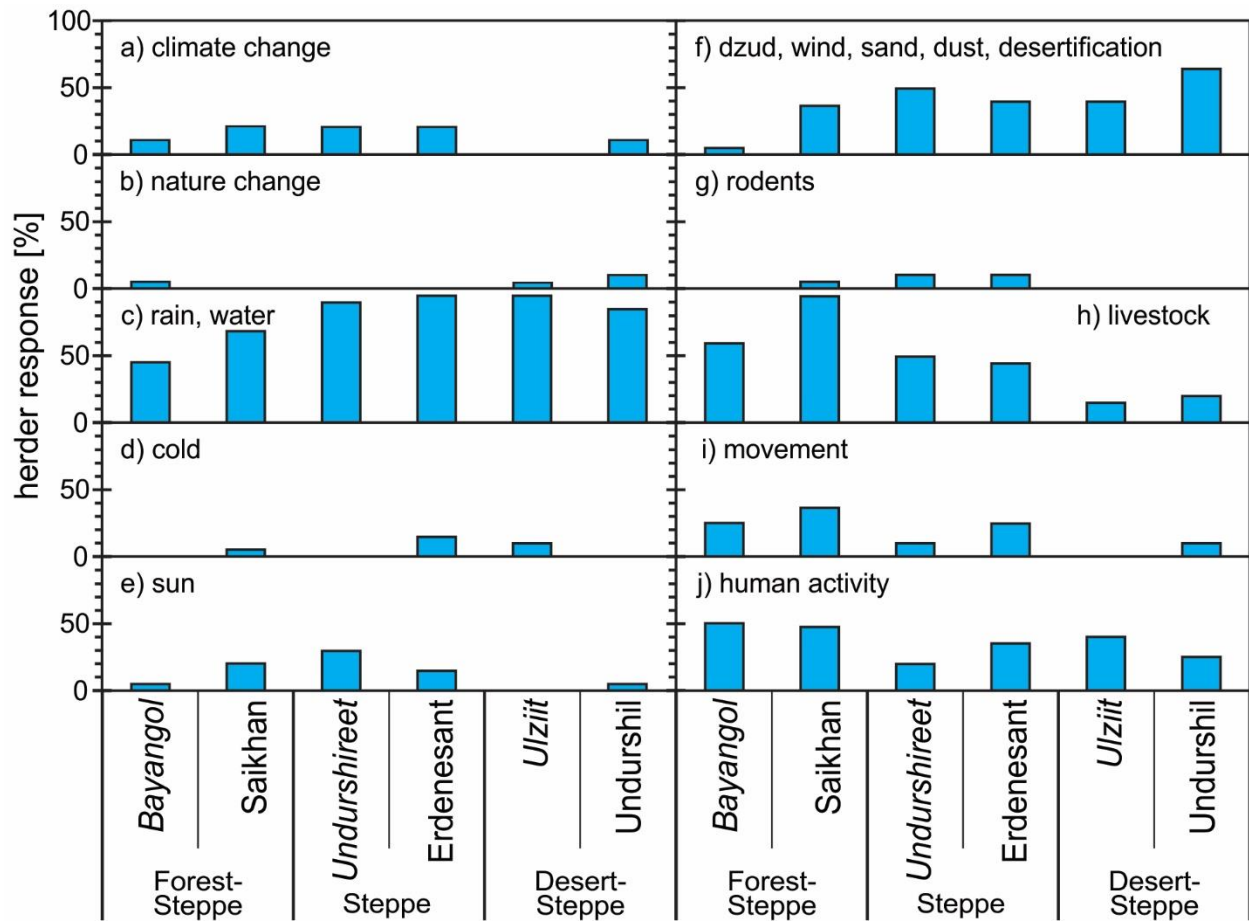


Figure 4-6: Mongolian herder causes responses in managed (in italics) and non-managed soums within three ecozones.

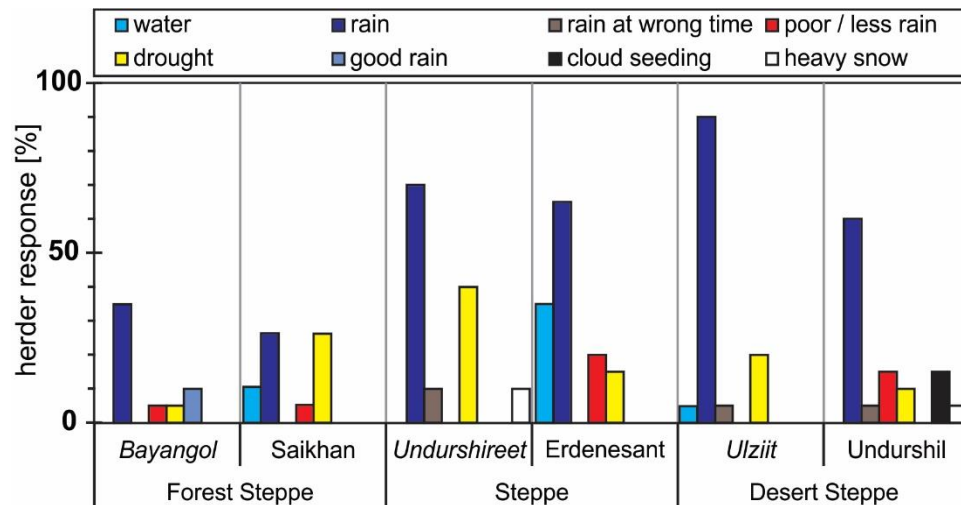


Figure 4-7: Detailed illustration of rain responses for the causes question, as per Figure 4-6c.

4.4.2 Herder Responses on Impacts

There were seven general impacts of the pasture and climate changes on the herder's life and livelihoods (Figure 4-8). There is a substantial impact on the livestock for all provinces with responses between 40 to 80 percent. Herders under CBRN managed *soums* were more likely to respond with impacts to livestock vs herders in non-managed *soums* based on the higher percentages seen in managed provinces (Figure 4-8a). Quality of life and money go hand in hand and received the highest responses as well in both the managed and non-managed *soums* with 30 to 80 percent responding that these two areas are affected as well (Figure 4-8f and Figure 4-8g). Herders also selected weather, vegetation, and *otor* as some of the other areas that are impacted by the changes (Figures 4-8b, 4-8c, and 4-8d). To be more specific, herders referred to all the storms and drastic weather events that altered their herding seasons and the vegetation such as late green-up and early brown-down. Based on the changes the herders now go on *otor* more often and for shorter periods of time thus costing them more financially over time. We also observed that very few herders responded stating that education was impacted (Figure 4-8e). Of those that did respond with education they referred to children's education being more costly,

and that they themselves had no educational background to find another job to provide for the family.

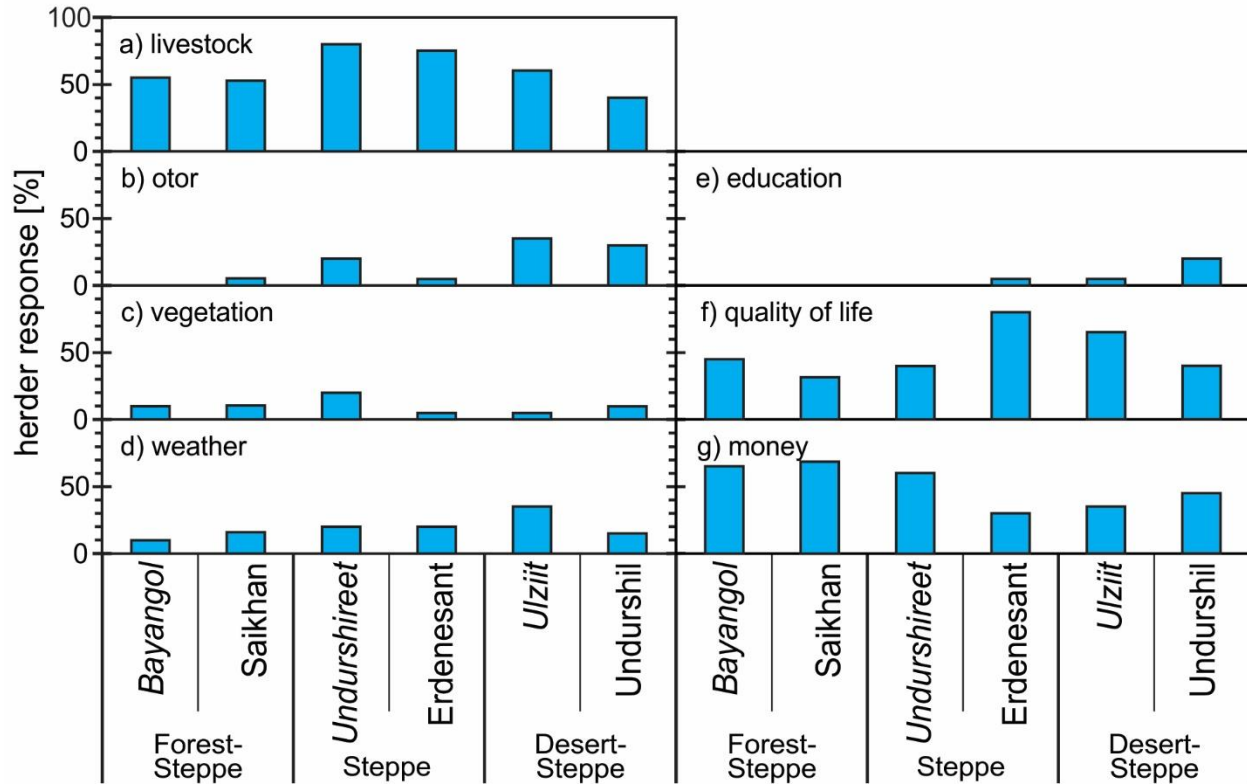


Figure 4-8: Mongolian herder responses to impacts of changes on their life and livelihood in managed (in italics) and non-managed *soums* within three ecozones.

4.4.3 Herder Responses on Adaptations

The last open-ended question asked herders to think about how they are adapting to these changes. Many herders in all provinces responded with going on *otor* more often with steppe and desert steppe ecozone responding higher than forest steppe (Figure 4-9a). Between 50 and 80 percent of herders in both the steppe and the desert steppe responded to more *otor* being something they need to adapt to versus only 26 to 27 percent of herders in forest steppe. A lower percentage of herders in managed *soums* in steppe and desert steppe responded to this as being

important for adaptation vs responses from herders from non-managed *soums*. Herders also agreed that herding practices need to adapt to the changes with a 10 to 50 percent response rate (Figure 4-9a). Herding practices go hand in hand with preparing hay, crops and purchasing hay and other supplies (Figure 4-9a). Between 5 and 79 percent of herders suggested that preparing hay and crops is important, especially herders in the managed *soums* where more herders responded stating this is important for adaptation. In forest steppe 79 percent in managed *soums* vs 42 percent in non-managed *soums*, in steppe 25 percent in managed *soums* vs 24 in non-managed *soums*, and in desert steppe 45 percent in managed *soums* vs 5 percent in non-managed *soums*. Purchasing hay was not as important as preparing hay with responses varying from no responses to between 5 and 47 percent in some *soums*. Responses such as following vegetation, and following water were also important (Figure 4-9b). Herders in the steppe and the desert steppe responded with following water as an adaptation mechanism vs in the forest steppe ecozone. Understanding weather/nature and other are some of the areas that herders mentioned in their responses to adaptation. These two areas received less than 16 percent of the total respondents. Under other, herders responded with not taking any action and finding other means to make money.

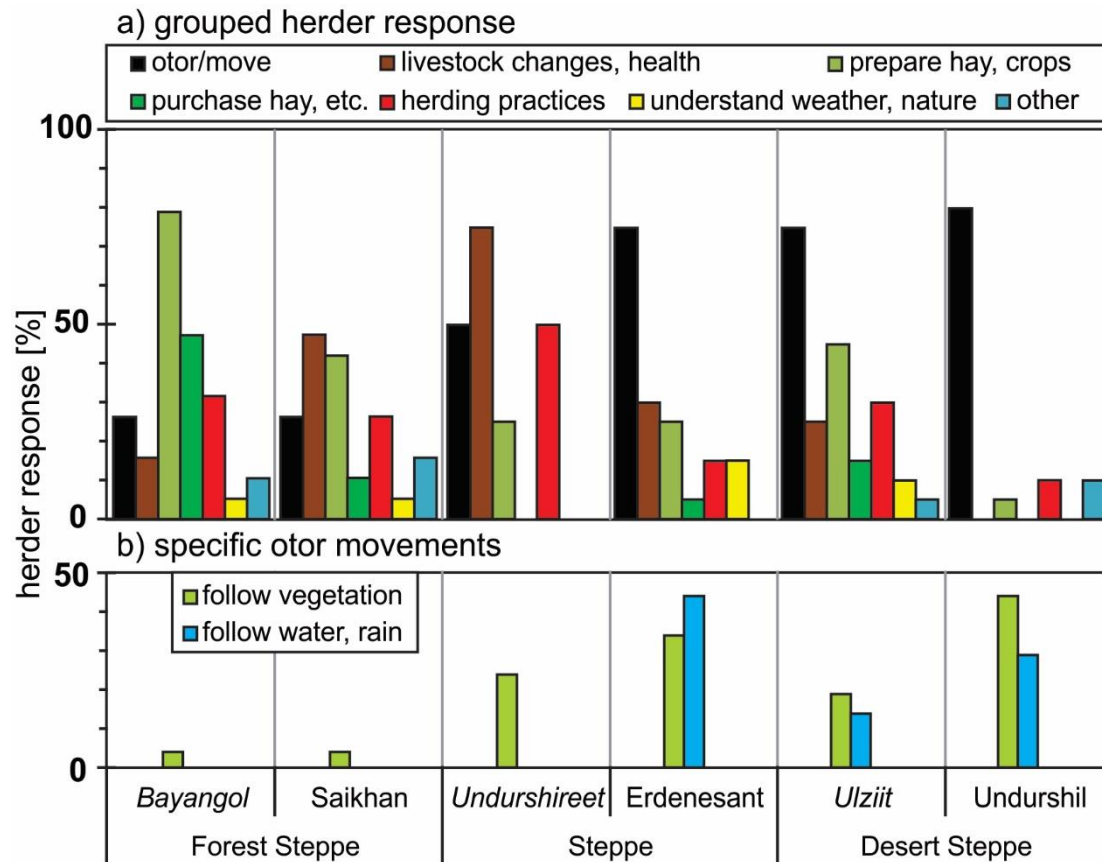


Figure 4-9: Mongolian herder adaptation responses in managed (in italics) and non-managed *soums* within three ecozones.

CHAPTER 5. DISCUSSION

5.1 Pasture Conditions

Remote sensing data in Mongolia demonstrates a decrease in pasture growth in the steppe *soums*, a significant increase in pasture growth in the Undurshil (non-CBRM) *soum* in the desert-steppe, and no change in the other desert-steppe *soum* or forest-steppe *soums* (Figure 4-1a). Similarly, previous research found most of the pasture degradation in Mongolia has been observed in the central and southern part of the country, specifically that the grasslands are retreating in these transition zones, and thus contributing to the desertification (Sternberg et al., 2011; Hilker et al., 2014). In addition, changes in summer precipitations (Figure 4-1a), as well as overgrazing (Figure 4-6h), contribute to desertification (Figure 4-6f) (Hilker et al., 2014). In a study conducted between 2001 and 2010, a decrease in pasture growth was also a result of a greater frequency and severity of droughts; consecutive droughts during growing season significantly contributed to decrease in pasture growth (Nandintsetseg and Shinoda, 2013). Declining plant species richness and diversity across all three ecozones was also observed (Khishigbayar et al., 2015). Decreased pasture growth (Figure 4-1a) was also observed by the herders where most herders responded with a somewhat lower to much lower observed pasture production in both 5- and 20-year time periods (Figures 4-2a and 4-2b, respectively). There was a high consensus among herders in four *soums* and moderate consensus in two *soums* that pasture growth was decreasing or strongly decreasing (Figure 4-1b).

In response to the question on causes of changes in pasture conditions (Table 3-1), herders in most *soums*, except for one (Bayangol with CBRM), responded stating that *dzud*, wind, sand, dust, desertification were some of the main causes of decreasing pasture growth

(Figure 4-6f). A high percentage of herders also stated that a lack of rain and water is another main cause of decreasing pasture growth (Figures 4-6c and 4-7). These responses align with the remote sensing data (Figure 4-1). Herders in the forest-steppe and steppe ecozones also stated that livestock contributed to the decrease in pasture growth, while herders in the desert-steppe had a lower response that livestock is one of the causes of decline in pasture growth (Figure 4-6h). This may be due to most herders in the desert-steppe *soums* tending to go on *otor* more than herders from the other two ecozones since desert-steppe region does not provide enough vegetation for livestock to survive (Jargalsaikhan et al., 2015). Pasture growth severely impacts herder's livelihoods by affecting the quality and quantity of their livestock (Figure 4-8a), their quality of life (Figure 4-8f), and money (Figure 4-8g) as herders' income depends largely on their livestock.

A majority of the herders responded that going on *otor*/more often adaptations to change in pasture conditions in the steppe and desert-steppe ecozones, while fewer herders responded about using *otor* in the forest-steppe ecozone (Figure 4-9a). These responses correlate with the lack of pasture growth in the central and southern parts of the country where herders have no choice but to go on *otor* more often (Jargalsaikhan et al., 2015). The central and southern parts of the country are much more dryer (Venable et al., 2015), and experience more frequent droughts (Sternberg et al., 2011; Hilker et al., 2014), in comparison to the forest-steppe. The intense and prolonged droughts can be attributed to lower precipitation and warmer temperatures, enhancing evapotranspiration (Nandintsetseg and Shinoda, 2013). The herder responses to adaptation also include following vegetation and/following water or rain (Figure 4-9b). Herders in the steppe and desert-steppe responded stating that following vegetation and water or rain is important for adaptation, except for Undurshireet which shows only following vegetation (Figure 4-9b). In the

forest-steppe ecozone following vegetation was not that important to herders, with none of the herders responding following water or rain (Figure 4-9b) as this ecozone provides enough vegetation and water for the herders (Venable et al., 2015).

Remote sensing data shows that green-up was later in both steppe *soums*, but earlier in the other four *soums* (Figure 4-1a). Meanwhile, brown-down was earlier in the steppe *soums*, later for one desert steppe *soum* (Ulziit), and no change for the other three *soums* (Figure 4-1a). The herder data showed a different result (Figure 4-1b). Majority of the herders in all *soums* stated that green-up was somewhat later to much later in the season, and brown-down was somewhat earlier to much earlier in the season, with high consensus on later green-up timeframe (Figure 4-3a), and higher consensus on slightly earlier brown-down (Figure 4-3b). Herder responses showed consensus on pasture production, and phenology (Fernandez-Gimenez et al., 2015). At the local level, herders might be observing much finer changes in pasture production and phenology than what is observable through remote sensing (Fernandez-Gimenez et al., 2015).

5.2 Precipitation

Station data shows that annual rain amount declined for all three ecozones (Figure 4-1a) (Venable et al., 2015), and the number of days between rainfall events significantly increased in the forest steppe and steppe ecozones. However, in the desert-steppe (Ulziit) saw fewer days between rainfall events, and Undershil saw a slight increase in the number of days between rainfall events (Figure 4-1a). The herder responses are in consensus with the station data (Fernandez-Gimenez et al., 2015), except in the desert-steppe where the herders had the greatest

consensus that the rain interval has strongly increased (Figure 4-1b). Similar patterns were also seen further west in Mongolia (Fassnacht et al., 2018).

The duration and intensity of rainfall are not available from the station data since measurements are manual and daily (Fassnacht et al., 2011; Sukh, 2012). However, herder observations assessed these variables (Figures 4-4b and 4-4d), with the majority of herders in agreement that the duration of rainfall was lower (Figures 4-4b), and the intensity of rainfall was greater (Figure 4-4d). The observed changes are that the rain amount in Mongolia is decreasing (Figure 4-1a), the duration of rainfall is lower, and the time between rainfall events is longer (Figure 4-1a), yet the intensity of the rainfall is greater. The changes in precipitation patterns and intensity correlate with the increase in the severity and the frequency of droughts (Fassnacht et al., 2018) and extreme weather (Tumenjargal et al., 2020), thus affecting the green-up and brown-down timing for the steppe *soums*. This is expected since the steppe is a sensitive or transitional ecozone and is the most affected by climate changes (Sternberg et al., 2011; Hilker et al., 2014). This concurs with the herders' responses to the causes of changes in pasture conditions. Herders responded that rain or water (as a general group) is a big cause of the changes in pasture conditions (Figure 4-6c). Specifically, a majority of the herders stated that rain is the main cause, followed by drought, with some stating water, and others stating poor/less rain (Figure 4-7). The herder observations present similar trend of precipitation changes as station data (Figure 4-1; Fassnacht et al., 2018).

It should be noted that the three open-ended questions (causes, impacts and adaptations; Table 3-1) were answered in Mongolian, then translated into English, and subsequently manually recoded to be consistent. Errors are possible in writing down the responses, translation and recoded (Orwin and Vevea, 2009; Gentzkow and Shapiro, 2014). Thus, terminology such as

“poor rain or less rain” may have different meanings among herders and it is possible that an error in any of the three steps caused these terms to be grouped together (Figure 4-7). However, it is likely that the intent was similar for both words.

5.3 Temperature

For spring temperatures, meteorological observations showed that forest steppe and steppe ecozones temperatures cooled slightly, while desert steppe temperatures warmed (Figure 4-1a). Summer and fall temperatures warmed for all *soums* and ecozones, and winter temperatures cooled for all *soums* and ecozones (Figure 4-1a). These trends are similar to trends seen across Mongolia (Venable et al., 2015).

Herder observations were slightly different, in spring most herders had moderate to high consensus that temperatures are cooling with small percentage stating much cooler temperatures (Figure 4-1b, and 4-5a). These herder observations may correspond to their responses of later green-up (Figure 4-3a) and less rainfall (Figure 4-4a). In the summer, most herders in five out of the six *soums* also stated that temperatures were cooling, except for herders in Undurshireet *soum* which stated that temperatures are warmer with some stating temperatures are much warmer (Figure 4-5b). For summer temperatures, there was a much lower consensus on the temperature changes between herders, especially seen for Undurshireet *soum*, where there was a much lower consensus on the temperature changes during the summer season (Figure 4-1b).

Herder responses for fall temperatures were similar to summer temperatures, except herders in Saikhan *soum* where there were little consensus with almost half saying that temperatures were cool or much cooler, and almost half saying that temperatures were warmer (Figure 4-5c). There was a moderate consensus with herders in Undurshireet *soum* having a

moderate to higher consensus, and herders having a moderate consensus on fall temperatures (Figure 4-1b). Previous research found this deviation in responses which could indicate that herders are responding to real differences in local conditions that are not detected by the meteorological sensors or at the scale of the remote sensing data (Fernandez-Gimenez et al., 2015). Local temperature patterns can vary across scales (Collados-Lara et al., 2020).

For winter temperatures, herders were more divided across *soums* in their responses, i.e., had the lowest consensus in the southern four *soums* (Figure 4-1b). In the desert-steppe more herders stated that winter temperatures warmed than cooled, and in the steppe and forest-steppe *soums*, more winter cooling was observed than warming. In the forest steppe, almost all said that winter temperatures were cooling (Figure 4-5d). Herder responses to causes of changes in pasture conditions were partially related to temperature, with some herders in Saikhan, Erdenesant, and Ulziit *soums* stating cold is a cause (Figure 4-6d). Herders in five out of the six *soums* stated sun is a cause (Figure 4-6d and 4-6e). Herders selected weather as an impact of the changes on their life and livelihood (Figure 4-8d), which may be temperature or rain, but the details were not explicitly stated. Thus, herders in four out of the six *soums* selected understanding weather or nature is an important adaptation skill (Figure 4-9a). Based on previous research these results were expected as both the station data, remote sensing data, and herder observation all reflect that the steppe is experiencing the strongest changes in climate and pasture production, with hot and dry summers, to colder winters (Fernandez-Gimenez et al., 2015). Further, there are significant warming and drying trends in the areas which support much of the population, such areas as the steppe ecozone (Venable et al., 2015).

Weather stations are sparse in Mongolia (Sukh, 2012; Venable et al., 2015) and may not provide comprehensive reporting, as a majority of Mongolia has inter-annual variability

(Shiklomanov et al., 2002; Harris et al., 2014; Reid-Shaw et al., 2021). Since weather stations are sparse the meteorological data collected is disproportionate and does not represent the area as a whole (Reid-Shaw et al., 2021). In addition, herders may have biases in observations over longer periods of time (Gantuya et al., 2021; Reid-Shaw et al., 2021; Knapp and Fernandez-Gimenez, 2009).

5.4 Causes, Impacts, and Adaptations

Most herders are in agreement that rain and water (Figures 4-6c and 4-7) as well as *dzud*, wind, sand, dust, and desertification (Figure 4-6f) are the biggest cause of the changes in pasture conditions. A smaller percentage stated human activity (Figure 4-6j) and movement (Figure 4-6i), while the responses on livestock (Figure 4-6h) seem to differ from forest steppe. There, the herders attributed themselves (livestock, movement, and human activity) as a large contributor to causes of change in pasture conditions (Figure 4-6h, 4-6i, and 4-6j). The biggest impact for herders is on their livestock (Figure 4-8a), quality of life (Figure 4-8f), and money (Figure 4-8g). In the desert-steppe, herders tend to go on more *otors* than herders in other ecozones (Figure 4-8b and 4-9a; Jargalsaikhan et al., 2015), as they need to go on more *otor* to fatten up their livestock (Xie and Li, 2008). Therefore, they do not tend to observe the effects of livestock on pasture conditions as pasture in this ecozone is sparse and they do not have any other choice but to take their herd to other areas. Herders in the steppe and desert-steppe stated that the increase in the number and distance of movements is related to a decrease in rangeland productivity (Jargalsaikhan et al., 2015). This decrease in pasture growth was only seen in the Erdenesant steppe *soum* (Figure 4-1a). *Otor* is used to follow the vegetation or water in the southern, drier *soums* (Figure 4-9b). Where herders use *otor* less, i.e., the wetter forest-steppe, they adapt more

by preparing or purchasing hay (Figure 4-9a). Previous research shows that herders were in agreement that precipitation and desertification are some of the biggest causes of change, however many herders named more than one cause that contributes to degradation (Bruegger et al., 2014). Effectively treating livestock changes and health conditions and incorporating effective herding practices such as herders working together, making camping schedules, send animals to pasture in spring were also important as some of the methods to prepare for adaptation to the changes in pasture conditions. Another adaptation to climate change impacts is to use herder observations of change through a survey and incorporating the collected herder data into rangeland management practices (Bruegger et al., 2014).

5.5 Community-Based Rangeland Management (CBRM) versus Non-CBRM

For 20 year pasture change we see a lower response for much lower pasture production in CBRM managed *soum* in the forest-steppe, and a higher response in the CBRM in the steppe (Figure 4-2b). For green up we observed that CBRM herder responses for much later green up are much greater in the steppe and lower in the forest-steppe and desert-steppe (Figure 4-3a). This is consistent with the remote sensing data in the transition areas such as the steppe. For brown down the herders in the desert-steppe CBRM *soum* had the greatest response to brown down being much earlier in comparison to other *soums* (Figure 4-3b).

Responses to questions on summer and fall temperatures saw the greatest difference in the steppe *soum* with herders in the CBRM responding with temperatures are warmer to much warmer versus non-CBRM responses of cooler to much cooler (Figure 4-5b). For fall

temperatures we found that more herders in the non-CBRM *soum* in the forest-steppe responded with temperatures are warmer in comparison to the CBRM *soum* (Figure 4-5c).

Under adaptations we observe that all CBRM *soums* responded with a higher percentage of responses that herding practices need to change in comparison to non-CBRM *soums* (Figure 4-9a). This is expected as it is our understanding that herders in the CBRM *soums* have access to more resources to understand the changes and adaptations. In the steppe ecozone we also observed higher percentage of herders in non-CBRM *soum* stating following vegetation is important in comparison to herder responses in CBRM *soum*, in addition herders in non-CBRM *soum* also responded with following water or rain in comparison to no responses from herders in the CBRM *soum* (Figure 4-9b).

5.6 Limitations and Future Work

The data for this research was collected in 2013, and the climate and pasture conditions have likely changed in the past decade, as compared to the timeframe considered herein. Change is not constant. The length of time used to evaluate change (e.g., Figure 4-1a) can strongly impact the amount and significance of change (Venable et al., 2012; Fassnacht et al., 2016). A cold winter, such as a *dzud* year (Figure 4-6f) at the end of a time series can significantly change the rate of change (Venable et al., 2012).

There are limited station data available in Mongolia, so hence the gridded global datasets were used. Further, station and remote sensing data were not available at the temporal resolution or in enough detail (e.g., snowfall changes) to integrate with herder observations of those changes (see Appendix A). The herder responses to questions about snow (Figure D-1) are

aligned with their other answers. Most say that there is more snow (Figure D-1a) and thus, snowmelt occurs later (Figure D-1b), which is hydrologically what typically occurs (Fassnacht et al., 2014). Later snowmelt also corresponds to later green-up (Figure 4-3a). It may be possible to integrate the herder responses not evaluated herein, even without station or remote sensing data (Fassnacht et al., 2018; Tumenjargal et al., 2020).

If such station and remote sensing data existed, they would be useful to do a similar comparison of the other factors involved in climate and pasture changes. Since the herder responses to pasture conditions and precipitation align with the station and remote sensing data (Figure 4-1; Fassnacht et al., 2018), we can use herder observations to evaluate the climate and pasture conditions in other areas. Many of the *soums* in Mongolia that are under the CBRM programs usually use different types of the CBRM programs (Fernández-Giménez et al., 2011). It would be useful to do a study to compare the effectiveness of each of the more common CBRM programs, and how each program may influence the herder responses to the questionnaire if this survey was to be repeated. Finally, a probabilistic regression or similar approach (DeMaris, 2004) could be used to further synthesize the herder datasets, possibly with the station and remote sensing data.

Much of the western United States is public lands, and many of those are rangeland for ranchers, especially here in Colorado. This is similar to herders in Mongolia, therefore the insight from Mongolia is relevant to the western United States (Reid et al, 2014). Degradation of the rangelands in Mongolia is not just a local Mongolian issue. Degradation usually means decrease in vegetation and thus more potential for aeolian erosion of soil (Ravi et al, 2010). This can lead to sandstorms, some of which have influenced the air quality in China, thousands of kilometers away (Li et al., 2021). Further, dust from the Gobi Desert has been seen on the snowpack of the

western United States (Huang et al., 2002); dust-on-snow is a key accelerator of snowmelt in various parts of the world, including the Southern Rocky Mountains (Fassnacht et al., 2010; Deems et al., 2013; Burges, 2014; Skiles et al., 2015; Reynolds et al., 2020). The idea of “the tragedy of the commons” is relevant to both United States and Mongolia. Herders and ranchers consume an open resource “rangeland” in order to provide enough food for their cattle, however if all individual herders consuming this resource out of their best interest continue to consume this resource, then it becomes a problem of over-grazing (Hardin, 1968). Therefore, it is important to manage the open-access land to control overconsumption.

CHAPTER 6: CONCLUSIONS

This research focused on using station and remote sensing data and evaluating herder observations of the hydro-climatic changes in Mongolia. In our research we compared the sensor-based trends versus the herder responses to close-ended questions across the ecozones-management pairs. We found that herder responses and sensor data were in agreement for the changes in pasture conditions and rainfall, but there was less agreement for temperature trends, depending on the season (winter trends were similar). There was the least consensus among herders for temperature trends versus pasture and rainfall trends. Temperature conditions can vary at a local level that is not captured by meteorological data but observed by herders and seen in their limited consensus for temperature trends.

Herder responses about the causes, impacts, and adaptations to pasture change varied across the ecozones. In the forest steppe, livestock, movement and human activity were more attributed to change than in the other ecozones, while in the steppe and desert-steppe water and weather events (*dzud*, wind, sand, dust, and desertification) were said to be the main causes. The specific water attribute for change also varied by *soum*. They correspond to the specific herder observations of change (close-ended question) and the sensor data. The main impacts of pasture change were livestock, quality of life, and money for all areas, with varying responses being acknowledged in different *soums*. The primary adaptations were to get more forage for the livestock by preparing or purchasing hay in the forest-steppe or moving to follow the vegetation (and water) in the steppe and desert-steppe.

There were differences in herder responses between the *soums* with Community-Based Rangeland Management (CBRM) and those without. For 20 year pasture production herders in the CBRM *soum* in the forest-steppe responded lower to much lower pasture production and a higher response in the steppe CBRM *soum*. Responses to questions on summer and fall temperatures saw the greatest difference in the steppe *soum* with herders in the CBRM responding with temperatures are warmer to much warmer versus non-CBRM responses of cooler to much cooler. For fall temperatures we found that more herders in the non-CBRM *soum* in the forest-steppe responded with temperatures are warmer in comparison to the CBRM *soum*. Under adaptations the majority of herders in CBRM *soums* responded with a higher percentage of herding practices need to change in comparison to non-CBRM *soums*. In the steppe ecozone a higher percentage of herders in non-CBRM *soum* stated following vegetation is important in comparison to herder responses in CBRM *soum*, in addition herders in non-CBRM *soum* also responded with following water or rain in comparison to no responses from herders in the CBRM *soum*.

This research advanced our understanding of herder observations about changes in pasture conditions, precipitation, and temperature and their correlation to sensor (remote sensing and station) data. We highly recommend using herder observations in conjunction with the remote sensing and station data, including areas not covered by remote sensing and station data. Herder observations are vital in understanding the small scale or local changes in the climate and pasture conditions.

REFERENCES

- 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.
- Batima, P., & Dagvadorj, D. (2000) Climate Change and Its Impacts in Mongolia. JEMR Publishing, Ulaanbaatar, Mongolia, 1-227.
- Batima, P., Natsagdorj, L., Gombluudev, P., & Erdenetsetseg, B. (2005). Observed climate change in Mongolia. *Assess Imp Adapt Clim Change Work Pap*, 12, 1-26.
- Batima, P. (2006). Climate change vulnerability and adaptation in the livestock sector of Mongolia. *International START Secretariat: Washington DC*, 204-209.
- Bruegger, R. A., Jigjsuren, O., & Fernández-Giménez, 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.
- Burgess, A. B. (2014). *Hydrologic impacts of dust on snow in the Upper Colorado River Basin*. (Doctoral dissertation, The University of Utah).
- Chen M, Shi W, Xie P, Silva VBS, Kousky VE, Wayne Higgins R, Janowiak JE. (2008). Assessing objective techniques for gauge-based analyses of global daily precipitation. *Journal of Geophysical Research: Atmospheres*, 113, DO4110.
- Collados-Lara, A. J., Fassnacht, S. R., Pulido-Velazquez, D., Pfohl, A. K., Morán-Tejeda, E., Venable, N. B., ... & Puntenney-Desmond, K. (2020). Intra-day variability of temperature and its near-surface gradient with elevation over mountainous terrain: Comparing MODIS land surface temperature data with coarse and fine scale near-surface measurements. *Int J Climatol*. 41.
- Dagvadorj D, Natsagdorj L, Dorjpurev J, Namkhainyam B (2009). *Mongolia: Assessment Report on Climate Change*. Ministry of Nature, Environment and Tourism, Mongolia.
- Deems, J. S., Painter, T. H., Barsugli, J. J., Belnap, J., & Udall, B. (2013). Combined impacts of current and future dust deposition and regional warming on Colorado River Basin snow dynamics and hydrology. *Hydrology and Earth System Sciences*, 17(11), 4401-4413.
- DeMaris, A. (2004). *Regression with social data: Modeling continuous and limited response variables*. John Wiley & Sons, Hoboken NJ, 446 pp.
- Densambuu, B., Ulambayar, B., Battur, A., Sainnemekh, S., Nyam-Ochir, G., Bestelmeier, B., & Action, N. (2015). Defining the ecological site descriptions and its use as a rangeland management tool in Mongolia. *Mountain Scholar Digital Collections of Colorado*.

- Densambuu B, Sainnemekh S, Bestelmeyer B, Budbaatar U (2018) National report on the rangeland health of Mongolia: Second Assessment. Green Gold-Animal health project. SDC; Mongolian National Federation of PUGs. Ulaanbaatar U.
- Eklundh L, Jonsson P. (2009). Timesat 3.0 software manual. University of Lund.
- Fassnacht, S. R., Toro Velasco, M., Meiman, P. J., & Whitt, Z. C. (2010). The effect of aeolian deposition on the surface roughness of melting snow, Byers Peninsula, Antarctica. *Hydrological Processes*, 24(14), 2007-2013.
- Fassnacht, S.R., T. Sukh, M.E. Fernandez-Gimenez, B.Batbuyan, N.B.H. Venable, M. Laituri, and G. Adyabadam. (2011). Local understandings of hydro-climatic changes in Mongolia. *In: Proceedings of the Cold Region Hydrology in Changing Climate Symposium as part of the International Union of Geodesy and Geophysics Conference; 28 June-7 July 2011; Melbourne, Australia. Wallingford, UK: International Association of Hydrological Sciences Publication 346, pp. 120-129.*
- Fassnacht, S. R., Deitemeyer, D. C., & Venable, N. B. (2014). Capitalizing on the daily time step of snow telemetry data to model the snowmelt components of the hydrograph for small watersheds. *Hydrological Processes*, 28(16), 4654-4668.
- Fassnacht, S. R., Cherry, M. L., Venable, N. B. H., & Saavedra, F. (2016). Snow and albedo climate change impacts across the United States Northern Great Plains. *The Cryosphere*, 10(1), 329-339.
- Fassnacht, S. R., Allegretti, A. M., Venable, N. B., Fernández-Giménez, M. E., Tumenjargal, S., Kappas, M., ... & Pfohl, A. K. (2018). Merging indigenous knowledge systems and station observations to estimate the uncertainty of precipitation change in central Mongolia. *Hydrology*, 5(3), 46.
- Fernandez-Gimenez, M. E. (2000). The role of Mongolian nomadic pastoralists' ecological knowledge in rangeland management. *Ecological applications*, 10(5), 1318-1326.
- Fernández-Giménez, M.E., X. Wang, B. Baival, J.A. Klein, and R.S. Reid (eds.), (2011). *Restoring community connections to the land: building resilience through community-based rangeland management in China and Mongolia*. CABI International, Cambridge MA, 245 pp.
- Fernandez-Gimenez, M. E., Angerer, J. P., Allegretti, A. M., Fassnacht, S. R., Byamba, A., Chantsallkham, J., ... & Venable, N. B. H. (2015, June). Integrating herder observations, meteorological data and remote sensing to understand climate change patterns and impacts across an eco-climatic gradient in Mongolia. *In Building Resilience of Mongolian Rangelands: A Trans-disciplinary Research Conference, Ulaanbaatar, Mongolia* (pp. 228-234).

- Gantuya, B., Biró, M., Molnár, Á., Agar, Á., Sharifian Bahraman, A., Babai, D., Molnár, Z. (2021). How Mongolian herders perceive ecological change in a "stable" landscape. *Ecology and Society* 26(2):21.
- Gao, W., Angerer, J. P., Fernandez-Gimenez, M. E., & Reid, R. S. (2015). Is overgrazing a pervasive problem across Mongolia. An examination of livestock forage demand and forage availability from 2000 to 2014. *Building resilience of Mongolian rangelands*. 35-41..
- Gentzkow, M., & Shapiro, J. M. (2014). Code and data for the social sciences: A practitioner's guide. *Chicago, IL: University of Chicago*, 51.
- Gilbert R O (1987). *Statistical Methods for Environmental Pollution Monitoring*. New York: John Wiley & Sons
- GISGeography. (2024, March 10). *What is NDVI (Normalized Difference Vegetation Index)?* GIS Geography. <https://gisgeography.com/ndvi-normalized-difference-vegetation-index/>
- Gombolhuudev P (2011) Vulnerability of rural people to extreme climate events in Mongolia. Dissertation, Institute of Meteorology and Hydrology, Ulaanbaatar.
- Goulden, C. E., Mead, J., Horwitz, R., Goulden, M., Nandintsetseg, B., McCormick, S., ... & Petraitis, P. S. (2016). Interviews of Mongolian herders and high resolution precipitation data reveal an increase in short heavy rains and thunderstorm activity in semi-arid Mongolia. *Climatic Change*, 136, 281-295.
- Hardin, G. (1968). The tragedy of the commons: the population problem has no technical solution; it requires a fundamental extension in morality. *science*, 162(3859), 1243-1248.
- Harris, I., Jones, P.D., Osborn, T.J. and Lister, D.H. (2014). Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. *International Journal of Climatology* 34:623–642.
- 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.
- Fernández-Giménez, M.E., et al., 2020. Research Data - Mongolian Rangelands and Resilience (MOR2). Mountain Scholar Digital Collections of Colorado. <https://hdl.handle.net/10217/201550>
- Huang, H., Qian, Y., Liu, Y., He, C., Zheng, J., Zhang, Z., & Gkikas, A. (2022). Where does the dust deposited over the Sierra Nevada snow come from?. *Atmospheric Chemistry and Physics*, 22(23), 15469-15488.
- IPCC (2022) Climate change 2022: Impacts, adaptation and Vulnerability. (n.d.). <https://www.ipcc.ch/report/ar6/wg2/>

- Jargalsaikhan, A., Batjav, B., Baival, B., Ulambayar, T., Lhagvasuren, T., Tsogtbaatar, S., & Action, N. (2015). Contemporary mobility of herders in central Mongolia. *Mountain Scholar Digital Collections of Colorado*.
- Kasymov, U., Ring, I., Gonchigsumlaa, G., Dejid, N., & Drees, L. (2023). Exploring complementarity among interdependent pastoral institutions in Mongolia. *Sustainability Science*, 18(1), 115-131.
- Kendall M G, Gibbons J D (1990). *Rank Correlation Methods*. 5th ed. London: Edward Arnold, a Division of Hodder and Stoughton
- Khishigbayar, J., Fernández-Giménez, M. E., Angerer, J. P., Reid, R. S., Chantsalkham, 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.
- Klein, J. A., Hopping, K. A., Yeh, E. T., Nyima, Y., Boone, R. B., & Galvin, K. A. (2014). Unexpected climate impacts on the Tibetan Plateau: Local and scientific knowledge in findings of delayed summer. *Global Environmental Change*, 28, 141-152.
- Knapp, C.N., and Fernández-Giménez, M.E. (2009). Understanding change: integrating rancher knowledge into state-and-transition models. *Rangeland Ecology and Management* 62:510–52.
- Kurosaki, Y., Shinoda, M., & Mikami, M. (2011). What caused a recent increase in dust outbreaks over East Asia?. *Geophysical Research Letters*, 38(11).
- Li, G., Lu, D., Yang, X., Zhang, H., Guo, Y., Qu, G., ... & Jiang, G. (2021). Resurgence of sandstorms complicates China's air pollution situation. *Environmental Science & Technology*, 55(17), 11467-11469.
- 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.
- Ma, X., Yasunari, T., Ohata, T., Natsagdorj, L., Davaa, G., & Oyunbaatar, D. (2003). Hydrological regime analysis of the Selenge River basin, Mongolia. *Hydrological Processes*, 17(14), 2929-2945.
- Mandakh, N., Dash, D., & Khaulenbek, A. (2007). Present status of desertification in Mongolia. *Geoecological issues in Mongolia*, 6, 63-73.
- Mann H B (1945). Nonparametric tests against trend. *Econometrica*, 13 (3): 245–259
- Marin, A. (2010). Riders under storms: contributions of nomadic herders' observations to analyzing climate change in Mongolia. *Global Environmental Change*, 20(1), 162-176.

- Mau, G., and G. Chantsalkham. (2006). Herder group evaluation, policy options for the government of Mongolia. Ulaanbaatar, Mongolia: UNDP Sustainable Grasslands Program.
- Meromy, L., Molotch, N. P., Link, T. E., Fassnacht, S. R., & Rice, R. (2013). Subgrid variability of snow water equivalent at operational snow stations in the western USA. *Hydrological Processes*, 27(17), 2383-2400.
- Mongolia-Guide.com. (n.d.-a). *Dundgobi*. Mongolia Guide. <https://mongolia-guide.com/destination/dundgobi>
- Mongolia-Guide.com. (n.d.). *TUV*. Mongolia Guide. <https://mongolia-guide.com/destination/tuv>
- Nandintsetseg, B., Greene, J. S., & Goulden, C. E. (2007). Trends in extreme daily precipitation and temperature near Lake Hövsgöl, Mongolia. 27(3), 341-347.
- Nandintsetseg B, Shinoda M. (2013). Assessment of drought frequency, duration, and severity and its impact on pasture production in Mongolia. *Natural Hazards*, 66, 995-1008.
- U.S. Geological Survey. (2018, November 29). *NDVI, The Foundation for Remote Sensing Phenology*. <https://www.usgs.gov/special-topics/remote-sensing-phenology/science/ndvi-foundation-remote-sensing-phenology#overview>
- Orwin, R.G., and J.L. Vevea, (2009). Evaluating coding decisions. Chapter 10 in *The Handbook of Research Synthesis and Meta-analysis 2nd ed.* (eds. H. Cooper, L.V. Hedges, J.C. Valentine), Russell Sage Foundation, New York, pp.177-203.
- Pielke Sr, R. A., Stohlgren, T., Schell, L., Parton, W., Doesken, N., Redmond, K., ... & Kittel, T. G. F. (2002). Problems in evaluating regional and local trends in temperature: an example from eastern Colorado, USA. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 22(4), 421-434.
- Pinzon J, Tucker C. (2014). A non-stationary 1981-2012 AVHRR NDVI3g time series. *Remote Sensing*, 6, 6929-6960.
- Ravi, S., Breshears, D. D., Huxman, T. E., & D'Odorico, P. (2010). Land degradation in drylands: interactions among hydrologic–aeolian erosion and vegetation dynamics. *Geomorphology*, 116(3-4), 236-245.
- Reid, R. S., Fernández-Giménez, M. E., & Galvin, K. A. (2014). Dynamics and resilience of rangelands and pastoral peoples around the globe. *Annual Review of Environment and Resources*, 39(1), 217-242.
- Reid-Shaw, I., Jargalsaihan, A., Reid, R. S., Jamsranjav, C., & Fernández-Giménez, M. E. (2021). Social-ecological change on the Mongolian steppe: Herder perceptions of causes, impacts, and adaptive strategies. *Human Ecology*, 49(5), 631-648.

- Reynolds, R. L., Goldstein, H. L., Moskowicz, B. M., Kokaly, R. F., Munson, S. M., Solheid, P., ... & Derry, J. (2020). Dust deposited on snow cover in the San Juan Mountains, Colorado, 2011–2016: Compositional variability bearing on snow-melt effects. *Journal of Geophysical Research: Atmospheres*, 125(7), e2019JD032210.
- Salmi, T. (2002). *Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates-the Excel template application MAKESENS*. Ilmatieteen laitos.
- Scenic Pictures of Mongolia - Selenge Province*. (n.d.). Mongolia Tours. https://www.toursmongolia.com/mongolia_travel_news/scenic-images-of-mongolia-selenge-province
- Sen P K (1968). Estimates of the regression coefficient based on Kendall's tau. *J Am Stat Assoc*, 63(324): 1379–1389
- Sharkhuu, A., Sharkhuu, N., Etzelmüller, B., Heggem, E. S. F., Nelson, F. E., Shiklomanov, N. I., ... & Brown, J. (2007). Permafrost monitoring in the Hovsgol mountain region, Mongolia. *Journal of Geophysical Research: Earth Surface*, 112(F2).
- Shiklomanov, A. I., Lammers, R. B., & Vörösmarty, C. J. (2002). Widespread decline in hydrological monitoring threatens pan-Arctic research. *Eos, Transactions American Geophysical Union*, 83(2), 13-17.
- Sirois, A. (1998). A brief and biased overview of time series analysis or how to find that evasive trend. *WMO report*, (133), 14-18.
- Skiles, S. M., Painter, T. H., Belnap, J., Holland, L., Reynolds, R. L., Goldstein, H. L., & Lin, J. (2015). Regional variability in dust-on-snow processes and impacts in the Upper Colorado River Basin. *Hydrological Processes*, 29(26), 5397-5413.
- Sternberg, T., Thomas, D., & Middleton, N. (2011). Drought dynamics on the Mongolian steppe, 1970–2006. *International Journal of Climatology*, 31(12), 1823-1830.
- Sukh, T. (2012). *Local understanding of hydro-climate changes in Mongolia* (Master's thesis, Colorado State University).
- Theil H (1950). A rank-invariant method of linear and polynomial regression analysis, I, II, III. *Proc R Neth Acad Sci*, 53: 386–392, 521–525, 1397–1412
- Tucker CJ, Vanpraet CL, Sharman MJ, Vanittersum G. (1985). Satellite remote-sensing of total herbaceous biomass production in the Senegalese Sahel - 1980-1984. *Remote Sensing of the Environment*, 17, 233-249.
- Tumenjargal, S., Fassnacht, S. R., Venable, N. B., Kingston, A. P., Fernández-Giménez, M. E., Batbuyan, B., ... & Adyabadam, G. (2020). Variability and change of climate extremes

from indigenous herder knowledge and at meteorological stations across central Mongolia. *Frontiers of Earth Science*, 14, 286-297.

Vaske, J.J., Beaman, J., Barreto, H., & Shelby, L.B. (2010). An extension and further validation of the potential for conflict index. *Leisure Sciences*, 32, 240-254.

Venable, N. B. H., S. R. Fassnacht, G. Adyabadam, S. Tumenjargal, M. E. Fernandez-Gimenez, and B. Batbuyan. (2012). Does the length of station record influence the warming trend that is perceived by Mongolian herders near the Khangai Mountains? *Pirineos* 167:71-88.

Venable N B H, Fassnacht S R, Hendricks A D (2015). Spatial changes in climate across Mongolia. In: Fernandez-Gimenez M E, Batkhishig B, Fassnacht S R, Wilson D, eds. *Proceedings of Building Resilience of Mongolian Rangelands: A Trans-disciplinary Research Conference*. Ulaanbaatar: 2015, 73-79.

Venable, N. B. (2016). *Trends and tree-rings: an investigation of the historical and paleo proxy hydroclimate record of the Khangai Mountain region of Mongolia* (Doctoral dissertation, Colorado State University).

Venable, N. B., Fassnacht, S. R., Jigjasuren, O., & Jamiyankhuyag, S. (2020). *MOR2 hydrology field data*. <https://mountainscholar.org/items/1ef93de9-38e0-4b38-9832-b1de36ebcebb>.

Xie, Y. and Li, W., 2008. Why do herders insist on Otor? Maintaining mobility in Inner Mongolia. *Nomadic Peoples*, 12(2), pp.35-52.

Appendix A: Computation of the Mann-Kendall Test and the Theil-Sen's Slope Test

We used the non-parametric Mann-Kendall test (Mann, 1945; Kendall and Gibbons, 1990) to evaluate the significance of trends in the spatial data and the NDVI-based rangeland condition data over time. The Theil-Sen's slope was used to estimate the rate of change, more information on the formulation can be found in (Theil, 1950; Sen, 1968; Gilbert, 1987; Salmi et al, 2002).

Mann-Kendall test is performed when the trend may be assumed to be monotonic (assumed to be increasing or decreasing with no seasonal or other cycles present in the data). The Theil-Sen's slope method uses a linear model to estimate the slope of the trend of the rate of change and the variance of the residuals is constant in time. The Theil-Sen's slope method is not affected by missing values, single data errors or outliers.

Mann-Kendall test was performed since the data values x_i of a time series followed the model below.

$$x_i = f(t_i) + \varepsilon_i \quad (A1)$$

$F(t)$ is a continuous increasing or decreasing function of time, and residuals ε_i is with zero mean and are from the same distribution. Since our data had more than 10 n (number of annual values), we used the normal approximation Mann-Kendall test. The variance of the S statistic is computed by the following equation which takes into account that there may be several tied values (equal values) in the time series.

$$VAR(S) = \frac{1}{18} [n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p - 1)(2t_p + 5)] \quad (A2)$$

The number of tied groups is represented by q , and t_p is the number of data values in the p^{th} group. The values that we get from both the S and $VAR(S)$ computations are then used to compute the test statistic Z in the following equation below.

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}} & \text{if } S < 0 \end{cases} \quad (A3)$$

Z value is used to evaluate the presence of a statistically significant trend. A positive Z value indicates an upward trend, and a negative Z value indicates a downward trend.

Theil-Sen's nonparametric slope method is used to estimate the true slope of the trend. This method is used in cases where trend is assumed to be linear.

$$F(f) = Qt + B \quad (A4)$$

Q is the slope, and B is the constant. To calculate Q , we calculate the slopes of all data value pairs, below is the equation.

$$Q_i = \frac{x_j - x_k}{j - k}, \quad \text{where } j > k \quad (A5)$$

If there are n values x_j in the time series we get as many as $N = n(n-1)/2$ slope estimates of Q_i . The Theil Sen's slope estimator is the median of these N values of Q_i . The N values of Q_i are ranked from the smallest to the largest. Below is the Theil Sen's slope estimator equations.

$$Q = Q_{[N+1]2}, \text{ if } N \text{ is odd} \quad \text{or} \quad Q = \frac{1}{2} (Q_{[\frac{N}{2}]} + Q_{[\frac{N+2}{2}]}), \text{ if } N \text{ is even} \quad (A6)$$

A $100(1-\alpha)\%$ two-sided confidence interval about the slope estimate is obtained by the nonparametric technique based on the normal distribution. MAKESENS computes the confidence interval at two different confidence levels: $\alpha = 0.01$ and $\alpha = 0.05$, resulting in two different confidence intervals.

$$C_\alpha = Z_{1-\alpha/2} \sqrt{\text{VAR}(S)} \quad (\text{A7})$$

$Z_{1-\alpha/2}$ is obtained from the standard normal distribution. Next we calculate $M_1 = (N - C_\alpha)/2$ and $M_2 = (N + C_\alpha)/2$. The lower and upper limits of the confidence interval, Q_{min} and Q_{max} , are the M_1^{th} largest and the $(M_2 + 1)^{\text{th}}$ largest of the N ordered slope estimates Q_i . If M_1 is not a whole number the lower limit is interpolated and if M_2 is not a whole number the upper limit is interpolated.

To obtain B the n values of differences $x_i - Q_{t_i}$ are calculated. The median of these values is an estimate of B (Sirois 1998). The estimates for the constant B of lines of the 99% and 95% confidence intervals are calculated by a similar process.

Appendix B: Computation of the Potential for Conflict Index 2 (PCI₂)

Detailed PCI₂ formulation can be found in (Vaske et al., 2010). Below are the key components of this formulation. Herder responses were recoded to scores of -2 to +2 (Fassnacht et al, 2018). In the PCI₂ responses in the same direction but with different magnitudes are considered not to be in conflict. In our responses we assumed that neutral responses were not in conflict (B2). The distance between two responses ($d_{x,y}$) for two responses (r_x and r_y) were only computed between any negative responses and any positive responses as.

$$d_{x,y} = (|r_x - r_y| - 1) \text{ if } \text{sign}(r_x) \neq \text{sign}(r_y) \\ \text{otherwise } d_{x,y} = 0 \quad (\text{B1})$$

The sign is the sign for a positive or a negative number for each response (r). For a scale we used 5. Below is the formula for PCI₂ index.

$$PCI_2 = \frac{\sum_{k=1}^I \sum_{h=1}^I n_k n_h d_{k,h}}{d_{max} (n_t^2 - Z) / 2} \text{ for } k \neq h, \quad (\text{B2})$$

In this equation n_k is the number of respondents at each scale value, number of respondents at the other scale values is n_h . The distance between respondents is $d_{k,h}$, maximum distance between extreme values is d_{max} , n_t is the number of respondents, and Z is 0 when n_t is an even number, and 1 when n_t is an odd number (Fassnacht et al, 2018).

Appendix C: Herder Survey

Survey Questions

1. How long have you lived in this area? Since which year have you lived here?

_____ Write year

2. Thinking about pasture conditions in your area 20 years ago (1993), is the amount of pasture growth now in comparison to 1993:

1. Much lower
2. Somewhat lower
3. About the same
4. Somewhat greater
5. Much greater
6. Respondent was not here or not old enough to remember 20 years ago

3. Thinking about pasture conditions in your area 5 years ago (2008), is the amount of pasture growth now in comparison to 2008:

1. Much lower
2. Somewhat lower
3. About the same
4. Somewhat greater
5. Much greater
6. Respondent was not here or not old enough to remember 20 years ago

4. Thinking about pasture conditions in your area 20 years ago, have there been any changes in the overall number of different kinds of plants that grow here now in comparison to 1993:

1. The overall number of different plants has declined since 20 years ago
2. The overall number of different plants has not changed 20 years ago
3. The overall number of different plants has increased since 20 years ago
4. Respondent was not here or not old enough to remember 20 years ago

5. Thinking about pasture conditions in your area 20 years ago, have the kinds of plants that grow here now in changed comparison to 1993 (OK to check both 2 and 3):

1. The kinds of plants are the same as they were 20 years ago
2. We are seeing new kinds of plants we did not see 20 years ago

(list names of new plants _____)

3. Some plants that used to grow here, we no longer see or have become much more rare

(list plants that are more rare or have disappeared: _____)

4. Respondent was not here or not old enough to remember 20 years ago

6. Thinking about pasture conditions in your area 20 years ago, has forage quality now changed in comparison to 1993?

1. Much worse

2. Somewhat worse

3. About the same

4. Somewhat better

5. Much better

6. Respondent was not here or not old enough to remember 20 years ago

7. Thinking about pasture conditions in your area 20 years ago, has the amount of bare ground now changed in comparison to 1993?

1. Much less

2. Somewhat less

3. About the same

4. Somewhat more

5. Much more

6. Respondent was not here or not old enough to remember 20 years ago

8. Thinking about pasture conditions in your area 20 years ago, has the amount of sand movement now changed in comparison to 1993?

1. Much less

2. Somewhat less

3. About the same

4. Somewhat more

5. Much more

6. Respondent was not here or not old enough to remember 20 years ago

9. Thinking about pasture conditions in your area 20 years ago, has the amount of soil loss (erosion) now changed comparison to 1993?

1. Much less

2. Somewhat less

3. About the same

- 4. Somewhat more
- 5. Much more
- 6. Respondent was not here or not old enough to remember 20 years ago

10. Please describe any other major changes in pasture conditions you have noticed in the past 20 years. [post-code]

- 1. No other changes in pasture conditions have occurred
- 2. Other changes in pasture conditions have occurred (describe below).

11. Thinking about all the changes you have mentioned so far (remind them of changes mentioned). Please tell me why (what causes) explain these changes? (list)

Causes	Ranking (1=most important)
_____	_____
_____	_____
_____	_____

12. A) Think of the most degraded pasture you have seen. Describe its characteristics.

B) Could the condition of the soils and vegetation of this pasture be improved or is it impossible to improve? (Is the degraded state permanent?) _____ Yes it can be improved. _____ No, it cannot be improved

C) If yes, what could improve the conditions? (prompts: management practices, weather)

D) If yes, how long would it take for this pasture to recover?

E) If conditions cannot be improved, why not?

13. In the following questions please think about the weather and water flow in your area compared to 20 years ago (1993).

Climate Variable	Perceived Amount of Change					
13.A. The amount of rainfall has	1. Decreased a lot	2. Decreased a little	3. Not changed	4. Increased a little	5. Increased a lot	6. Don't know/Not applicable
13.B. The rains have become	1. Much less intense	2. Less intense	3. No change	4. More intense	5. Much more intense	6. Don't know/Not applicable
13.C. The duration of rainfall events has become	1. Much shorter	2. Shorter	3. No change	4. Longer	5. Much longer	6. Don't know/Not applicable
13.D. The number of days between rainfall events has become	1. Much shorter	2. Shorter	3. No change	4. Longer	5. Much longer	6. Don't know/Not applicable
13.E. The amount of snow has	1. Decreased a lot	2. Decreased a little	3. Not changed	4. Increased a little	5. Increased a lot	6. Don't know/Not applicable
13. F. Snow melts	1. Much earlier	2. Earlier	3. No change	4. Later	5. Much later	6. Don't know/Not applicable
13. G. The timing of when the grass turns green is	1. Much earlier	2. Earlier	3. No change	4. Later	5. Much later	6. Don't know/Not applicable
13. H. The timing of when the grass turns brown is	1. Much earlier	2. Earlier	3. No change	4. Later	5. Much later	6. Don't know/Not applicable
13. I. The volume of river flow is	1. Decreased a lot	2. Decreased a little	3. Not changed	4. Increased a little	5. Increased a lot	6. Don't know/Not applicable
13.J. The timing of peak river flow is	1. Much earlier	2. Earlier	3. No change	4. Later	5. Much later	6. Don't know/Not applicable
13. K. Water levels in lakes are	1. Much lower	2. Lower	3. No change	4. Higher	5. Much higher	6. Don't know/Not applicable
13. L. Water availability in springs is	1. Much less	2. Less	3. No change	4. More	5. Much more	6. Don't know/Not applicable

13.M. Water availability in wells is	1. Much less	2. Less	3. No Change	4. More	5. Much more	6. Don't know/Not applicable
13.N. Average spring temperatures are	1. Much cooler	2. Cooler	3. No change	4. Warmer	5. Much warmer	6. Don't know/Not applicable
13.O. Average summer temperatures are	1. Much cooler	2. Cooler	3. No change	4. Warmer	5. Much warmer	6. Don't know/Not applicable
13.P. Average fall temperatures are	1. Much cooler	2. Cooler	3. No change	4. Warmer	5. Much warmer	6. Don't know/Not applicable
13.Q. Average winter temperatures are	1. Much cooler	2. Cooler	3. No change	4. Warmer	5. Much warmer	6. Don't know/Not applicable
13.R. The frequency of dust storms has	1. Decreased a lot	2. Decreased a little	3. Not changed	4. Increased a little	5. Increased a lot	6. Don't know/Not applicable
13.S. The frequency of sand storms has	1. Decreased a lot	2. Decreased a little	3. Not changed	4. Increased a little	5. Increased a lot	6. Don't know/Not applicable

14. **Do you know any traditional ways to conserve water?** Yes No

15. **If yes, please describe.**

16. **How are changes in climate and pasture affecting your life and livelihood?**

17. **What measures are you taking to adapt to these changes?**

Appendix D: Herder Snow Responses

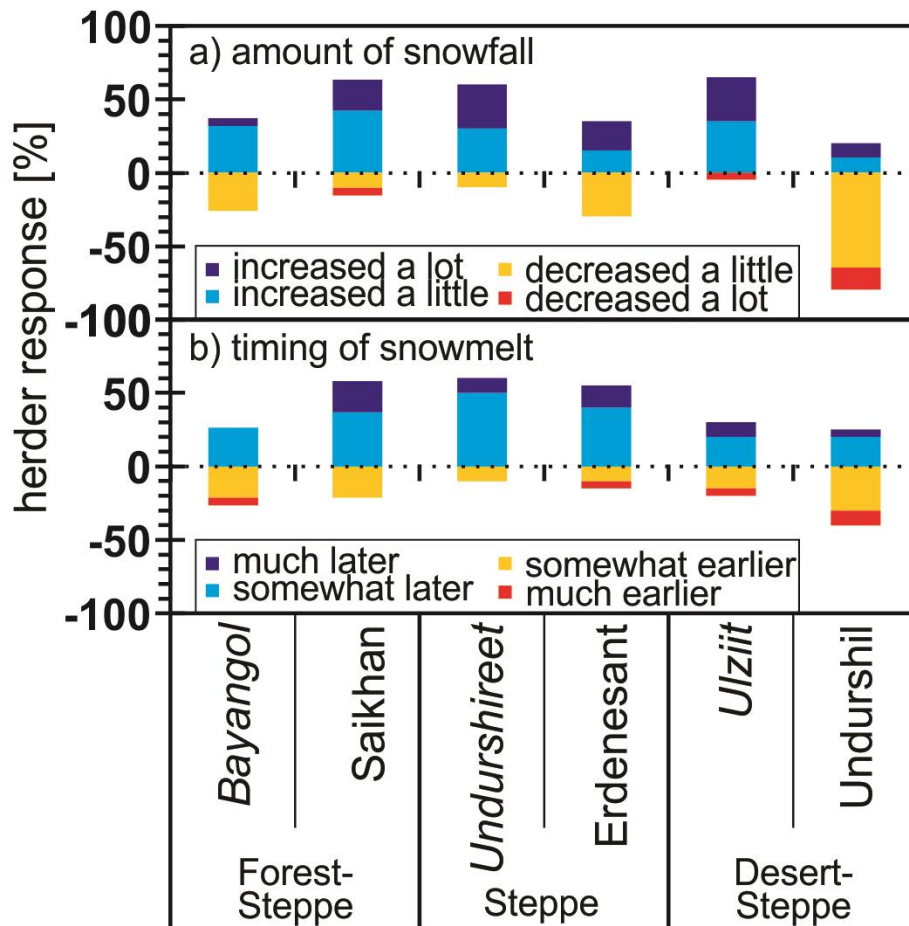


Figure D-1: Mongolian herder observed amount of snowfall and the timing of snowmelt in managed (in italics) and non-managed *soums* within three ecozones. Yellow and red colors represent decreased snowfall and earlier snowmelt, while blue colors represent increased snowfall and later snowmelt.