EXAMINING THE IMPACT OF GRAZING PRESSURE AND SEVERE WINTER DISASTERS ON LIVESTOCK POPULATION DYNAMICS IN MONGOLIAN RANGELAND

A Thesis

by

WEIQIAN GAO

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Richard Conner
Co-Chair of Committee,	Jay Angerer
Committee Member,	William Grant
Head of Department,	Kathleen Kavanagh

December 2016

Major Subject: Ecosystem Science and Management

ABSTRACT

Rangelands in Mongolia provide biomass for livestock grazing and support the environment that pastoralists have depended on for thousands of years. The quantity and quality of livestock and pasture are critically important to the pastoralists and entire country. Dzud is Mongolian term of severe winter disasters, which can be characterized by heavy snowfall, extreme low temperatures and lack of access to forage and water. The overall research aim is to study the influence of grazing pressure and severe winter disasters on livestock population dynamics on rangeland in Mongolia. The primary objectives were to evaluate Mongolian rangeland grazing pressure and analyze its relationship with livestock losses both spatially and temporally, especially during the dzud periods; in addition, simulation modeling was used to examine thresholds of forage use, extreme low temperature and snowfall conditions on livestock population dynamics.

During the period from 2000 to 2014, the number of hectares delineated as overgrazed was highest in 2014, and was lowest in 2003. Large areas of overgrazing were identified in the central and southern portions of the country. Land areas that were consistently overgrazed (> 10 years) totaled 8.6% of the total land area in Mongolia. The desert steppe zone had the largest amount of area classified as consistently heavily grazed or overgrazed. Climate and human management variables were evaluated to assess their influence on forage availability and livestock population dynamics. Precipitation was the dominant variable influencing forage availability for the majority of the county. Grazing pressure was the dominant variable influencing livestock population dynamics. In the future, the methodologies for grazing pressure assessment could be used in developing guidelines for livestock stocking rates and sustainable pasture management for local communities and the national government.

A simulation model was developed to simulate the effects of grazing pressure and winter disasters on livestock population dynamics in Mongolia. The calibration and verification results indicated that the simulation model did a good job in predicting sheep and goat population dynamics in steppe and forest steppe ecological zones, but needs improvement for predicting cattle, horse, and camel population changes in all ecological zones. With additional improvements, the simulation could be useful for government agencies and planning organization in preparing for winter disasters. The prediction of livestock populations could also provide reference data on livestock losses to enhance development of winter disasters response guidelines.

ACKNOWLEDGEMENTS

Many people have contributed to the completion of this research and have provided feedback, moral support, encouragement, and financial support. First of all, I would like to thank my committee chair, Dr. Richard Conner, co-chair, Dr. Jay Angerer, and committee members, Dr. William Grant, for their guidance and support throughout the course of this research.

I really appreciate Dr. Angerer's willingness to accept me as a student and giving me an opportunity to work and study with him. Dr. Angerer always has patience to answer my questions and listen to my ideas, no matter how harebrained they might be. Dr. Conner's class was gave me the chance to study ecological economics and provided feedback and suggestions on the first draft of this research outline. Dr. Grant's class was extremely helpful in understanding the simulation modeling process, and I would like to thank his support and advice on building this research model.

I am very grateful to Dr. Maria Fernandez-Gimenez and Mongolian Rangelands and Resilience (MOR2) group at Colorado State University. Dr. Fernandez-Gimenez served as my undergraduate advisor, who introduced Mongolia and range management to me. I would like to sincerely thank her for providing me the opportunity to attended a research conference in Mongolia last summer. Dr. Khishigbayar Jamiyansharav and Dr. Chantsallkham Jamsranjav were always helpful when I had questions on Mongolia, and I appreciate their support.

Thanks also go to my friends and the department faculty and staff for making my time at Texas A&M University a great experience. Thank you to my colleagues for their support on my proposal and thesis writing process; it was always a great time to talk about research and take classes with them.

Lastly, I greatly appreciate my parents and family for their encouragement, patience and love over the years.

NOMENCLATURE

A	Adult livestock
BR	Birth Rate
DEM	Digital Elevation Model
D-S	Desert Steppe
FA	Forage Availability
FD	Forage Demand
F-S	Forest Steppe
J	Juvenile livestock
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NSOM	National Statistical Office of Mongolia
PU	Forage Percentage Use
S	Steppe
SFU	Sheep Forage Units
Y	Yearling livestock

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CHAPTER I

INTRODUCTION

Over 70% of Mongolia's 1.56 million square kilometers of territory that lies between latitude 41° and 52° is grassland. This land area has six major ecological zones distributed from north to south: alpine, mountain taiga, forest steep, steppe, desert steppe and desert zones (Yunatov et al., 1979) that generally follow a precipitation gradient with higher precipitation in the north and lower precipitation in the south. The rangeland ecosystem has been described as having equilibrium and non-equilibrium dynamics, with the difference being that livestock numbers on non-equilibrium rangelands are generally driven by high variability in rainfall, whereas equilibrium systems have less variable rainfall and livestock numbers relate to carrying capacity of the land (Ellis and Swift, 1988; Fernández-Giménez and Allen-Diaz, 1999; Vetter, 2005). Previous studies in Mongolia indicate that desert and desert-steppe vegetation appears to conform to non-equilibrium dynamics and steppe and mountain-steppe conform to equilibrium dynamics or combination of equilibrium and non-equilibrium dynamics (Fernández-Giménez and Allen-Diaz, 1999; Khishigbayar et al., 2015).

The majority of precipitation in Mongolia comes during summer in the form of sudden torrential thunderstorms (Hirano and Batbileg, 2013); therefore, the summer rainy season plays an critical role in rangeland vegetation and livestock production. In the winter season, the average lowest temperature in northern mountains steppe is -30˚C,

-25˚C in the central steppe, and -20˚C in the southern Gobi steppe.   Maximum snowfall averages 20cm in the north and 5cm in the south region (Purev, 1990).

Rangelands in Mongolia provide biomass for livestock grazing and supports the environment that pastoralists have depended on for thousands of years (Sheehy et al., 2006). Pastoral livestock production is considered a pillar of the Mongolian economy. The livestock herd components in Mongolia include sheep, goats, cattle, yaks, horses and camels; the herders move their livestock seasonally in every year. Therefore, both the quantity and quality of livestock and pasture are critically important to the pastoralists and entire country. Because of this importance, an understanding of the different factors that affect Mongolian rangeland and livestock production, in addition to how these influence pastoralist livelihoods and the national economy are needed. Recently, because of the rapid increase in livestock populations since the early of 1990s, the issue of how to sustainably manage Mongolian rangeland has been under consideration by the Mongolian people (Saizen et al., 2010). Increasing livestock numbers and losses of livestock resulting from natural disasters has increased focus on sustainable management.

Historically, natural disasters were a main factor affecting livestock production across Mongolia. The range of natural disasters that can occur include summer drought and flood, forest and steppe fires, and winter disasters, also known locally as “dzud”. Dzuds can result in large decreases in livestock population due to extreme cold temperatures, or animal starvation due to lack of forage and water. The two most recent severe dzuds occurred in 1999-2002 and 2009-2010, which resulted in more than a 30%

reduction in livestock herds across the country (Angerer, 2012; Fernández-Giménez et al., 2012).

Previous studies analyzed the factors influencing changes in livestock quantity or quality in Mongolia (Begzsuren et al., 2004; Rao et al., 2015). A need exists to examine the thresholds influencing livestock mortality during winter disasters to understand how grazing pressure and environmental conditions interact to influence livestock populations and herder livelihoods on Mongolian rangeland. There is also a need to develop an improved understanding of natural disaster management for Mongolia and in developing monitoring, mitigation, and adaptation strategies for management of Mongolian rangelands.

Problem Statement

Livestock production in Mongolia is impacted by severe winter disasters (dzud), which can be characterized by heavy snowfall, extreme low temperatures and lack of access to forage and water. These conditions can result in high livestock mortality rates (Fernández-Giménez et al., 2012), which in turn, can cause the pastoralists to lose income, thus reducing quality of life. The national economy is also affected. Therefore, studies are needed to examine critical environmental and livestock management factors that influence livestock losses due to dzud conditions and to build models to examine environmental and management thresholds that can be used for monitoring and mitigation assessments of winter disasters. This research is targeted toward providing

Mongolia decision makers and livestock producers with critical information for monitoring vulnerability and risk associated with winter disasters in Mongolia.

Dzud is Mongolian term of severe winter disasters and it is a complex social-ecological phenomenoen (Fernández-Giménez et al., 2012). The parameters that define dzud include previous summer condition (whether there was drought), rangeland grazing pressure, snow cover extent and depth, and air temperature (Erdenetsetseg, 2015). Dzud usually represents conditions such as deep snow, continuous extremely low temperatures (<-30˚C) for a week to 10-day time scale (Iijima, 2015), which can lead to large numbers of livestock dying primarily due to starvation because of lack of forage and water, or die directly from the cold temperatures (Angerer, 2012; Batima, 2006; Fernández-Giménez et al., 2012).

One major factor driving Mongolia livestock dynamics is extreme climate variability (Batima, 2006; Shinoda, 2015). During the past twenty years, Mongolia has suffered two severe national dzuds: 1999-2002 and 2009-2010 (U.N., 2001; UNDP and NEMA, 2010). The dzud of 1999-2002 caused 35% of Mongolia livestock lost (Siurua and Swift, 2002), the dzud of 2009-2010 caused 20% of the national herds to perish and influenced 28% of Mongolian population (Fernández-Giménez et al., 2015; ReliefWeb, 2010). Extremely cold winter temperatures and summer drought can explain almost 50% of livestock mortality based on and analysis of a historical dataset (Rao et al., 2015). In addition, projected impacts of global climate change indicate an increased frequency and the range of extreme dry summer and cold winter dynamics (Hessl et al., 2015). Moreover, climate change will increase not only the climate variables effect on livestock dynamics and production (Begzsuren et al., 2004), but also will increase risk for sustainable natural resources management (Batima, 2006).

Pastoral herders receive the majority of their financial income from animal production. In addition to the herders daily household demand for resources that come from the livestock, herders also trade livestock meat, milk and dairy, wool production, fat byproducts, and bone's crafts (Dorligsuren et al., 2012). At the same time, some species of livestock that are used in transportation, such as horse and camel, are traded. As discussed previously, dzuds that have occurred since the change to a market economy have resulted in large losses of livestock and influenced herder's livelihoods. Research on more than 700 herders households' interviews (Batima, 2006) found that the dzuds not only resulted in declines of vegetation species and livestock weight, but also decreased the production of meat, milk, wool, and cashmere. Other severe impacts from dzud affecting herders livelihoods include herders being trapped in their home because of snow, wind, ice and cold temperatures; an increase in illness, inability for children to attend school; and lack of stored food (Batima, 2006; Dorligsuren et al., 2012). Therefore, winter disasters (dzud) play a large role in affecting quantity of livestock and quality of herder's life (Siurua and Swift, 2002).

Research Questions and Hypotheses

The overall research aim is to study the influence of grazing pressure and severe winter disasters on livestock population dynamics on rangeland in Mongolia. Specific objectives include:

1. Calculating Mongolian rangeland grazing pressure and analyzing its relationship with livestock losses, both spatially and temporally, especially during the dzud periods.
   a. Question:

      Does a change of livestock number and livestock mortality have a relationship with grazing pressure on Mongolian rangelands?

   b. Hypotheses:

      Areas with forage percentage use exceeding 70% (i.e., overgrazing) have higher correlations with livestock mortality during droughts and winter disasters than those areas with lower percent use of forage.

2. Examine severe winter disaster thresholds based on forage use, extreme low temperature and snowfall conditions.
   a. Question:

      Do Mongolian rangelands have thresholds of forage use, extreme temperature and snowfall that can be used in a simulation model to detect vulnerability to severe winter disasters (dzud)? If so, what are the thresholds values?

b. Hypotheses:

   A model representing the dynamics of three factors, forage availability, temperature dynamics and extremes, and snowfall depth better corresponds to livestock losses than examination of these thresholds individually.

CHAPTER II

AN EXAMINATION OF GRAZING PRESSURE AND LIVESTOCK POPULATION CHANGE ON MONGOLIAN RANGELANDS

Introduction

In Mongolia, pastoral livestock production is considered a pillar of the economy and a large portion of the rural population depends on livestock production for their livelihood. Livestock producers are generally semi-nomadic herders who extensively graze their animals in surrounding regions during the spring, summer, and fall, then return to protected camps for the winter months (Bedunah and Schmidt, 2004). Sheep and goats are the predominant kinds of livestock, followed by cattle, horses, yaks and camels. Since 1991, Mongolia has been transitioning to a market economy and livestock numbers during this period have generally increased each year with the exception of 1999-2002 and 2010 where large-scale drought and winter disasters (locally called "dzud") (Fernández-Giménez et al., 2012) resulted in 35% and 22% reductions in livestock numbers nationwide (NSOM, 2016).

Large increases and fluctuations in livestock numbers has been a more recent occurrence in Mongolia and have followed a "boom-bust" pattern where increases in livestock numbers are halted by dzud events. Prior to 1990, livestock numbers remained relatively the same across years. In 1990, the communist regime ended in Mongolia, and this policy change resulted in a difficult transition period from command economy to market economy until around 1994 (Nixson and Walters, 2000; Spoor, 1996). Mongolia joined the World Trade Organization in 1997, which expanded the Mongolian market and trade region. A good economic environment and new freedom in economic policy improved Mongolia's livestock situation and economic development (Kovacic, 1995). The regime change led to a transfer from state-owned enterprises to informal economy, and the livestock population and herder numbers increased dramatically by the late 1990s (Lkhagvadorj et al., 2013; Mearns, 2004). The increase in herd size benefited not only the individual herder families, but also reduced the regional and national poverty (Fernández-Giménez et al., 2012).

In previous studies, degradation of Mongolian rangeland has been attributed to large numbers of livestock, especially an increase in goat numbers (Addison et al., 2012; Sekiyama et al., 2014). Other studies have evaluated livestock numbers in relation to vegetation biomass proxies derived from remote sensing data (Hilker et al., 2014; Kawamura et al., 2005; Liu et al., 2013). Climate trends of increasing temperature and decreasing precipitation have also influenced Mongolian rangeland degradation (Liu et al., 2013; Wesche and Retzer, 2005). On the other hand, a long-term study (Khishigbayar et al., 2015) indicated that the integration of climatic factors and grazing pressure influenced rangeland conditions, but rangelands had not yet degraded to an irreversible state. In an evaluation of degradation assumptions of Mongolia rangelands, Addison et al. (2012), indicated that factors influencing degradation are complex and dynamic, and cannot be attributed to single factors.

Recent remote sensing studies, using proxies for vegetation biomass such as the Normalized Difference Vegetation Index (NDVI), have indicated that widespread overgrazing and changing climate in Mongolia are leading to land degradation (Hilker et al., 2014; Liu et al., 2013). In these studies, overgrazing was generally attributed to increases in animal numbers; however, no evaluations were conducted to assess whether the vegetation production on Mongolian rangelands could support the number of animals measured in annual statistical surveys. Moreover, numbers for each species of livestock were not converted to a common forage intake unit (e.g., a sheep) to account for forage intake differences across species so that forage demand and grazing pressure could be interpreted correctly.

To date, no studies in Mongolia have been conducted on a national scale to examine spatial and temporal grazing pressure that links forage biomass production with forage demand by livestock. The overall aim of this study was to fill this gap by examining grazing pressure and its influence on changes in livestock numbers over time in relation to climatic conditions (especially conditions for dzud).

An understanding of temporal and spatial trends is important for evaluating how changing climate and livestock management influence vegetation change and resilience in these systems. For this study, a spatial and temporal analysis of grazing pressure was conducted to evaluate the relationship between livestock forage availability and livestock forage demand across soums (similar to districts) in Mongolia during the period from 2000 to 2014. The objectives were to: 1) define land areas having grazing pressure indicative of overgrazing, 2) examine trends in grazing pressure over time to identify areas that have had prolonged overgrazing that could result in rangeland degradation, and 3) examine how abiotic factors (temperature, rainfall, and drought) and grazing pressure influence changes in livestock numbers over time.

Methods

Study Area

Mongolia is a landlocked country in east-central Asia (latitudes 41˚ to 52˚N; longitude 87˚ to 120˚E), located between China and Russia. Ulaanbaatar is the capital and the largest city. The political administration in Mongolia is divided into 21 aimags (similar to provinces), which are further sub-divided into 329 soums (Batima, 2006). Mongolia has varied geography with the mountain areas to the north and Gobi Desert to the south (Figure 1). The major ecological zones and their general productivity are expressed by mountain forest steppe as having the highest productivity, followed by steppe, desert steppe, and desert zones. The climate of Mongolia is continental; it has warm wet summers with cold dry winters of which some can be extremely severe, leading to declines in livestock populations (Fernandez-Gimenez, 1999).

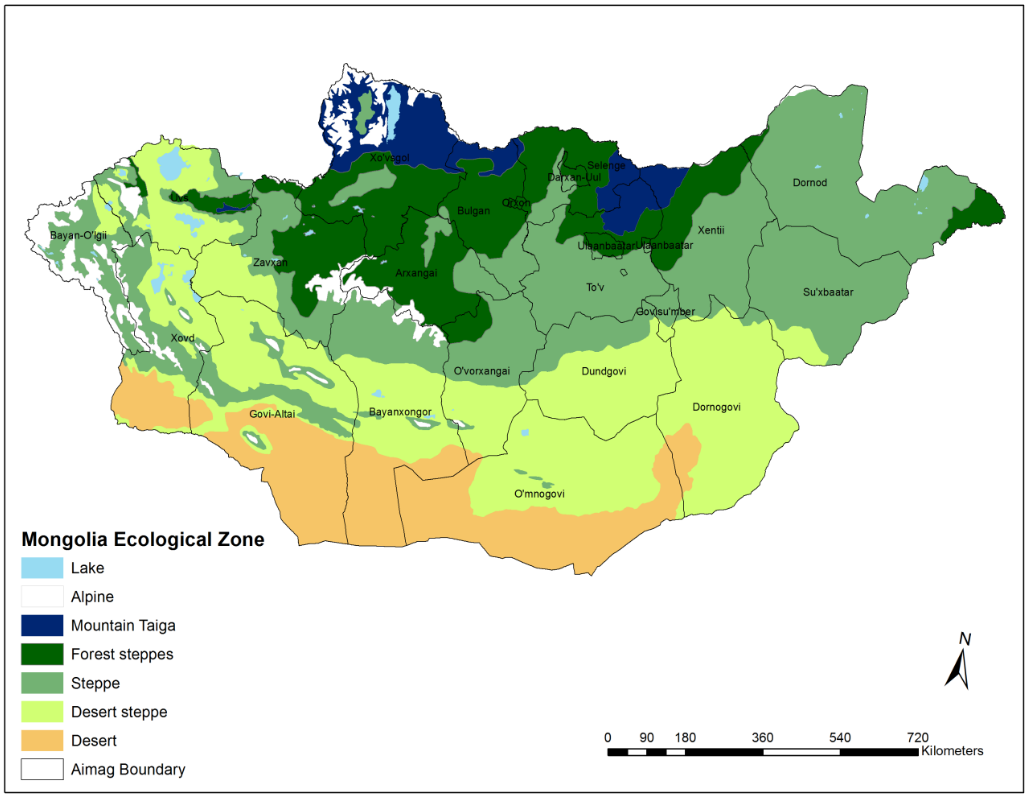

Figure 1. Ecological zone classification of the study area in Mongolia. Boundaries were acquired from the Mongolia Information and Computer Center (ICC) Environmental Database Vegetation Map (Baival, 2016).

The National Statistics Office of Mongolia (NSOM, 2016) estimates that the human population in Mongolia is approximately 2.9 million people occupying approximately 1.5 million km^2 land area. In addition, National Statistics Office conducts yearly surveys in each soum to determine the number and species of livestock. Mongolian economic activities have traditionally been based on herding, livestock trade, agricultural and mineral operation (Mearns, 2004).

Grazing Pressure

To quantify grazing pressure, a temporal and spatial analysis was conducted to analyze the relationship between livestock forage availability and forage demand across soums during the 2000 to 2014 period. The workflow for this assessment is depicted in Figure 2.

To assess forage demand by livestock, livestock census data, by soum, were acquired from NSOM for the period from 2000 to 2014 (NSOM, 2016). Livestock species numbers we converted to sheep forage units (SFU) using conversion factors of 1, 0.9, 6, 7, and 5 sheep forage units for sheep, goats, cattle, horses, and camels, respectively (Bedunah and Schmidt, 2000).

Forage demand was based on livestock density and herd composition, and was calculated by multiplying the SFU densities in each soum by the forage intake of an individual SFU (i.e., 365 kg of forage intake/yr) (Bedunah and Schmidt, 2000). The forage demand for each district was then divided by the total hectares of grazeable land in each district to derive livestock forage demand per hectare for each year. Because grazing is not always efficient and vegetation is lost through trampling, soiling, insects, and natural senescence (Smart et al., 2010), a loss factor of 20% of the forage available was included in the calculation of forage demand.

Forage availability on the landscape was estimated using a linear regression relationship between herbaceous biomass and the 250-m Moderate Resolution Imaging Spectroradiometer (MODIS) Normalized Difference Vegetation Index (NDVI) product

(Huete et al., 2002). The herbaceous biomass data were collected from plots that were clipped along vegetation transects as part of a forage monitoring study conducted in Mongolia during 2004 to 2010 (Angerer, 2012). For the forage monitoring study, transect locations were collocated with NDVI pixels and NDVI values were extracted from MODIS scenes for the time periods when biomass data were collected. The resulting regression had an $r^2 = 0.70$ and a root mean square error of 164 kg/ha (Khishigbayar et al., 2015). The regression was used to predict herbaceous biomass for the maximum NDVI that occurred for each 250-m pixel within the district boundaries for each year (2000 to 2014). In order to more accurately represent the forage availability, land area with slopes greater than 60 % were identified using the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (Ramirez, 2014) and were removed from the calculations since these steep slopes are generally not accessible to grazing animals (Holechek, 1988). The MODIS land cover data (Friedel et al., 2002) was used to delineate grazeable land cover types and non-rangeland land cover types. Non-rangeland types were masked out since they generally do not contribute to forage grazing in Mongolia. Spatial statistics tools were used to calculate the total herbaceous biomass in each soum. The total herbaceous biomass in each soum was divided by the number of grazeable hectares in the soum to derive forage available for livestock per hectare.

Forage percentage use (PU) was used as an indicator of grazing pressure. PU was calculated as the forage demand divided by the forage available multiplied by 100. Fifty percent (50%) use of forage is a general recommendation for promoting forage regrowth and soil protection on grazing lands; however, research in arid and semi-arid regions of the United States indicate that percent use values of 25 to 45% are needed to prevent overuse in these areas, whereas values of 50 to 60% are reasonable in more humid areas or annual grasslands (Holechek, 1988). Since no research has been conducted to determine the ideal percent use of forage in Mongolia, a PU≤50 was used in this study to indicate light to moderate grazing pressure that would support sustainable pasture regrowth. Percent use between 50% and less than 70% was used to indicate heavy grazing pressure, and use greater than 70% indicated overgrazing or overuse. If the land areas had percent use of greater than 70% for 10 years or more, the land area was considered to be consistently overgrazed.

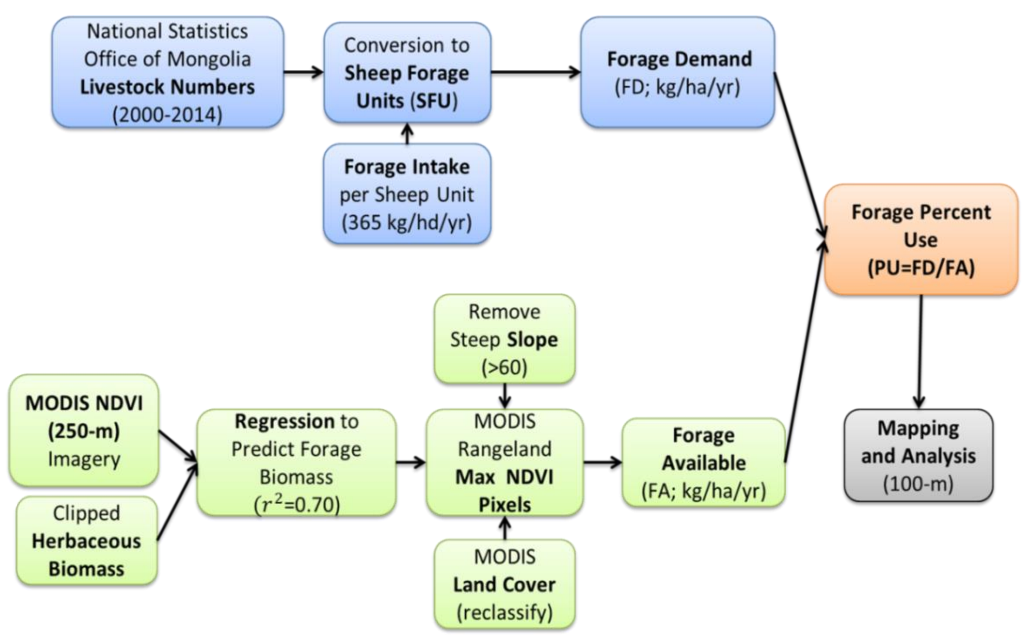

Figure 2. Workflow for assessing Grazing Pressure (PU).

Statistical Analysis

Regression analyses were used to examine relationships between climate and livestock density variables and forage availability. Stepwise regressions were conducted for each soum using forage availability (average kg/ha/soum) as the dependent variable. Growing season (June to August) average temperature (˚C), and annual average precipitation (mm) per soum were used as independent variables to assess which climate factors (or combination of these) influenced forage availability during the 2000 to 2014 period. For the stepwise regressions, variables had to meet an $\alpha \leq 0.05$ to enter and stay in the model. If a significant regression was not found in the stepwise regression for a soum, then the average livestock density (SFU/ha) per soum was added as another independent variable in the stepwise regression analysis, to assess if livestock density or a combination of livestock density and the climate variables had a strong relationship with forage availability.

A second stepwise regression analysis was conducted to evaluate factors that could influence changes in livestock numbers. Changes in livestock numbers from year to year were calculated as:

$$SFU\ percentage\ change = \frac{SFU_{Year2} - SFU_{Year1}}{SFU_{Year1}} * 100 \qquad [1]$$

and was used as the dependent variable in the stepwise regression analysis. Percent use (PU) from the previous year, winter season (January to March) soum average monthly minimum temperature (˚C) for the current year, and soum average annual precipitation (mm) from the previous year were used as independent variables to examine which factors (or combination of these) may have influenced changes in livestock numbers over time. These independent variables were chosen to reflect forage availability in the previous year (grazing pressure and rainfall) as indicators of livestock condition, and temperature during the winter months as an indicator of the dzud potential.

Temperature and precipitation data were acquired from the National Oceanic and Atmospheric Administration (NOAA) global data archives. For temperature, the Global Historical Climate Network monthly average temperature dataset was used (Lawrimore et al., 2011). For rainfall, the Climate Prediction Center (CPC) Unified Precipitation dataset (Chen et al., 2008) was used to calculate the annual sum of rainfall for the study period. Both datasets are interpolated from weather station data and have a spatial resolution of 0.5° x 0.5°.

Spatial Analysis

An evaluation of thresholds between livestock mortality and grazing pressure was implemented via spatial comparison between SFU percentage change and grazing pressure. Furthermore, a spatial comparison of forage availability and climate factors was used to examine evidence of whether climate factors or human management (through stocking rate decisions) was influencing vegetation production.

After the stepwise regression analyses, the independent variables were categorized by type (i.e., only one variable significant, a combination of variables significant, or all variables significant). A unique identifier and color code were assigned to each type to allow mapping of significant variables.

The grazing pressure, forage availability and livestock mortality were intersected with ecological zones, and non-grazeable rangeland area was masked in geographic information system (GIS) software. Spatial statistics were conducted to categorize areas based on grazing pressure, forage availability, and livestock mortality to potentially identify areas approaching tipping points toward irreversible degradation or large losses of livestock under dzud weather conditions. Moreover, the mapped areas would provide more evidence to the relationship between grazing pressure, livestock morality and severe winter disasters.

Hypothesis Testing

A non-parametric two sample test was used to compare livestock population change in soums having percent use of forge greater than 70% (overgrazed) to those having lower percent use (not overgrazed). The number of soums categorized as "not overgrazed" over time greatly exceeded those categorized as "overgrazed". In order to have equal sample sizes for statistical comparison, a random sub-sample was selected from the "not overgrazed" group to equal the number from the "overgrazed" group. Normality tests were conducted on the "overgrazed" and "not overgrazed" groups and the data were non-normal. Therefore, the two sample Mann-Whitney U test (Mann and Whitney, 1947) (a non-parametric alternative to the two sample t-test) was used to analyze for statistically significant differences in the “overgrazed” and “not overgrazed” groups. Significant differences in the median change in livestock numbers was considered significant at $p<0.05$.

Results

Grazing Pressure Distribution

Nationally, total SFUs approached 64 million in 2000 and declined in both 2001 and 2002 to 45 million due to drought and winter disasters (dzud). After 2003, SFUs increased steadily each year until 2010, when drought conditions in 2009 and dzud in early 2010 resulted in a 21% decrease in SFUs. Since 2010, SFUs have increased more than 10% each year, and in 2014, SFUs approached 85 million (Figure 3A). After the 2000 to 2002 dzud period, goat populations increased rapidly and exceeded historical levels (Figure 3B). Cattle and horse populations declined after the 2000 to 2002 dzud period. During subsequent years, their numbers did increase, but not as rapidly as goats. With the exception of camels, all species increased rapidly after the 2010 dzud and had comparable SFUs on a national basis (Figure 3B).

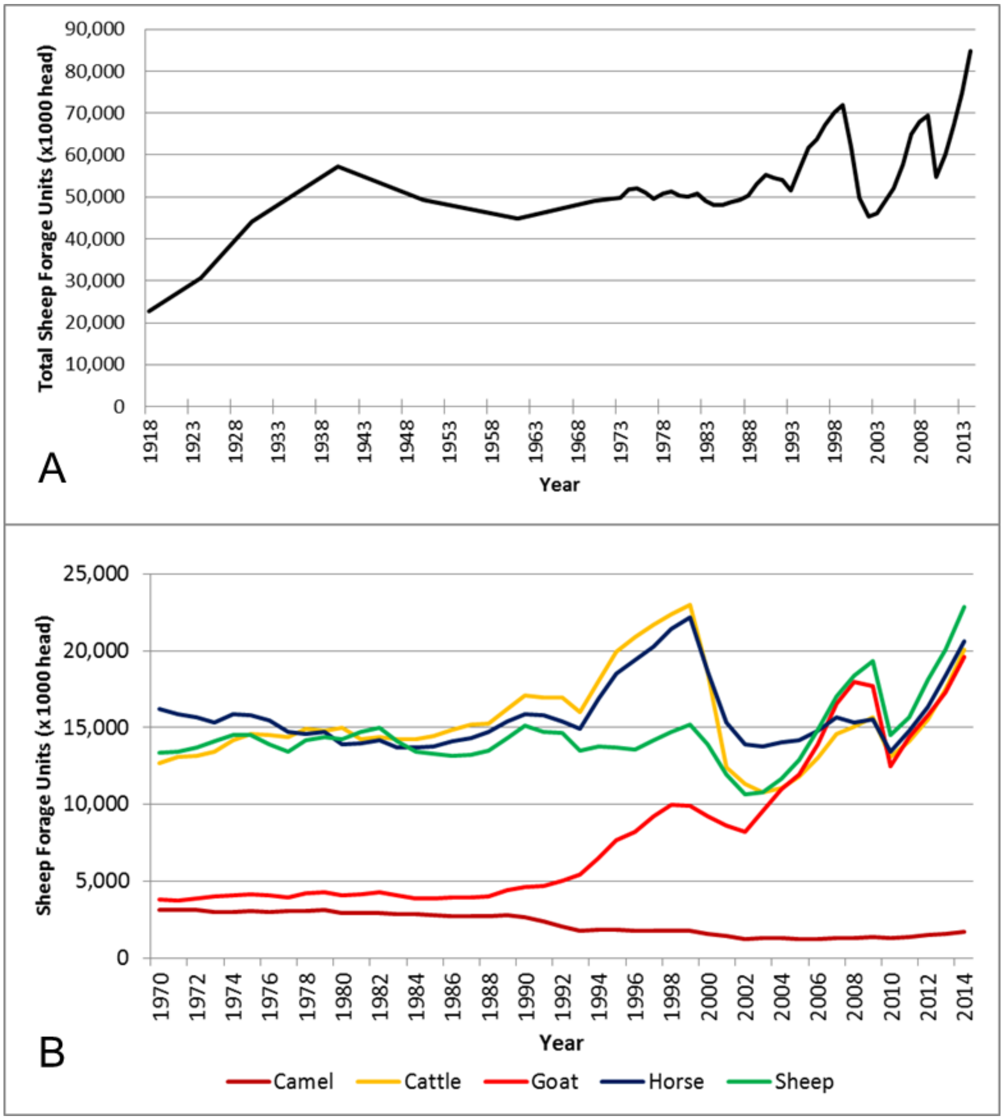

Figure 3. Mongolia livestock Sheep Forage Units trend from 2000 to 2014 (NSOM, 2016). Note differences in time periods in panel A and B.

During the period from 2000 to 2014, grazing pressure was variable across Mongolia both temporally and spatially (Figures 4, 5, 6). In 2014, Mongolia had the highest grazing pressure, on a spatial basis, of the 14-year period with almost 57 million hectares delineated as overgrazed (Figure 6 and Figure 7). Grazing pressure was lowest in 2003, with almost 5 million hectares overgrazed (Figure 4 and Figure 7). Light to moderate grazing occurred on 132 million hectares during 2003, which was the highest of any year during the study period. Generally, grazing pressure was proportionally lower after dzud years (2003 and 2010) due to lower animal numbers and an increase in forage production in response to higher rainfall (Figure 4D, Figure 5E, Figure 7; and Appendix I).

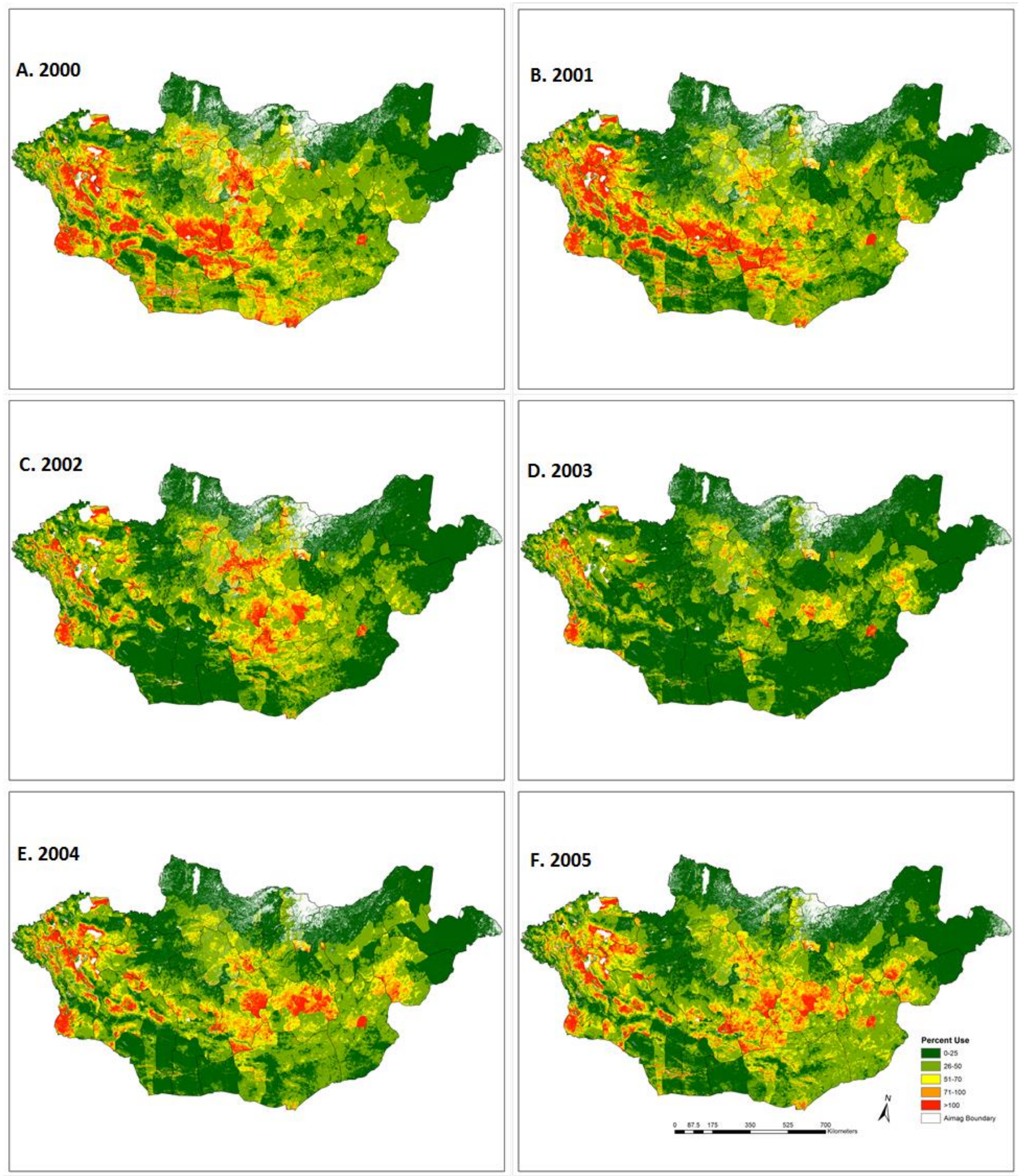

Figure 4. Percent use of forage by livestock across aimags in Mongolia during 2000 (A) to 2005 (F).

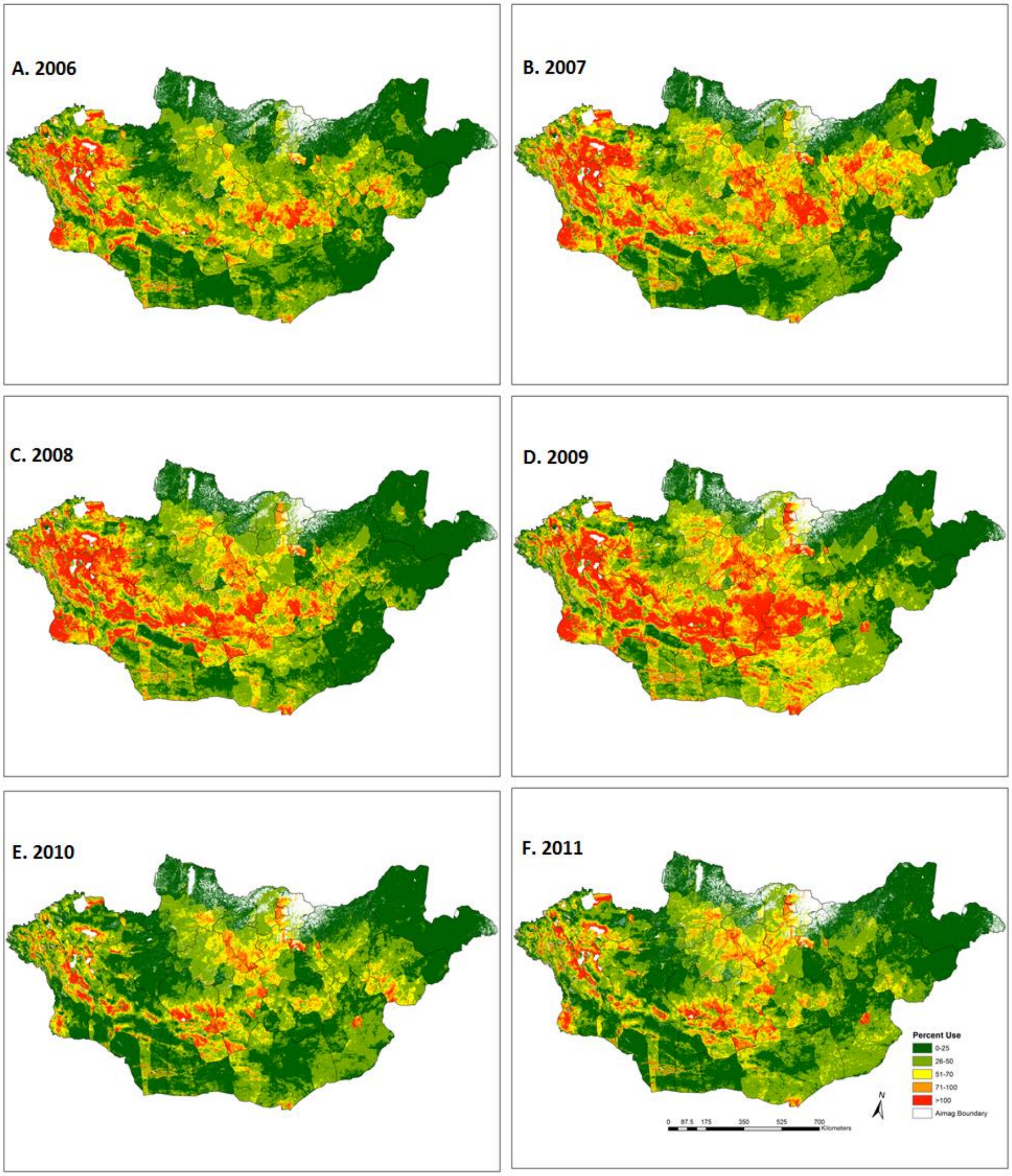

Figure 5. Percent use of forage by livestock across aimags in Mongolia during 2006 (A) to 2011 (F).

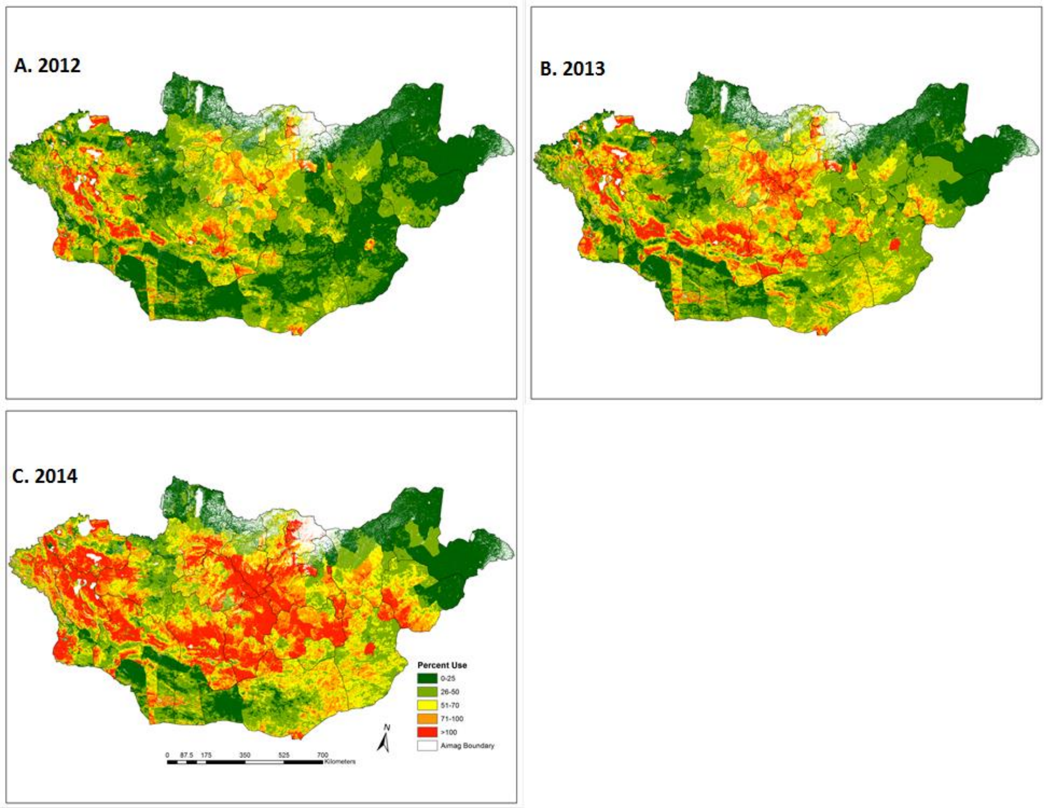

Figure 6. Percent use of forage by livestock across aimags in Mongolia during 2012 (A) to 2014 (C).

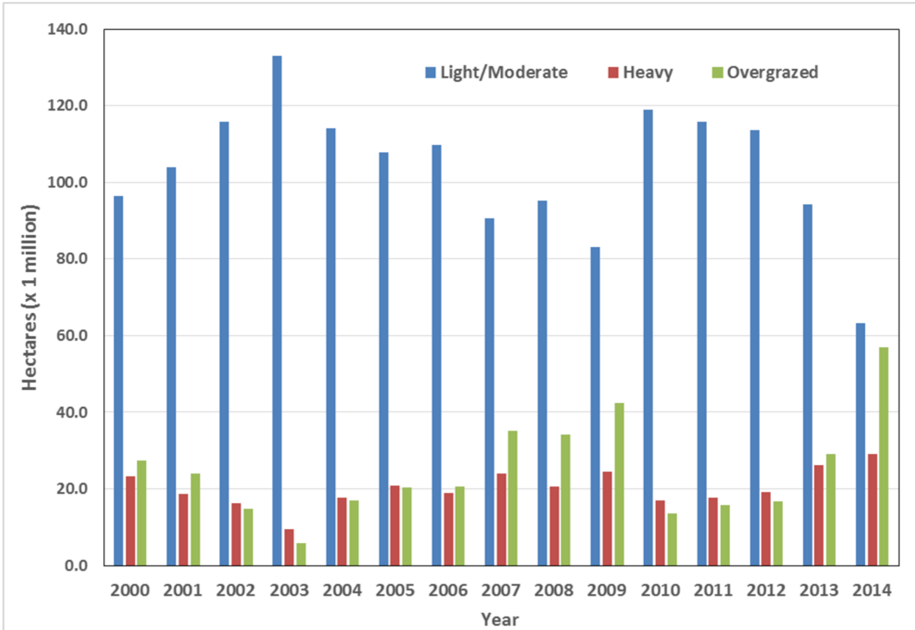

Figure 7. Total hectares by grazing pressure class (light/moderate, heavy, overgrazed) during the period from 2000 to 2014 in Mongolia.

Grazing pressure during the 2000 to 2014 period was generally higher in the central and western *aimags*, and lowest in the eastern *aimags* (Figure 8 and 9). Land areas delineated as having consistent heavy grazing (i.e. percent use between 50% and 70% in 10 or more years in the time series) were relatively small (0.2% of grazeable land) (Figure 8B), However, land areas that were consistently overgrazed (i.e., percent use greater than 70% for 10 or more years) totaled 8.6% of the total land area (Figure 9B).

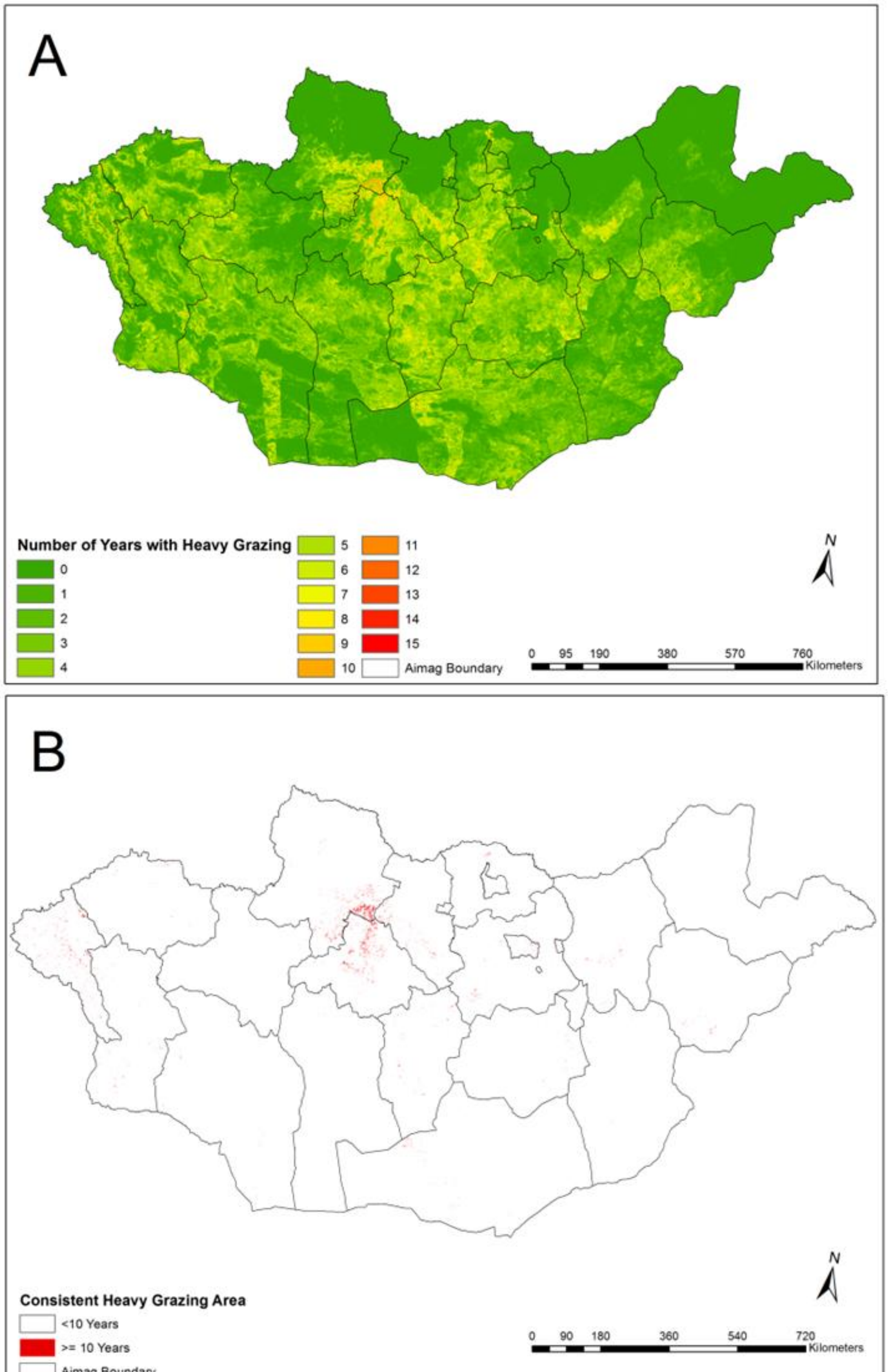

Figure 8. Mongolia Grazing Pressure: A) areas delineated by number of years having heavy grazing pressure (50%<PU<70%), and; B) delineation of areas having 10 or more years of heavy grazing across Mongolia during the 2000 to 2014 period.

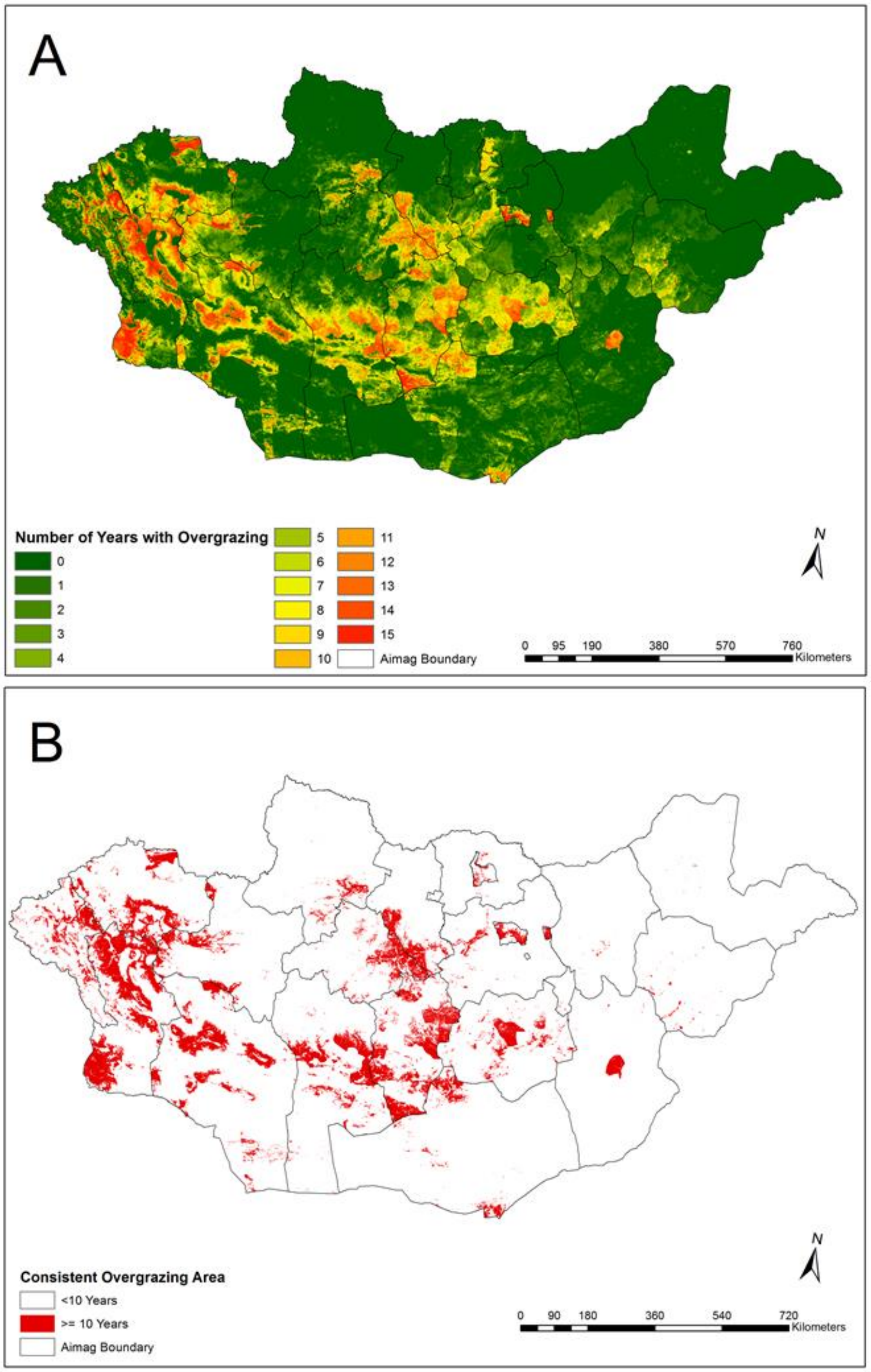

Figure 9. Mongolia Grazing Pressure: A) areas delineated by the number of years having grazing pressure identified as overgrazing (PU≥70%); and B) delineation of areas having 10 or more years of overgrazing across Mongolia during the 2000 to 2014 period.

Within ecological zones, land areas within zone boundaries classified as heavily grazed were greatest for the desert steppe, followed by forest steppe, steppe and desert zone (Table 1). Desert steppe also had the greatest amount of land area classified as overgrazed (Table 2). Percent of overgrazed area varied over time, but was generally lower in years immediately after dzuds period and higher before dzud period (Table 2).

Table 1. Percentage of land area classified as heavy grazing (50%<PU<70%), by year, within Mongolia ecological zone classes.

	Year	Ecological Zone Class					
		Alpine	Mountain Taiga	Forest Steppe	Steppe	Desert Steppe	Desert
Heavy Grazing	2000	6.19%	0.34%	15.69%	12.78%	18.96%	**22.32%**
	2001	6.82%	0.05%	9.83%	12.59%	**16.68%**	11.77%
	2002	4.83%	0.14%	9.97%	11.13%	**15.78%**	4.87%
	2003	3.95%	0.05%	6.83%	6.79%	**7.68%**	3.38%
	2004	4.60%	0.04%	7.53%	13.05%	**17.44%**	5.92%
	2005	3.97%	0.04%	9.28%	12.77%	**21.72%**	10.14%
	2006	6.82%	0.05%	9.74%	14.49%	**15.43%**	9.42%
	2007	11.05%	0.50%	16.33%	**20.29%**	15.58%	9.84%
	2008	10.63%	0.97%	**15.51%**	14.43%	14.20%	12.95%
	2009	10.03%	3.54%	18.71%	14.33%	17.71%	**21.28%**
	2010	4.74%	1.48%	11.06%	**13.25%**	12.57%	7.64%
	2011	5.31%	2.12%	**15.45%**	10.43%	14.77%	9.88%
	2012	6.86%	1.59%	**17.94%**	12.24%	13.33%	12.17%
	2013	8.18%	1.32%	18.70%	14.87%	**22.18%**	19.80%
	2014	21.23%	5.45%	19.94%	17.21%	**23.90%**	18.96%

Table 2. Percentage of land area classified as being overgrazed (PU≥70%), by year, within Mongolia ecological zone classes.

	Year	Ecological Zone Class					
		Alpine	Mountain Taiga	Forest Steppe	Steppe	Desert Steppe	Desert
Over Grazing	2000	7.18%	0.03%	12.11%	11.57%	28.38%	**28.43%**
	2001	7.04%	0.01%	3.66%	9.35%	**33.63%**	14.27%
	2002	5.20%	0.02%	8.59%	9.98%	**14.04%**	6.35%
	2003	4.68%	0.00%	2.63%	3.79%	**4.65%**	4.26%
	2004	5.09%	0.00%	2.13%	10.13%	**20.98%**	7.12%
	2005	4.53%	0.00%	4.32%	11.44%	**24.87%**	9.41%
	2006	7.05%	0.01%	3.80%	12.45%	**23.42%**	11.36%
	2007	10.83%	0.07%	10.97%	29.25%	**30.44%**	14.52%
	2008	11.31%	0.09%	11.28%	19.33%	**37.83%**	18.55%
	2009	8.51%	0.21%	18.47%	22.26%	**46.75%**	25.57%
	2010	4.25%	0.10%	6.90%	8.78%	**13.63%**	5.01%
	2011	5.12%	0.20%	9.96%	9.03%	**16.32%**	6.70%
	2012	6.00%	0.12%	10.73%	9.68%	**15.37%**	10.19%
	2013	7.62%	0.10%	15.48%	16.29%	**29.52%**	17.30%
	2014	21.95%	2.03%	33.44%	39.37%	**52.00%**	23.03%

A comparison of consistently (>10 years) heavy grazed and overgrazed land area across ecological zones indicated that the forest steppe had the largest amount of land that is heavy grazed (0.81%), and desert steppe has the largest amount of land area with consistent overgrazing (15.43%) (Table 3).

Table 3. Percentage of land area classified as heavy grazing or overgrazed for ≥10 years, within ecological zone classes in Mongolia.

	Ecological Zone Class					
Category	Alpine	Mountain Taiga	Forest steppe	Steppe	Desert steppe	Desert
Heavy grazing	0.27%	0.01%	**0.81%**	0.18%	0.06%	0.06%
Overgrazing	4.76%	0.01%	5.13%	6.96%	**15.43%**	7.66%

Livestock Mortality

An examination of the yearly percent change in livestock numbers from 2000 to 2007 indicated that the central and western portions of Mongolia had large negative changes (losses >5%), and south eastern had greater loss (>10%) when compared to other regions. Eastern Mongolia had an increase in livestock numbers (Figure 10A, B).

The fluctuations in animals number during the period from 2000 to 2014 was highest in the central portions of Mongolia as indicated by coefficients of variation that exceed 30% (Figure 10C). The high degree of variability is reflective of the “boom” and “bust” cycle of livestock numbers driven by high livestock mortality after dzuds and almost linear increases in livestock numbers in years between dzuds (Figure 3B). The eastern and western portions had lower coefficients of variability, with some areas having values less than 15% (Figure 10C).

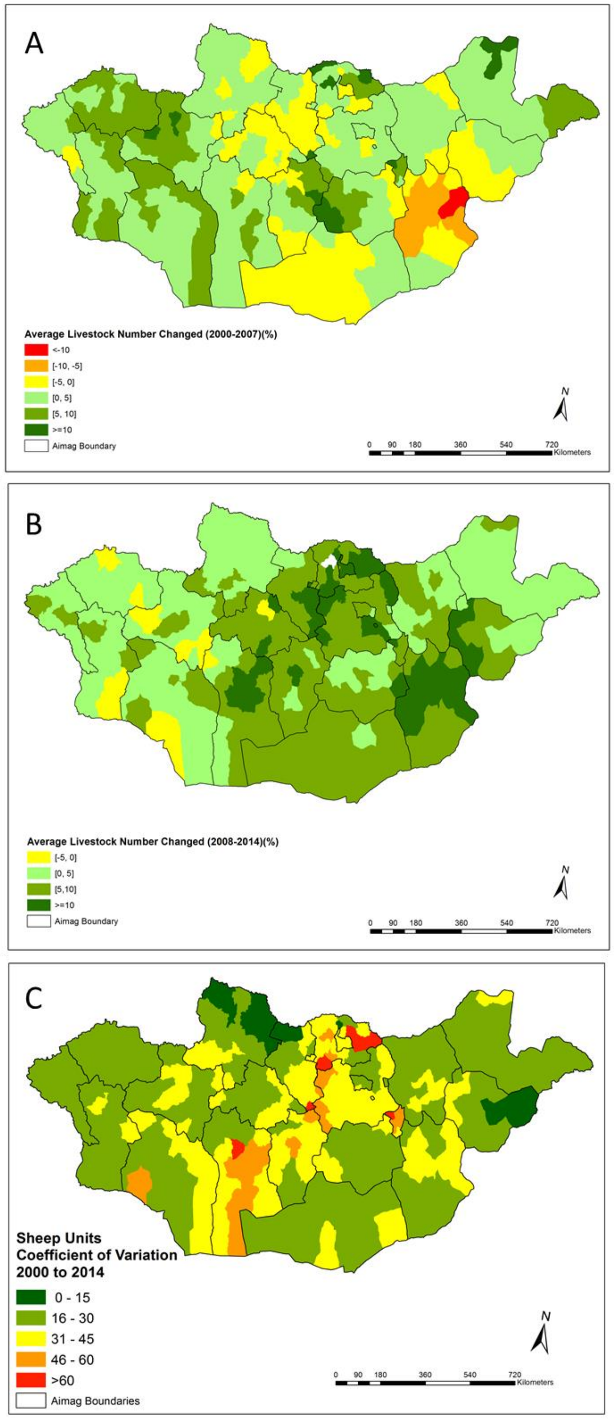

Figure 10. A) Livestock number percentage changed during the 2000 to 2007 time period; B) Livestock number percentage changed during the 2008 to 2014 time period; C) Coefficient of Variation of sheep units during the 2000 to 2014 time period.

Stepwise regressions were used to evaluate which factors most influenced forage availability at the soum level: climate, livestock management or a combination of these. Results indicated that growing season temperature was a significant variable in 8.1% of the soums (Figure 11). Precipitation was a significant variable in 42.9% of the soums; however, only 4.8% of soums had significant response to SFUs/ha. (Figure 11, Appendix I.1). Approximately 11% of the soums had significant two way combinations of precipitation, temperature, and SFU/ha. Only 1.6% soums had all three variables significant (Figure 11, Appendix I.1). Almost a third (28%) of the soums in Mongolia showed no significant response between forage availability and rainfall, temperature, or SFU/ha (Figure 11, Appendix I.1).

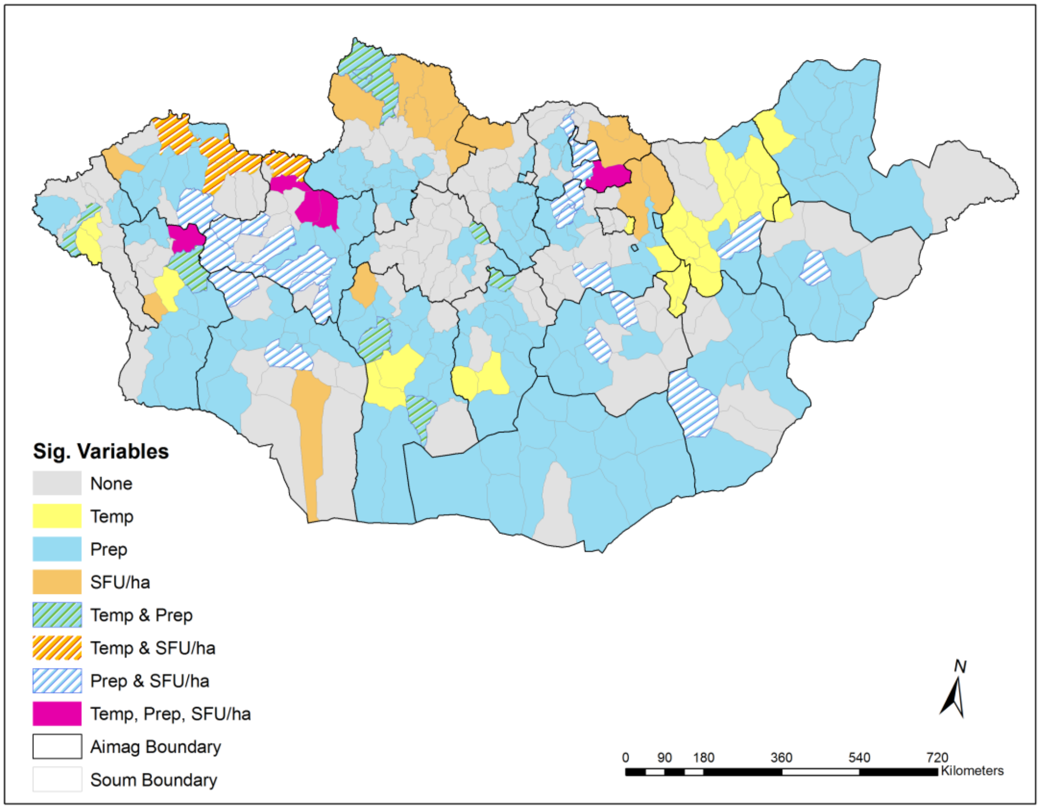

Figure 11. Soums, color coded according to significant stepwise regressions, where forage availability was evaluated in response to growing season temperature, annual rainfall, and livestock density (SFU/ha) or combinations of these as independent variables during the 2000 to 2014 period in Mongolia.

Factors influencing forage availability within ecological zones, as indicated by the significance of the stepwise regression, varied across the zones in Mongolia. In the mountain taiga zone, grazing pressure had the strongest influence with almost 59% of the land area showing significance for this variable (Table 4). Within the steppe zone, growing season temperature and annual precipitation was significant for 49% and 9% of land area in this zone, respectively. Forage availability on a majority of land in the desert steppe was influenced by precipitation (57.1%). Within the forest steppe zones, precipitation was the dominant factor found to influence forage availability; however, for almost 45% of the land area, no significant variables were identified in the stepwise analysis (Table 4).

Table 4. Percentage of land area (ha) in ecological zones having significant stepwise regressions for climate, livestock density, and combinations of these variables influencing forage availability across Mongolia during 2000 to 2014.

Sig. Variables	Ecological Zone Classes					
	Alpine	Mountain Taiga	Forest steppes	Steppe	Desert steppe	Desert
Temperature	4.7%	0.0%	6.2%	9.2%	5.4%	0.0%
Precipitation	29.4%	0.2%	31.5%	49.1%	57.1%	59.9%
SFU/ha	15.0%	59.9%	5.2%	2.0%	0.6%	6.2%
Temp & Prep	12.7%	13.2%	0.6%	1.6%	2.7%	0.1%
Temp & SFU/ha	0.0%	0.0%	2.4%	1.3%	1.4%	0.0%
Prep & SFU/ha	2.1%	0.0%	4.6%	6.4%	9.1%	2.4%
Temp & Prep & SFU/ha	0.0%	1.5%	3.7%	0.5%	0.8%	0.0%
None[1]	35.5%	24.2%	45.8%	29.8%	22.8%	31.2%

[1] Indicates none of the variables were significant for the stepwise regression at $p < 0.05$.

Stepwise regressions conducted with the percent change in livestock numbers between years as the dependent variable, and percent use (PU) from the previous year, winter season average temperature (˚C) for the current year, and average annual precipitation (mm) from the previous year as independent variables showed that livestock populations in 39.7% of the soums were influenced by grazing pressure (PU).

(Figure 12, Appendix I.2). In 3.2% of the soums, temperature was the significant factor, whereas 3.9% of the soums had precipitation as the significant factor influencing changes in livestock number. Livestock numbers in only 5.2% of soums were found to be influenced by combinations of precipitation, temperature, or grazing pressure.

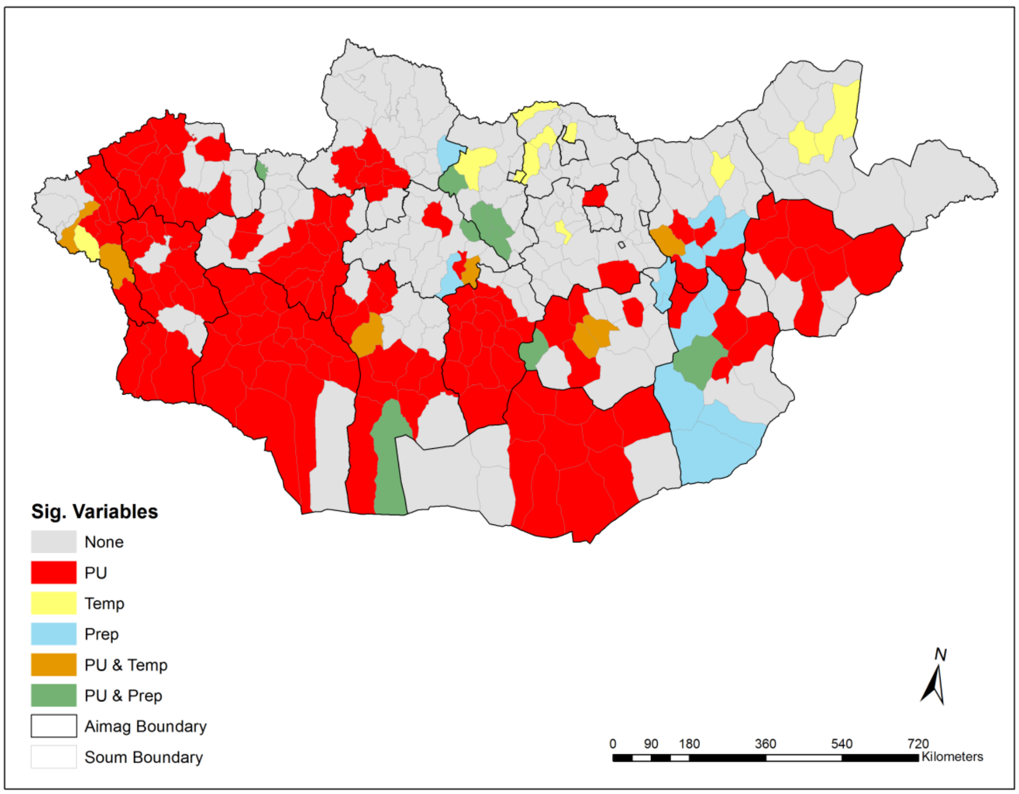

Figure 12. Soums, color coded according to significant stepwise regressions, where yearly percent change in livestock numbers was evaluated in response to forage percent use (PU) from the previous year, winter season average temperature (˚C) for the current year, and average annual precipitation (mm) from the previous year or combinations of these as independent variables during the 2000 to 2014 period in Mongolia.

In the examination of the amount of land area in each ecological zone that was influenced by significant stepwise regression variables for changes in livestock numbers over time, grazing pressure (PU) was the dominant factor in the all ecological zones (Table 5). In addition, large percentages of land area within all zones had no significant factors in the stepwise regressions.

Table 5. Percentage of land area (ha) in ecological zones having significant stepwise regressions for climate, grazing pressure, and combinations of these variables influencing changes in livestock numbers across Mongolia during 2000 to 2014.

Sig. Variables	Ecological Zone Classes					
	Alpine	Mountain Taiga	Forest steppes	Steppe	Desert steppe	Desert
PU	37.7%	1.5%	21.5%	38.8%	59.4%	53.8%
Temperature	3.9%	0.5%	5.4%	3.4%	0.0%	0.0%
Precipitation	0.0%	1.2%	2.4%	3.2%	9.8%	3.7%
PU & Temp	7.0%	0.0%	1.6%	1.8%	2.1%	0.0%
PU & Prep	0.0%	0.0%	3.4%	1.6%	3.4%	6.5%
None[1]	50.9%	95.8%	65.6%	51.1%	25.2%	35.9%

[1] Indicates none of the variables were significant for the stepwise regression at $p < 0.05$.

In order to test the hypothesis of areas with forage percentage use exceeding 70% (i.e., overgrazing) having higher livestock mortality than those areas with lower percent use of forage, a two sample Mann-Whitney U analysis was conducted. Results indicated that the median percentage change in livestock numbers in the "not overgrazed" category was 7.83, and -3.48 in the "overgrazed" category (n=407 for each category). The Mann Whitney U statistic indicated significant differences (U= 51900.0; Z=-9.31; p

< 0.0001). Therefore, the results support that forage percentage use exceeding 70% had greater livestock mortality during droughts and winter disasters than those areas with lower percent use of forage.

Discussion

In previous studies, degradation of Mongolian rangeland was simply attributed to increases in livestock numbers (Sekiyama et al., 2014) and evaluation of grazing impacts generally lacked a comprehensive consideration of the relationship between climate factors and grazing pressure as determined through the examination of forage availability and forage demand. This study represents the first national-level evaluation of grazing pressure in Mongolia and how grazing pressure and climate have influenced livestock densities over time.

Livestock densities appeared to follow a boom-bust cycle with drought and dzud events reducing animal numbers nationally with linear increases in animal numbers following dzud events (Fernández-Giménez et al., 2012; Murphy, 2014) (Figure 3). Land area classified as consistently overgrazed (PU≥70 for 10 or more years) accounted for approximately 8.6% of the land area in Mongolia and generally occurred in the desert steppe and the steppe ecological zones in the central and western portions of Mongolia (Figure 9, Table 2 and 3). Long-term data on effects of high grazing pressure on Mongolia rangeland plants species is generally lacking (Khishigbayar et al., 2015). In the United States, 30-40% use of key species in semi-desert grass and shrubland are suggested for sustainable grazing in these areas (Holechek, 1988). In the semi-desert regions in this study (i.e. steppe and desert steppe), percent use of vegetation >40% occurred in a majority of years. Therefore, additional monitoring is needed in Mongolia to determine thresholds of percent use for sustainable grazing in each ecological zone.

In the current study, grazing pressure was a major factor influencing changes in livestock numbers in all ecological zones except mountain taiga. The results in this study provided an indication that grazing pressure is an important factor that needs to be considered in evaluating how Mongolia rangelands should be managed efficiently and sustainably. In a previous study examining the effects of grazing management systems in the Inner Mongolian Steppe region, researchers found that sward characteristics (soil coverage and litter accumulation) and aboveground net primary production were significantly decreased as grazing intensity increased (Schönbach et al., 2011). The central and western portions of Mongolia are generally some of the most productive rangeland areas in Mongolia; therefore, long-term overgrazing in these zones could lead to reduced rangeland productivity, increased vulnerability to soil erosion, irreversible degradation, and/or loss of resilience. Long-term studies are needed in these ecological zones, in order to have a better understanding of the effects of overgrazing on rangeland plant species production, composition shifts, and rangeland recovery.

Other studies have evaluated grazing pressure by calculating livestock numbers in relation to vegetation biomass proxies derived from remote sensing data collected for less than a 10 year period (Hilker et al., 2014; Liu et al., 2013). Hilker et al (2014) reported "widespread" degradation of national grasslands, although they did not provide a total percent of land area that was degraded or overgrazed. They also noted that overgrazing was highest in the central and southern portions of Mongolia. In this study, overgrazing was also identified in the central and southern portions of Mongolia (Figure 9B); but in contrast to Hilker et al study, the analysis in this study also identified overgrazing in the western portions of Mongolia. Also, in contrast to the Hilker et al. study, only 8.6% of the land area in Mongolia was identified as having consistent overgrazing (>10 years during the 14 year time series), which would not indicate that overgrazing was "widespread". The differences may relate to the fact that Hilker et al. did not calculate grazing pressure and did not evaluate animal numbers as sheep units, thus not accounting for differences in forage demand among kinds of animals.

A recent study reported that trends in NDVI in Mongolia were explained by variability in rainfall during the same period (Eckert et al., 2015). In the evaluation of whether climate factors or human management factors (i.e. changes in livestock numbers) have impact on vegetation production, the regression results in this study indicate that forage availability on the majority of the Mongolian land area is influenced by precipitation. Temperature significantly influenced forage availability in the central steppe and northern forest steppe ecological zones. Precipitation significantly influenced forage availability in the southern desert steppe and desert region (Table 4).

Liu et al (2013) conducted an analysis of vegetation optical depth (VOD, a proxy for aboveground biomass), and found that VOD decreased in the majority of the steppe region in Mongolia from 1988 to 2008. The degradation and vegetation biomass decline were attributed to increasing livestock numbers, especially for goats (Liu et al., 2013).

However, the Liu et al. study used actual head of goats rather than conversion of goats and other livestock species to sheep units. A review of the national level of livestock population (Figure 3B) by livestock species indicated that all of species increased in numbers after 2002. Goat numbers did increase, but on a sheep unit basis, there were proportionally similar to the other livestock species with the exception of camels. Therefore, there is little evidence to indicate that increasing goat numbers alone would be the reason for rangeland degradation or the decline in VOD since sheep, cattle, horses, and goats would have had similar forage use on the landscape. In fact, sheep would have had the highest grazing pressure for the majority of years between 2002 and 2014 as indicated by the number of SFUs (Figure 3B).

Results from the current study indicate that less than 10% of Mongolia's land area could be classified as consistently overgrazed (PU≥70 for 10 or more years) and these areas were located in the central and western part of country (Figure 9; steppe and desert steppe zone). In addition, it appears that opportunities for vegetation recovery do exist during periods after dzuds when forage demand is lower due to reduced animal numbers and higher rainfall that promotes vegetation growth (Figure 4D and Figure 5F; Appendix I). Periodic overgrazing or overuse does not necessarily equal degradation of the landscape, but persistent overgrazing over a period of time can be an indicator that rangeland may be reaching a tipping point or has passed a tipping point toward degradation. Rangeland degradation can be defined as unsustainable or improper human land use that results in biological and economic productivity reductions over a period of time and impacts vegetation composition, soil processes, and hydrology (Bedunah and

Angerer, 2012). In order to identify whether consistently overgrazed areas in Mongolia are degraded or have passed a tipping point, field studies and monitoring are needed to assess vegetation biomass, soil conditions, and hydrology data in these areas. A recent study of long-term vegetation trends in mountain steppe, steppe and desert steppe ecological zones in south-central Mongolia indicated that the interaction of climate and grazing pressure resulted in degradation in these zones; however, the degradation appeared to be reversible and not permanent (Khishigbayar et al., 2015).

With regard to changes in livestock numbers, growing season precipitation was not a strong variable in explaining the variability in livestock numbers over time (Figure 12, Table 5). This provides an indication that human decisions on livestock management were probably not driven by precipitation/drought cycles. In general, after 1990, livestock numbers increased linearly in most years after dzuds, regardless of climatic effects on forage availability (Figure 3A). Grazing pressure had the strongest effect on changes in livestock numbers over time in the majority of the ecological zones. In a previous study on arid and semiarid grazing systems in Africa, there was an increased risk that the sites could become degraded when an uncoupling between grazing management and vegetation occurs, especially on sites having greater amounts of key resources (Illius and O'connor, 1999). The results presented here indicated a general uncoupling of human management of livestock (i.e., stocking rate decisions) with trends in climate, therefore indication that there may be increased risk toward degradation.

Of the soums evaluated in Mongolia, forage availability in almost one-third of the soums did not show any significant response to climate factors or grazing management (Figure 11, Table 4). When examining factors influencing changes in livestock numbers over time, 149 soums showed no significant relationships with climatic factors or grazing pressure. The reasons for this are not clear. One possible difference may be related to the resolution of the vegetation/grazing pressure response and the climate variables. The forage availability and grazing pressure assessments had the resolution of the MODIS NDVI (250 m) whereas the resolution of the precipitation and temperature data was 55 km. Therefore, the rainfall and temperature data may not have the precision to capture the variability of the forage response. Another possible difference may be related to precipitation and forage availability having positive trends in the majority of cases, however, the trends were not significant. This could have been exacerbated by high grazing pressure reducing the forage production signal, but this was not consistent across all years because of lower grazing pressure after dzuds.

The testing of the hypothesis that livestock losses were greater on overgrazed areas indicated that areas with forage percentage use exceeding 70% had greater livestock mortality during droughts and winter disasters than those areas with lower percent use of forage. This result provides some evidence of the importance for herders to keep a balance between stocking rate and forage availability to promote sustainable rangeland management.

The methodologies for grazing pressure assessment used in this study could be useful for dzud monitoring and assessments of sustainable stocking rates. Grazing pressure mapping and mapping areas of historically high livestock losses could allow local community based rangeland management groups or aimag governments to develop guidelines to reduce animal numbers and/or plan actions for dzuds in the case of low forage conditions. The mapping of areas that have been consistently overgrazed could provide locations for studies to examine if degradation has occurred, or if these areas are approaching vegetation and soil conditions that could lead to irreversible degradation. At the national level, the spatial analysis of grazing pressure and livestock numbers would be beneficial in developing pasture management guidelines for stocking rates, dzud management, and determining the potential economic impacts of dzud. Lastly, the ability to define the degree of grazing pressure across Mongolia can aid in disentangling effects of livestock management and changing climate in assessing the resilience of these rangeland systems.

CHAPTER III

SIMULATION MODELING TO ANALYZE THE IMPACT OF SEVERE WINTER DISASTERS ON LIVESTOCK IN MONGOLIA

Introduction

Mongolia is a large pastoral landlocked country where livestock production is considered a key component in the Mongolian economy. However, droughts followed by extremely cold winter conditions (dzud), can lead to massive livestock losses that affect pastoralists' livelihoods.

Dzud is Mongolian term for severe winter disasters, and are characterized by deep snow, ice, continuous severe cold temperatures (<-30˚C) for a week to 10-day time scale (Erdenetsetseg, 2015; Fernández-Giménez et al., 2012; Iijima, 2015), which can lead to large numbers of livestock dying primarily due to starvation because of lack of forage and water, and in other cases directly die from the cold (Angerer, 2012; Batima, 2006; Fernández-Giménez et al., 2012). Dzuds are also a complex social-ecological phenomenon, which includes interaction between regional and local communities to cooperate and communicate disaster response, and increased awareness of sustainable grazing management (Fernández-Giménez et al., 2012). During the past twenty years, Mongolia has suffered two severe national dzuds which were 1999-2002 and 2009-2010 (U.N., 2001; UNDP and NEMA, 2010), both of these two national dzuds affected around 30% of national herd (Fernández-Giménez et al., 2012; ReliefWeb, 2010; Siurua and Swift, 2002).

The livestock that are managed in Mongolia include sheep, cattle, goat, camels and horses. Livestock and livestock production not only support the majority of pastoral herders' financial income, but also provide the main resources for the herder's livelihood, such as livestock meat, dairy and wool production, fat byproducts, and bone's crafts (Dorligsuren et al., 2012). Therefore, winter disasters (dzud) can play a significant role in affecting quantity of livestock and quality of herder's life (Siurua and Swift, 2002).

Although winter temperatures play a large role in affecting livestock mortality during the dzud, forage conditions and summer drought also can influence livestock populations. In previous studies, storage of forage as hay had been reported as one of the most important strategies for reducing livestock loss during the winter disasters (Fernández-Giménez et al., 2015). The lack of precipitation in growing season can significantly affect forage availability and limit livestock gain weight (Tachiiri and Shinoda, 2012). The combination of winter disasters with summer drought can increase livestock mortality more than that in years where livestock are suffering from dzud only (Erdenetsetseg, 2015; Tachiiri et al., 2008).

Climate change has influenced Mongolian livestock and rangelands (Batima et al., 2005). Vegetation productivity is projected to decline due to higher annual temperature and lower summer precipitation (Angerer et al., 2008). The environmental changes can lead to reduced livestock mobility, decreased water availability, increased grazing pressure, and increased frequency of summer droughts and extreme winters (Sternberg, 2008).

In previous studies using simulation models for Mongolia livestock, the population dynamics were simulated according to different species, age and sex to evaluate livestock populations for infectious disease (Alsonso, 2007; Shabb et al., 2013). Although the previous models included long-term livestock population and historical winter disasters data, the livestock classes in their models represented only a few of the major species, for example, sheep and cattle. The time steps of previous studies were yearly, which did not provide a detailed evaluation on livestock seasonal changes. Moreover, the study areas in the previous studies were limited to one location and did not examine specific threshold values of climate factors or forage conditions that could affect livestock populations.

This study presents a simulation model to evaluate livestock dynamics at an average household level, for the livestock species owned by the household. Households were examined across ecological zones. The livestock species included in the simulation model were sheep, cattle, goats, horses, and camels. In order to simulate environmental conditions affecting livestock dynamics, the model contained a component of forage conditions; therefore, the feedback from grazing pressure could be reflected on livestock population changes. In addition, the time step of simulation model was monthly, which could allow the seasonal livestock population changes caused by climate variables or forage conditions to be reflected. For this study, the objective was to use the simulation model to examine thresholds based on forage use, extreme low temperature and snowfall conditions that influence livestock population dynamics in Mongolia, especially during periods of dzud. Moreover, the hypothesis was that a simulation model representing the dynamics of three factors, 1) Forage availability, 2) temperature dynamics and extremes, and 3) snowfall depth better corresponds to livestock losses than examination of these thresholds individually.

Background Information

For this study, three study sites were selected in the different ecological zones (Figure 13, Table 6) representing an increasing rainfall gradient from south to north. Each site was chosen based on nearness to a weather station where daily data on temperature and snowfall could be acquired. For the simulations, a representative herd was developed based on the numbers of animals in the soum (district) where the study sites were chosen, and the number of herders in the soum based on census counts by the national government in 1999 (NSOM, 2016). The three study sites were located in forest steppe, steppe, and desert steppe ecological zones (Figure 13). The forest steppe's site was located in north central region of Mongolia and had colder minimum temperatures than the other sites. The steppe's site was located in central Mongolia and represented moderate temperatures compared to the other sites, whereas the desert steppe's site was located in south central Mongolia and had the warmest temperature among the sites (Figure 14, 15).

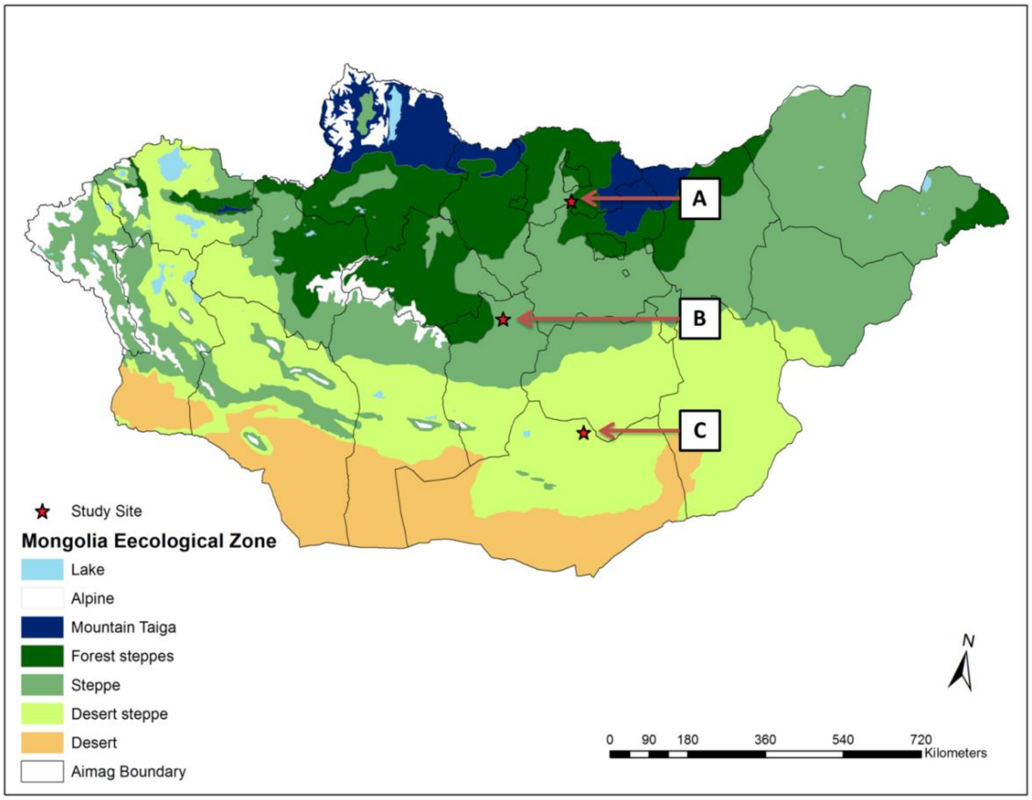

Figure 13. Locations of three study sites in different ecological zones in Mongolia; (A) Forest Steppe, (B) Steppe, (C) Desert Steppe.

Table 6. Information on the official recording weather stations that were chosen to provide climate data for the simulation modeling (data acquired from NCDC, 2016).

Station Name	Latitude	Longitude	Aimag	Soum	Ecological Zone
Baruunharaa	48.92	106.07	Selenge	Bayangol	Forest Steppe
Hujirt	46.90	102.77	O'vorxangai	Xujirt	Steppe
Tsogt-Ovoo	44.42	105.32	O'mnogovi	Cogt-Ovoo	Desert Steppe

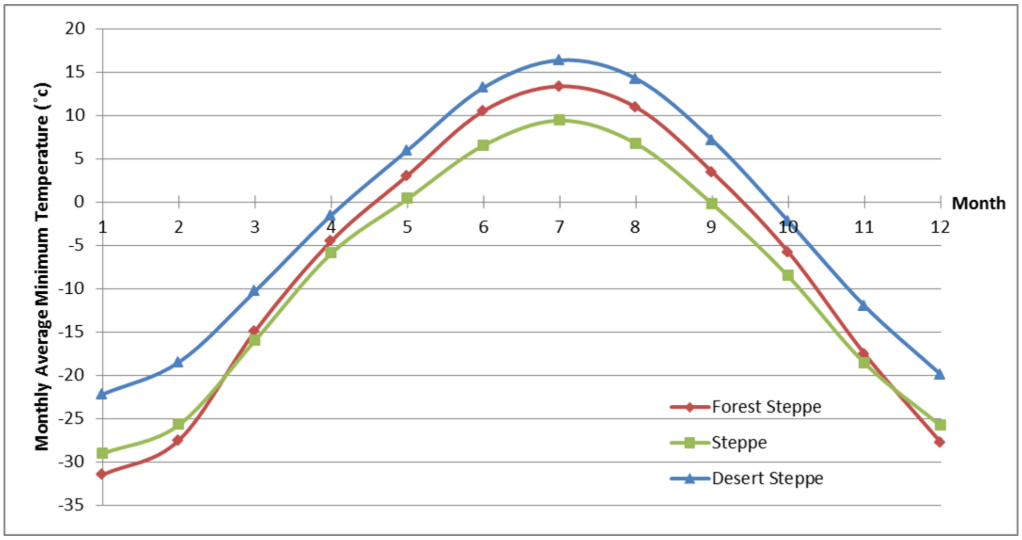

Figure 14. Monthly average minimum temperature (˚C) during the period from 2000 to 2013 at the official recording weather station closest to three study sites (data acquired from NCDC, 2016).

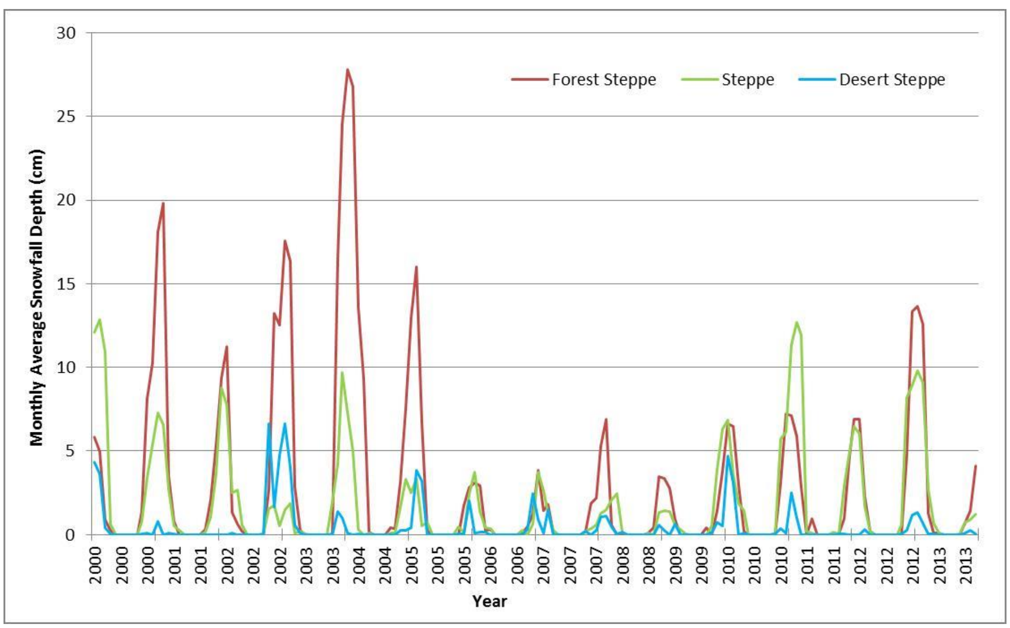

Figure 15. Monthly average snowfall depth (cm) during the period from 2000 to 2013 at the official recording weather station closest to the three study sites (NCDC, 2016).

Model Description

Overview of Model Structure

The model was developed to simulate the effects of grazing pressure and winter disasters on livestock population dynamics in Mongolia. Livestock census data are collected yearly in Mongolia for the different kinds of livestock that are grazed for agricultural production. These data provide an opportunity to develop and evaluate models for improving winter disaster contingency planning and assessment.

The simulation model was developed with three main components: 1) climate factors (snowfall and temperature), 2) grazing pressure (PU) based on forage availability and forage demand by livestock, 3) and a livestock dynamics component that represented birth, mortality, and sales for each kind and class of livestock (Figure 16). Climate data used for the simulations were acquired from weather stations (NCDC, 2016) closest to each monitoring site. When dzuds occur, either extremely low temperature or heavy snowfall can reduce the quantity of forage eaten by the animal, resulting in loss of body condition or starvation. Moreover, grazing pressure can influence livestock birth rates and selling rate as a lack of forage can reduce body condition and affect conception rates and reproductive status. Therefore, these components were included in the model to better reflect conditions that could influence changes in livestock population over time, especially during dzud conditions.

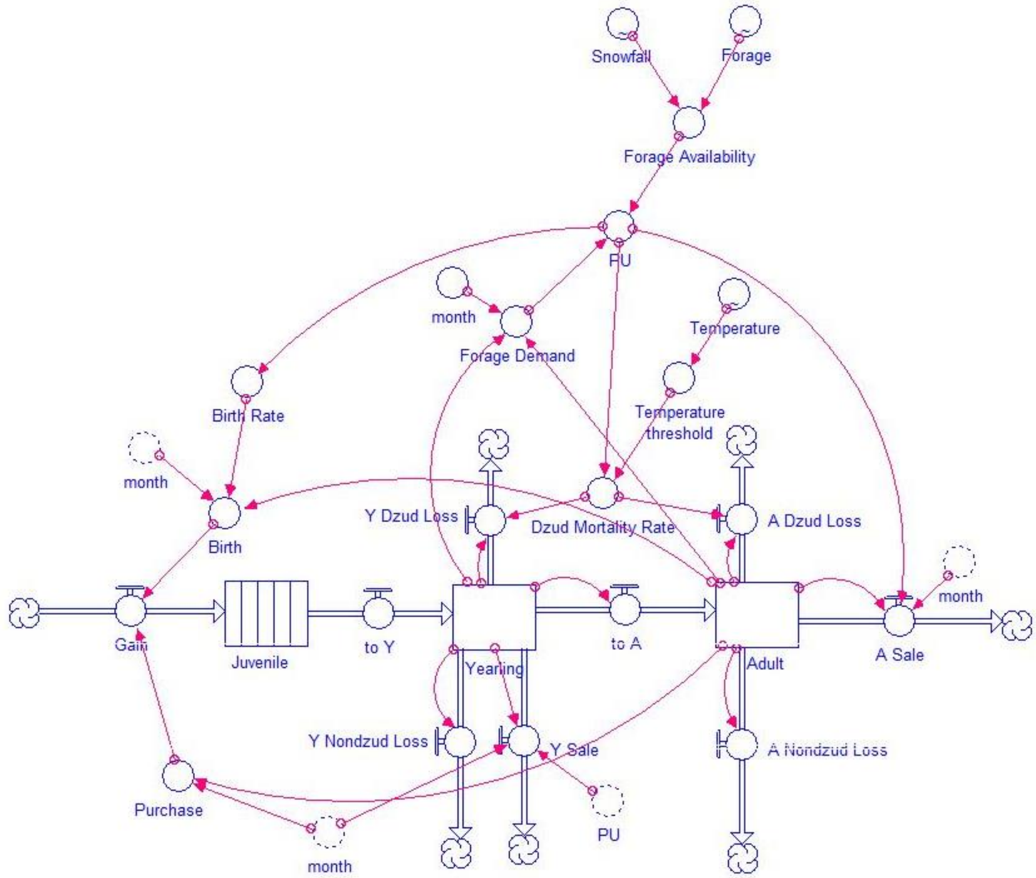

Figure 16. General structure of the livestock simulation model. Separate models, having similar structure, but different parameters were developed for each ecological zone and kind of livestock. The example represented here is for sheep in the steppe ecological zone (see Table 7 and 8 for the equations and parameters).

The model was designed to represent livestock population dynamics for each of the major kinds of livestock in the forest steppe, steppe, and desert steppe ecological zones. The model was developed as a compartment model based on difference equations ($\Delta t = 1$ month) with representations of natality, mortality, purchases, and sales of livestock. For each kind of livestock, the general form of the differencing equations for changes in livestock numbers is given in Table 8.

Table 7. Summary of parameters, abbreviation, description, values, and sources.

Process	Abbreviation	Description	Value	Source
Climate factors	Temp	Monthly average minimum temperature	Table 14	(NCDC, 2016)
	Snow	Monthly average snowfall	Refer to "Grazing Pressure"	
Livestock cycle	A	Adult livestock	Table 9 & 10	(MOFA, 2010; Suttie, 2000)
	Y	Yearling		
	J	Juvenile		
	BR	Natality (Birth rate)	Table 12	(Alsonso, 2007; MOFA, 2010; Suttie, 2000)
	FD	Forage demand		(NRCS, 2003; Redfearn and Bidwell, 2016)
	FA	Forage availability		(Stuth et al., 2003)
	PU	Grazing pressure (Forage Percentage Use)	Table 11	Calculated by FD/FA*100
	NMR	Natural mortality rate	Table 13	(Rao et al., 2015)
	DMR	Dzud mortality rate	Table 15	(Fernández-Giménez et al., 2012; Fernández-Giménez et al., 2015; ReliefWeb, 2010; Shabb et al., 2013)
	dt	Δ time		

Table 8. Summary of model equations (see Table 7 for abbreviations).

Livestock Numbers
J(t) = J(t - dt) + (Gain(t) - J(t)) * dt
Y(t) = Y(t - dt) + (J(t) - Y(t) - Y_Dzud loss(t) - Y_Nondzud loss(t) - Y_sale(t)) * dt
A(t) = A(t - dt) + (Y(t) - A_Dzud loss(t) - A_Nondzud loss(t) - A_Sale(t)) * dt
Livestock Production Cycle
Gain(t) = birth(t) + purchase(t)
Sheep Birth = If (3<month<8) then (BR * 0.5* Sheep_A), else (Sheep_A*0.5*0.001)
Cattle Birth = If (3<month<8) then (BR * 0.5* Cattle_A), else (Cattle_A*0.5*0.0006)
Goat Birth = If (3<month<8) then (BR * 0.5* Goat_A), else (Goat_A*0.5*0.001)
Camel Birth = If (3<month<8) then (BR * 0.5* Camel_A), else (Camel_A*0.5*0.001)
Horse Birth = If (3<month<8) then (BR * 0.5* Horse_A), else (Horse_A*0.5*0.001)
Dzud loss(t) = (A(t) + Y(t))* DMR
Natural loss(t) = (A(t) + Y(t)) * NMR
Sale(t) = (A(t) + Y(t)) * selling rate
Purchase(t) = A(t) * purchase rate
Forage and Grazing Pressure
Sheep FD(t) = if (month=12 or month ≤3) then ((((Sheep_A(t) *0.97) + (Sheep_Y(t) *0.7275)) *30)/Household area), else ((((Sheep_A(t) *1.8)+(Sheep_Y(t) *1.35)*30)/ Household area)
Cattle FD(t) = if (month=12 or month ≤3) then ((((Cattle_A(t) *8.48) + (Cattle_Y(t) *5.088)) *30)/Household area), else ((((Cattle_A(t) *11.2)+(Cattle_Y(t) *6.72)*30)/ Household area)
Goat FD(t) = if (month=12 or month ≤3) then ((((Goat_A(t) *0.7275) + (Goat_Y(t) *0.485)) *30)/Household area), else ((((Goat_A(t) *1.35)+(Cattle_Y(t) *0.9)*30)/ Household area)
Camel FD(t) = if (month=12 or month ≤3) then ((((Camel_A(t) *8.48) + (Camel_Y(t) *5.088)) *30)/Household area), else ((((Camel_A(t) *11.2)+(Cattle_Y(t) *6.72)*30)/ Household area)
Horse FD(t) = if (month=12 or month ≤3) then ((((Horse_A(t) *8.48) + (Horse_Y(t) *5.088)) *30)/Household area), else ((((Horse_A(t) *11.2)+(Horse_Y(t) *6.72)*30)/ Household area)
FA(t) = If (Snow(t) ≤ threshold values) then (FA(t)), else (0.01*FA(t))
PU(t) = (FD(t)/FA(t)) *100

The scale of simulation model was at the household level. To determine grazeable area for an average household in each ecological zone, the total hectares of land area available for grazing in each soum was divided by the number of herder households in each soum. Grazeable area was determined by removing non-rangeland land cover types (identified through MODIS land cover data [Friedel et al., 2002]) , and area with slopes greater than 60 % (as identified using the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (Ramirez, 2014) (see Chapter II for information on these calculations).

Livestock Dynamics

Livestock species in the simulation model were assigned into different growth stages by age and kind of animal. Three age classes were defined, including juvenile, yearling and adult. In the modeling framework, and aging system was used to define time periods for each stage of growth by livestock species (Table 9) (MOFA, 2010; Suttie, 2000). For the simulations performed in this study, the model was initialized on January of 2000, therefore, the initial livestock numbers in each compartment were based on the household livestock numbers in the December 1999 census (NSOM, 2016) and the proportions of age classes were based on household surveys (Table 10) (Jamsranjav, 2015).

Table 9. Number of months for transition of livestock species to different age classes.

Species	Stage	Periods (Month)
Sheep	Adult	>13
	Yearling	1
	Juvenile	12
Cattle	Adult	>24
	Yearling	12
	Juvenile	12
Goat	Adult	>13
	Yearling	1
	Juvenile	12
Camel	Adult	>60
	Yearling	12
	Juvenile	48
Horse	Adult	>24
	Yearling	12
	Juvenile	12

Table 10. Livestock numbers by age class, species and ecological zones that were used to initialize the model.

Initial Number (Head)		Forest Steppe	Steppe	Desert Steppe
Sheep	Adult	49	89	255
	Yearling	14	26	73
	Juvenile	7	13	36
Cattle	Adult	14	29	19
	Yearling	4	8	6
	Juvenile	2	4	3
Goat	Adult	15	73	168
	Yearling	4	21	48
	Juvenile	2	10	24
Camel	Adult	-	-	20
	Yearling	-	-	6
	Juvenile	-	-	3
Horse	Adult	10	23	57
	Yearling	3	7	16
	Juvenile	1	3	8

Grazing Pressure

To define climatic conditions for effects of snow on forage availability in the simulations, the model defined low forage availability as periods having monthly average snow depth of greater than 10cm in forest steppe and steppe, and greater than 5cm in desert steppe. In the model, forage availability would dramatically decline if snow depth exceeded the monthly average value.

Another important and necessary driving variable was grazing pressure (PU), which influences livestock natality, dzud mortality rate and selling rate (Figure 16). The PU thresholds for natality were also defined differently based on livestock species (Table 11) to reflect effects of low forage availability on reproductive status of the animal. Forage percentage use (PU) was used as an indicator of grazing pressure and was calculated as livestock intake (FD) divided by the forage available (FA) (Table 8).

Livestock forage demand (kg/ha/month) was calculated as the product of the forage daily intake for a species multiplied the number of animals owned by the herder for a given month (for the simulations a month was considered to be 30 days). The product was then divided by the hectares of pasture available to the herder in order to represent demand on a kg/ha/month basis. Forage availability (kg/ha/month) data was determined using monthly forage estimates acquired from the Phytomass Growth Simulation Model (PHYGROW) simulation model outputs reported by the Mongolia Livestock Early Warning System (Angerer, 2012) for each of the study sites.

Table 11. Grazing pressure (PU) threshold values used in natality rate equations to exponentially reduce natality rate when grazing pressure (expressed as percent use) exceeded the threshold by kind of livestock.

PU Threshold (%)	Forest Steppe	Steppe	Desert Steppe
Sheep	≤ 70	≤ 70	≤ 70
Cattle	≤ 70	≤ 70	≤ 70
Goat	≤ 100	≤ 100	≤ 100
Camel	-	-	≤ 70
Horse	≤ 70	≤ 70	≤ 70

Natality

In the model, the largest portion of livestock births was allowed to occur during the period from April to July each year. The natality was based on a previous sheep and cattle dynamics study (Alsonso, 2007) that reported rates for cattle and sheep. The natality for sheep was used for goats and the rate for cattle was used for horse and camels after adjustments for livestock gestation periods, grazing pressure, and ecological zones (Table 12) (Alsonso, 2007; MOFA, 2010; Suttie, 2000). For natality calculations, it was assumed that the number of reproducing adult females represented half of the population for each kind of animal, and a fixed natality rate (0.0001) was used as the out of season natality (Table 8).

Table 12. Livestock natality (BR) by species and ecological zones with adjustments for effects of grazing pressure (PU).

Natality (BR) (%)		Forest Steppe	Steppe	Desert Steppe
Sheep	PU < 100%	0.4	0.4	0.4
	PU ≥ 100%	1*exp(-4*PU)	1*exp(-4*PU)	1*exp(-4*PU)
Cattle	PU < 70%	0.18	0.18	0.18
	PU ≥ 70%	0.335*exp(-4*PU)	0.335*exp(-4*PU)	0.335*exp(-4*PU)
Goat	PU <100%	0.4	0.4	0.4
	PU ≥ 100%	1*exp(-4*PU)	1*exp(-4*PU)	1*exp(-4*PU)
Camel	PU < 50%	-	-	0.044
	PU ≥ 50%	-	-	0.22*exp(-4*PU)
Horse	PU < 70%	0.12	0.12	0.12
	PU ≥ 70%	0.285*exp(-4*PU)	0.285*exp(-4*PU)	0.285*exp(-4*PU)

Natural Mortality

The natural mortality represents livestock losses caused by natural aging, diseases, or other reasons not associated with extreme temperatures or snow. Natural mortality rates were based on the annual natural mortality rates used for the livestock loss insurance program in Mongolia (Rao et al., 2015). Slight adjustments were made to the rates depending on livestock gestation periods, age class, and ecological zones (Table 13). The assumption was made that yearling livestock had the same natural mortality rates as adults, thus the natural loss was calculated by natural mortality rate multiplied by the sum of yearling and adult livestock numbers (Table 8).

Table 13. Natural mortality rate for species of livestock by age class and ecological zones.

Natural Mortality Rate (%)		Forest Steppe	Steppe	Desert Steppe
Sheep	Adult	0.007	0.007	0.005
	Yearling	0.008	0.008	0.005
Cattle	Adult	0.005	0.005	0.002
	Yearling	0.005	0.007	0.005
Goat	Adult	0.003	0.003	0.002
	Yearling	0.005	0.005	0.005
Camel	Adult	-	-	0.002
	Yearling	-	-	0.005
Horse	Adult	0.005	0.005	0.002
	Yearling	0.005	0.005	0.005

Dzud Mortality

Livestock dzud mortality in the model was mainly influenced by extreme cold temperature, where lower temperatures would lead to higher dzud mortality. To reduce potential for excessive dzud mortality in the model, an absolute average minimum temperature was set to cap mortality rate as defined in Table 14. This cap value prevents exponential losses of animals for increasing lower temperature past this threshold.

Dzud mortality rates were based on previous studies on impacts of dzud (Fernández-Giménez et al., 2012; Fernández-Giménez et al., 2015; ReliefWeb, 2010; Shabb et al., 2013). The assumption was made that yearling livestock had the same dzud mortality rates as adult (Table 15). Thus, the dzud loss was calculated using power functions where yearling and adult livestock numbers (Table 8) declined rapidly during periods of extreme cold temperatures.

Table 14. Monthly average minimum temperature threshold values used to cap mortality rate in modified power equations for dzud mortality.

Livestock Kind	Minimum Temp. (˚C)		
	Forest Steppe	Steppe	Desert Steppe
Sheep	≤ -34.5	≤ -32.5	≤ -26
Cattle	≤ -34	≤ -31.5	≤ -25.5
Goat	≤ 34.5	≤ -32.5	≤ -26
Camel	-	-	≤ -25.5
Horse	≤ -34	≤ -31.5	≤ 25.5

Table 15. Dzud mortality rate power functions for kinds of livestock by species, ecological zones, and grazing pressure.

Dzud Mortality Rate (%) by Ecological Zone				
Kind	Grazing Pressure	Forest Steppe	Steppe	Desert Steppe
Sheep	PU < 70%	4.68E-06*0.744^Temp	6.86E-06*0.739^Temp	2.49E-05*0.724^Temp
	PU ≥ 70%	3.32E-06*0.713^Temp	1.85E-09*0.551^Temp	1.17E-08*0.505^Temp
Cattle	PU < 70%	4.68E-06*0.744^Temp	6.86E-06*0.739^Temp	2.49E-05*0.724^Temp
	PU ≥ 70%	5.3E-10*0.549^Temp	3.91E-10*0.517^Temp	7.09E-09*0.492^Temp
Goat	PU <100%	4.68E-06*0.744^Temp	6.86E-06*0.739^Temp	2.49E-05*0.724^Temp
	PU ≥ 100%	1.09E-10*0.52^Temp	3.39E-10*0.5145^Temp	4.36E-09*0.48^Temp
Camel	PU < 70%	-	-	2.49E-05*0.724^Temp
	PU ≥ 70%	-	-	7.09E-09*0.492^Temp
Horse	PU < 70%	4.68E-06*0.744^Temp	6.86E-06*0.739^Temp	2.49E-05*0.724^Temp
	PU ≥ 70%	5.3E-10*0.549^Temp	3.91E-10*0.517^Temp	7.09E-09*0.492^Temp

Selling and Purchasing

In the simulation model, selling rate and purchase rate were the same across different ecological zones, and were based on previous studies (NSOM, 2016; Shabb et al., 2013; Suttie, 2000). Both adult and yearlings of all five kinds of livestock had the same selling rate. When grazing pressure was greater than 70% (PU>70%) during the summer months (June, July and August), the selling rate was 1.67% per month to reflect culling and destocking during drought. A selling rate of 2.5% was used for traditional at the end of year sale of livestock (December) and 0.2% was used for the other months. Purchases of livestock were assumed to occur from April to November each year. The purchase rate of sheep, cattle goat, camel and horse were 0.15%, 0.09%, 1.5%, 0.3%, 0.6%, respectively. Both selling and purchase numbers were calculated by multiplying selling rate or purchase rate by yearling and adult livestock numbers (Table 8).

Model Evaluation

The simulation model was evaluated based on the period from 2000 to 2013 with a monthly time step. The period from 2000 to 2009 was used as a calibration period, where slight adjustments were made to parameters of the model to better capture livestock dynamics across ecological zones and livestock species. The period from 2010 to 2013 was used for verification of the calibrated models. The model outputs were evaluated against the yearly household livestock numbers (by species) calculated for each soum where the study sites were located. Given that the yearly livestock census is conducted in December each year, the predicted animal numbers for December of each year, represented as the sum of juvenile, yearling, and adult age classes, were compared to the census numbers for the calibration and verification evaluations.

The performance of the simulation model for the calibration, verification evaluations, and hypothesis testing were measured using the following goodness of fit metrics: percentage estimation bias (BIAS), mean bias error (MBE), root mean square difference (RMSD), index of agreement (*d*), and R^2 between observed and predicted data. The BIAS reflects the normalized difference between observed data and data predicted by the simulation model:

$$BIAS\ (\%) = \frac{\bar{P} - \bar{O}}{\bar{O}} * 100 \qquad [2]$$

where $\bar{P}$ is the mean of the prediction data and $\bar{O}$ is the mean of the observed data. A positive BIAS value indicates simulation model overestimated yearly livestock numbers, whereas a negative BIAS value indicates the opposite. MBE reflects the average magnitude of the under-prediction or over-prediction of the simulation model (Andales et al., 2006), which is expressed as follows:

$$MEB = \frac{\sum_{i=1}^{n}(P_i - O_i)}{n} \qquad [3]$$

where P_i is the i^{th} instance of the predicted value, O_i is the i^{th} instance of the observed data, and n represents the pairs of predicted and observed data. RMSD reflects the average magnitude of the difference between simulation model predicted and observed values, it is similar to MEB, but it is more sensitive to extreme differences between the prediction and observation data (Willmott, 1982). RMSD is calculated as:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \quad [4]$$

The index of agreement (*d*) is a kind of relative error measurement (Legates and McCabe, 1999; Willmott, 1982). It measures the degree of closeness between observed and simulated model predictions (Andales et al., 2006; Willmott, 1982), and is expressed as follows:

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad [5]$$

The *d* value can range from 0 to 1, and *d* values that are close to 1 indicate that predicted and observed values are nearly 1:1.

The calibration results of the simulation model are reported in Table 16, and Figure 17, 18, 19. In the forest steppe, cattle, goat, and horse numbers were underestimated, and sheep numbers were overestimated. Both goat and sheep had higher degrees of closeness between observed and predicted data than cattle and horse (Table 16, Figure 17). In the steppe zone, after calibration, all four livestock species populations were overestimated (Table 16). Goat and sheep had a higher degree of closeness between observed and predicted data (Table 16, Figure 18 C and D), which was better than in forest steppe. In the desert steppe ecological zone, the models for cattle, goat, horse, and sheep over-predicted livestock numbers on average (Table 16). The camel model in the desert steppe generally under-predicted the population over time (Table 16, Figure 19 E).

Table 16. Model performance metrics for calibration outputs by livestock species and ecological zones.

Calibration	Metrics	Cattle	Goat	Horse	Sheep	Camel
Forest Steppe	BIAS	-33.49	-18.55	-43.73	29.52	-
	MEB	-5.97	-11.27	-6.82	29.20	-
	RMSD	10.23	23.85	7.59	40.16	-
	d	0.36	0.82	0.28	0.82	-
	R^2	0.25	0.68	0.19	0.68	-
Steppe	BIAS	72.58	12.02	5.16	17.94	-
	MEB	11.16	15.29	1.11	32.42	-
	RMSD	12.31	22.55	5.87	57.33	-
	d	0.36	0.95	0.19	0.87	-
	R^2	0.08	0.93	0.25	0.73	-
Desert Steppe	BIAS	192.84	290.28	119.11	181.10	-7.18
	MEB	9.51	439.50	31.06	327.22	-1.62
	RMSD	11.43	472.86	34.18	349.77	6.44
	d	0.15	0.17	0.22	0.30	0.34
	R^2	0.06	0.01	0.01	0.02	0.00

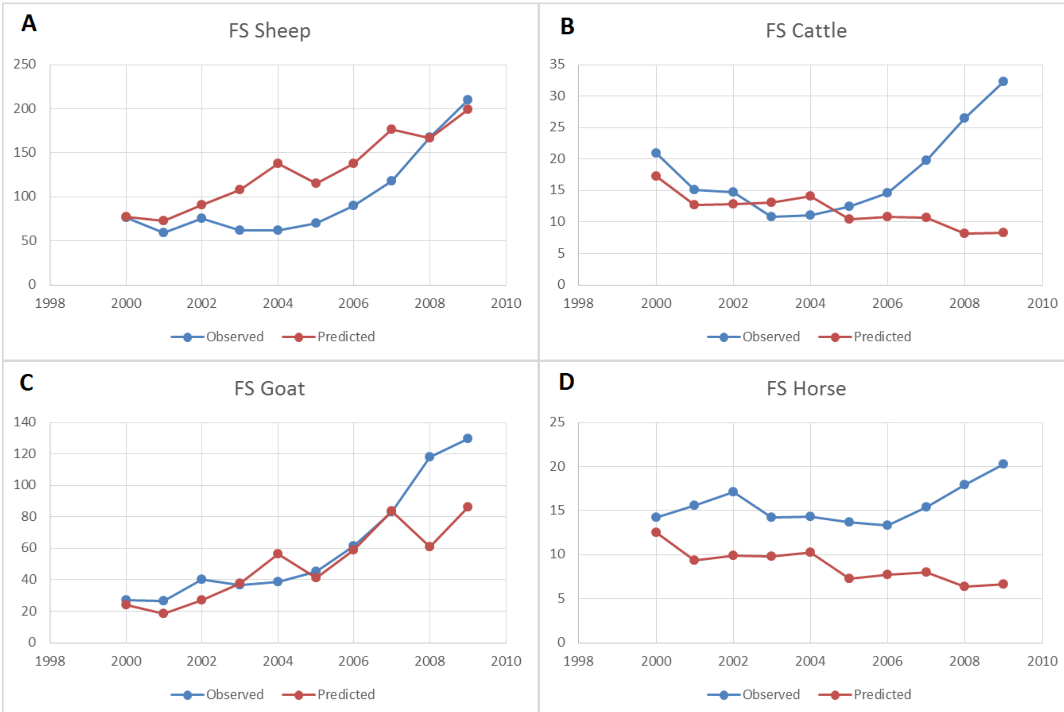

Figure 17.Comparisons of observed vs. model predicted livestock species numbers in the calibration evaluation conducted for the forest steppe (FS) ecological zone (see Table 16 for performance metrics).

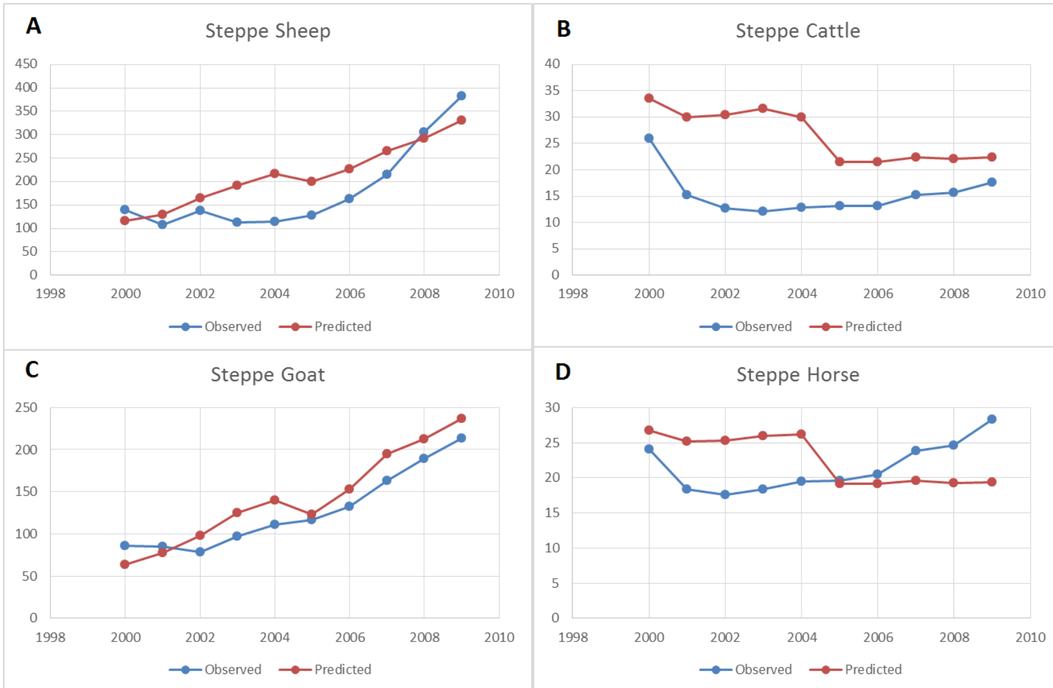

Figure 18. Comparisons of observed vs. model predicted livestock species numbers in the calibration evaluation conducted for the steppe ecological zone (see Table 16 for performance metrics).

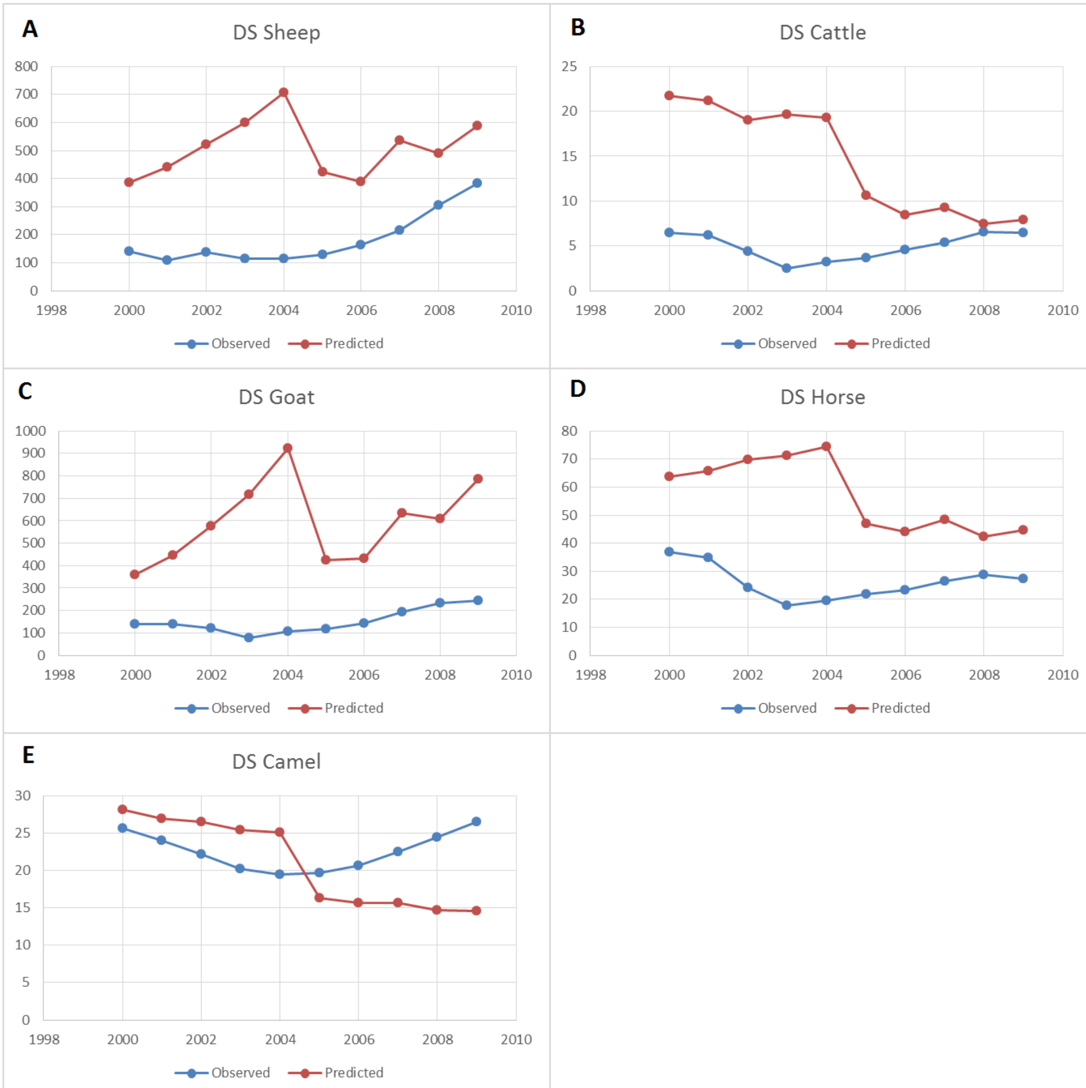

Figure 19. Comparisons of observed vs. model predicted livestock species numbers in the calibration evaluation conducted for the desert steppe (DS) ecological zone (see Table 16 for performance metrics).

Model Verification

Model verification used the same statistical metrics as used in calibration (BIAS, MBE, RMSD, *d*, and R^2) (Figure 20, 21, 22; Table 17). In the forest steppe, the calibrated model under-predicted livestock numbers, on average, for all four livestock species during the validation period (Figure 20; Table 17). Sheep and cattle had higher degree of closeness between observation and simulation predictions. The model predictions for cattle, horse, and sheep showed high correlative trends with observed data; however, the degree of difference between observed and predicted values was high as indicated by the *d* statistics. This indicates that the models for these species predicted the trend in livestock change over time, but was not very accurate in the predictions. In the steppe zone, the model over-predicted cattle and goat numbers, and horse and sheep were generally under-estimated (Figure 21; Table 17). The closeness between predicted and observed data of sheep was higher than the others species. Horse and sheep had higher correlative trends (0.66, 0.67) than cattle and goat (0.55, 0.55); however, like in the forest steppe, the accuracy of the predictions was generally low. In the desert steppe, the model generally overestimated cattle, sheep, goats, and horses and underestimated camels (Figure 22; Table 17). The predictions of cattle, sheep and camel were closer than the other species. In addition, camel and sheep had good correlative trends with prediction and observation (0.98, 0.9).

Table 17. Simulation model performance metrics for model verification by species and ecological zones.

Verification	Metrics	Cattle	Goat	Horse	Sheep	Camel
Forest Steppe	BIAS	-85.85	-42.44	-81.74	-10.66	-
	MEB	-37.48	-49.50	-21.73	-21.82	-
	RMSD	32.76	46.11	18.86	34.70	-
	d	0.14	0.08	0.06	0.27	-
	R^2	0.96	0.19	0.91	0.94	-
Steppe	BIAS	30.57	7.77	-32.05	-14.65	-
	MEB	3.32	10.30	-6.91	-41.11	-
	RMSD	5.38	68.08	9.69	55.34	-
	d	0.22	0.04	0.27	0.43	-
	R^2	0.55	0.55	0.66	0.67	-
Desert Steppe	BIAS	29.78	243.33	86.11	46.99	-65.16
	MEB	1.13	346.34	13.15	131.88	-19.28
	RMSD	2.25	393.96	15.31	151.31	19.73
	d	0.23	0.13	0.18	0.20	0.23
	R^2	0.43	0.28	0.51	0.90	0.98

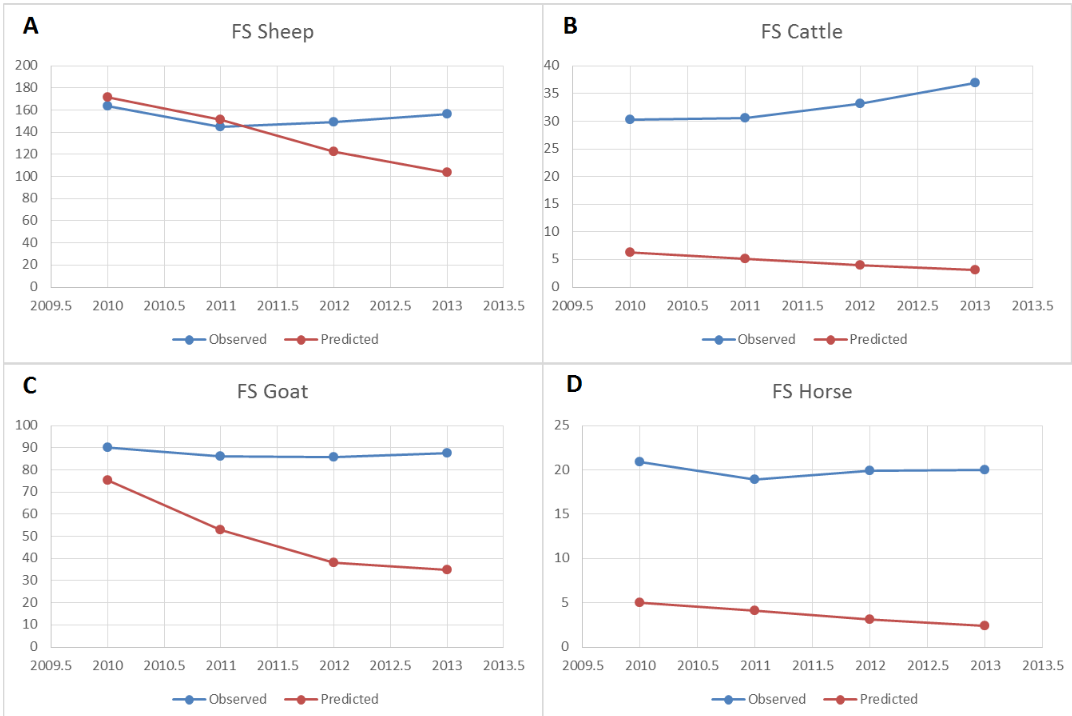

Figure 20. Comparisons of observed vs. model predicted livestock species numbers in the model verification evaluation conducted for the forest steppe (FS) ecological zone (see Table 17 for performance metrics).

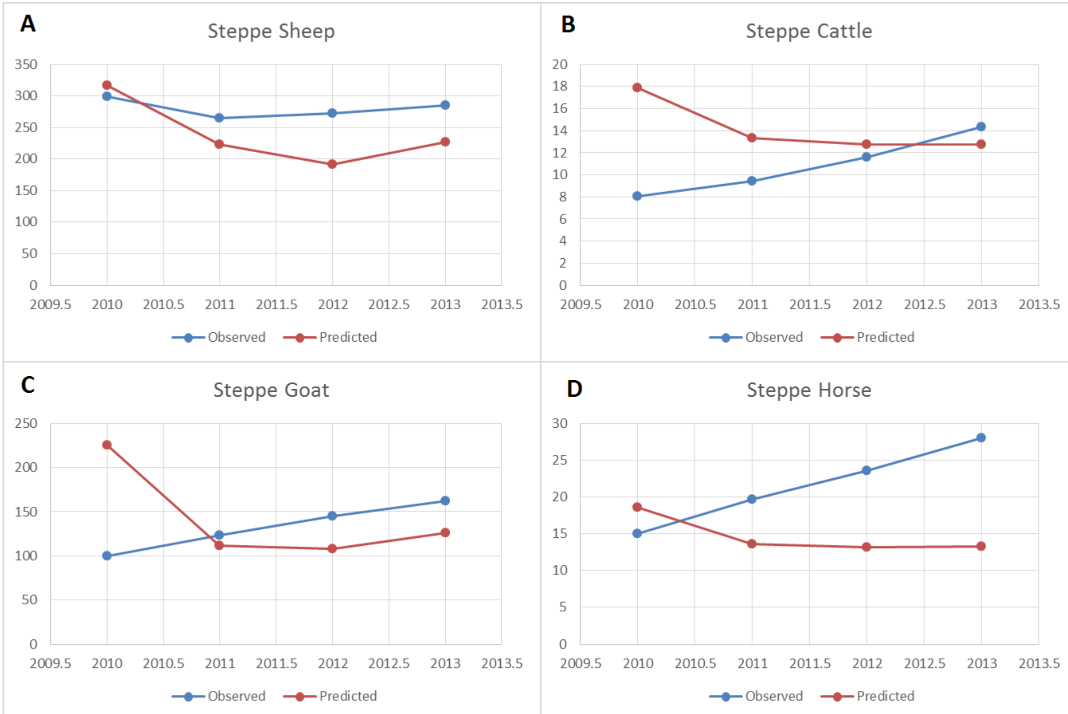

Figure 21. Comparisons of observed vs. model predicted livestock species numbers in the model verification evaluation conducted for the steppe ecological zone (see Table 17 for performance metrics).

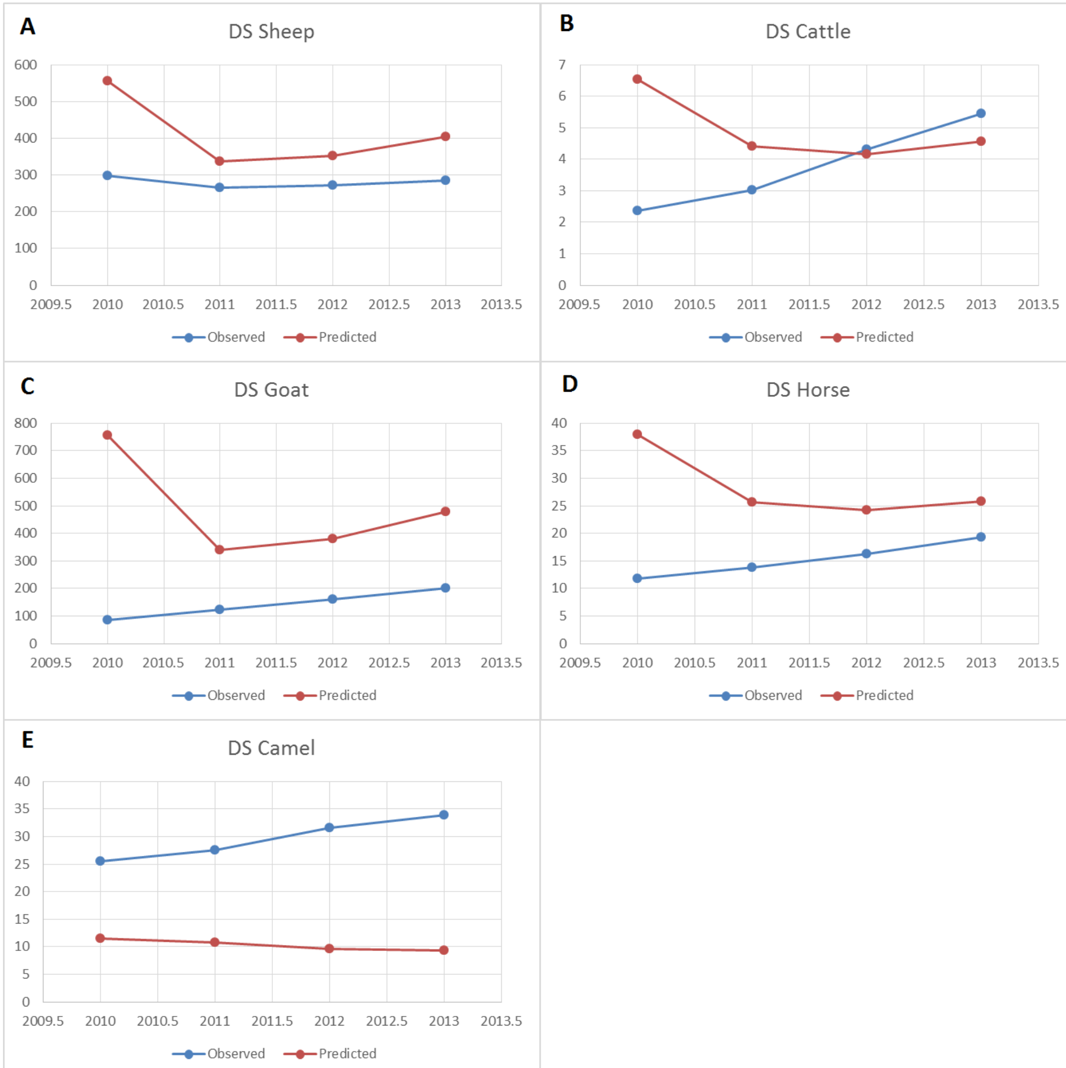

Figure 22. Comparisons of observed vs. model predicted livestock species numbers in the model verification evaluation conducted for the desert steppe (DS) ecological zone (see Table 17 for performance metrics).

Hypothesis Testing

In order to test hypothesis that the simulation model containing forage availability, temperature dynamics and extremes, and snowfall depth components would better correspond to livestock losses than a model that examined these thresholds individually, the goat model in steppe zone was used to evaluate the model under four different scenarios. These scenarios were as follows: 1) the verified goat model with the dynamic grazing pressure, snowfall, and temperature variables included together; 2) the model with a fixed snowfall (1.5cm) and minimum temperature (-9˚C) where grazing pressure was allowed to be dynamic; 3) the model with a fixed minimum temperature, and grazing pressure and snowfall allowed to be variable over time; 4) the model with a fixed grazing pressure (PU=0.5) no snowfall, with minimum temperature allowed to be variable over time.

Model results for scenarios 2, 3, and 4 were difference from that of the verified model (scenario 1) (Figure 23, Table 18). In general, scenario 2, 3, and 4 over-predicted livestock numbers compared to the scenario 1 which included the dynamics for snow, temperature and forage availability. Minimum temperature appeared to be the most sensitive variable. Livestock numbers increased exponentially when temperature was the only one variable allowed to be dynamic (Figure 23, Scenario 4). Scenario 2 and 3 appear to have similar results. This is because of the linkage between snowfall and grazing pressure as snowfall reduces forage availability when a specified depth is exceeded. However, the result from these two scenarios indicate that snowfall was the least sensitive variable for influencing livestock dynamics in the model.

A test of homogeneity of slopes for the four scenarios indicated that the slopes of the trends for each scenario were significantly different ($p<0.05$). Therefore, the results indicated that the simulation model that represented the dynamics of forage availability, temperature, and snowfall depth better corresponds to livestock losses than examination of these thresholds individually.

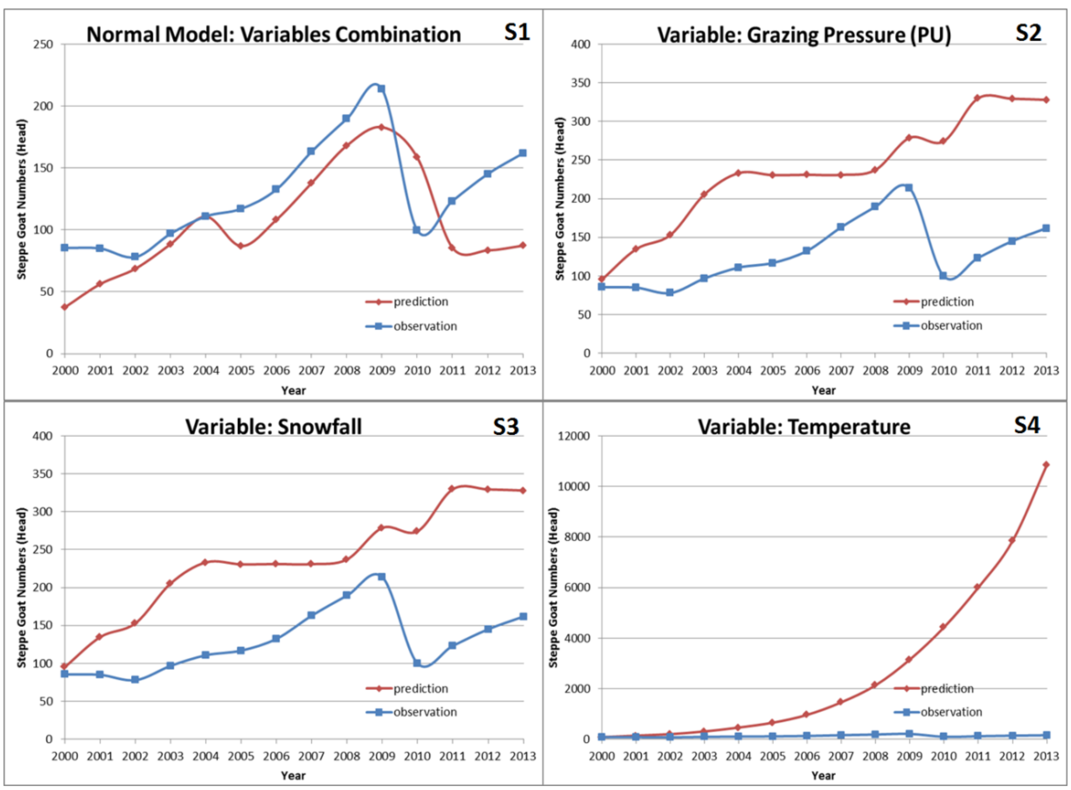

Figure 23. Comparisons of observed vs. model predicted livestock species numbers in the calibration evaluation conducted for the desert steppe ecological zone (see Table 18 for performance metrics).

Table 18. Model performance metrics for by testing scenarios.

	Combination	PU	Snowfall	Temperature
d	**0.79**	0.40	0.40	0.01
R^2	**0.53**	0.33	0.33	0.17

Discussion

In the previous simulation studies conducted on livestock population dynamics in Mongolia, the research was restricted to diseases and only sheep and cattle dynamics were studied (Alsonso, 2007). In another study of livestock population dynamics only one study site was analyzed (Shabb et al., 2013). This study is novel in that it represents the first time a livestock population dynamics model has been developed to simulate dzud and its impact on livestock populations. The current simulation model included climate variables and forage conditions, in addition to different livestock age classes and species examined in three ecological zones. The model was designed to evaluate livestock population dynamics at the household level of scale in order to include livestock management details. The simulation model is also unique in that it provides specific equations of natality and dzud mortality, and numerically expresses the natural mortality, selling, and purchasing of the major livestock species in the three ecological zones.

Dzud winter disasters can be characterized by deep snow, ice, continuous severe cold temperatures, and combinations of these can result in livestock loss. As previous studies have discussed, the combination of a winter disaster and previous summer drought can increase livestock mortality when compared to years with dzud only (Begzsuren et al., 2004). The extreme low temperature can caused livestock loss due to freezing, and the summer drought could lead to limitations in livestock weight gain if there is not adequate forage or hay storage (Fernández-Giménez et al., 2015). The simulation model of this study provided evidence on how the combination of forage availability, extreme low temperature, and snowfall depth resulted in predicted livestock losses that were more similar to observed data when compared to models using forage availability, temperature and snowfall individually (Figure 23; Table 18).

The calibration metrics results of simulation model indicated that the models generally predicted trends and numbers of animals well for sheep and goat in steppe zone, but was less successful in predicting numbers of animals in cattle and horses (Figure 17, 18, 19; Table 16). The verification results indicated that the model predicted trends well, but was not as accurate in the predictions (Figure 20, 21, 22; Table 17). These differences on model performance may be related to several different issues. The first may be related to the short verification periods. The period from 2000 to 2009 was used as the calibration period, and the period from 2010 to 2013 was used for verification of the calibrated models. If the verification periods could be extended for as long as the calibration period, the accuracy of verification may be improved. The reason sheep and goats may have had better predictions in the model was because they had a shorter transition from juvenile to adult than cattle, horses, and camels; the higher birth rates and faster aging of sheep and goat could make their populations change quicker after the dzud. In addition, sheep and goat had lower forage demand than other livestock species, which could make their populations respond to the dzud effects quicker too.

Although the model performed well for sheep and goats in the forest steppe and steppe evaluations, the current modeling approach has several limitations. First, the model was initialized in January 2000, a month in which a dzud started in Mongolia. If the model period would have been extended to include a start year before the dzud occurred, it may have improved model calibration.

The climate variables from the weather station data used in this study may have limitations with regard to the size of the soum, the location of the station, and quality of the data. In an evaluation of the deviations between predicted and observed data in the desert steppe, the average minimum temperature data from February 2005 shows temperatures that were colder than in February in 2000 and 2001 when the large scale dzuds were reported for Mongolia. This may indicate that conditions at the weather station may represent localized dzud conditions that may not have been reflective of the soum as whole. Therefore, if livestock losses occurred in these localized dzud conditions, it may not be reflected in animal numbers measured for the entire soum.

At present, the simulation model has three major driving variables: snowfall, minimum temperature and grazing pressure. However, wind speed was not considered for inclusion as a driving variable. Sustained winds during extremely cold temperatures can lead to increased livestock deaths. Providing a wind function in the simulation model could more fully express characteristics of winter disasters, especially in desert steppe where shelter for livestock can be lacking (Begzsuren et al., 2004).

The purchasing and sales functions in the model could be improved. Assumptions on the purchase and selling rates were based on limited historical data. In order to improve the model, surveys should be conducted to gather information about how, when, where and why herders decide to purchase and sell livestock.

Another limitation of the model is the current inability to track livestock body condition. Currently, natality and mortality in the model are influenced by grazing pressure during the month. Under higher grazing pressures, birth rates will decrease and mortality will increase. However, to more effectively simulate effects of high grazing pressure and low forage availability, the inclusion of a body condition index variable that tracks consecutive months of high grazing pressure could be used as a proxy for body condition. Research on characteristics of dzud in Mongolia indicate that extended drought or lack of forage in the summer and fall result in livestock not being able to accumulate enough fat resources to survive the winter (Begzsuren et al., 2004; Fernández-Giménez et al., 2012; Fernández-Giménez et al., 2015; Kang et al., 2015; Sternberg, 2010; Tachiiri and Shinoda, 2012). Therefore, including a proxy to represent degree of animal fatness or body condition could be added to mortality calculations to increase deaths of animals in poor body condition during snow and extreme temperature events. The limitation needs to be addressed in the next generation model.

The simulation model would be useful for predicting livestock losses in preparing winter disasters. The local community and national government could use the simulation model to predict the livestock trends with current local temperature, snowfall, and grazing pressure, in order to prepare livestock wintering areas and increase hay storage. The prediction of livestock population could also provide reference data on livestock losses to develop the winter disasters aid response guidelines.

CHAPTER VI

SUMMARY

The overall research aim was to study the influence of grazing pressure and severe winter disasters on livestock population dynamics on rangeland in Mongolia. During the period from 2000 to 2014, grazing pressure was variable across Mongolia, both temporally and spatially. In 2014, Mongolia had the highest grazing pressure with almost 57 million hectares delineated as overgrazed. Grazing pressure was lowest in 2003 with almost 5 million hectares overgrazed. Overgrazing was identified in the central and southern portions in this study, where some of the most productive rangeland areas in occur in Mongolia. Land areas that were consistently overgrazed (> 10 years) totaled 8.6% of the total land area. Within ecological zones, land areas within zone boundaries classified as heavily grazed were greatest for the desert steppe. In addition, desert steppe had the largest amount of land area with consistent overgrazing. A comparison of livestock population changes in areas that had forage percentage use exceeding 70% (overgrazing) compared to those had lower grazing pressure indicated that livestock losses were greater in the overgrazed area.

The results of stepwise regressions evaluating the influence of climate and human management variables on vegetation production indicated that precipitation was a significant variable in 42.9% of the soums. Growing season temperature was significant in 8.1% of the soums, and only 4.8% of soums had a significant response to livestock density (SFU/ha). Across ecological zones, grazing pressure had the strongest influence on forage availability in mountain taiga zone, whereas growing season temperature was primarily the significant variable in the steppe zone. Precipitation was the most significant variable in forest steppe and desert steppe zones. Results of stepwise regressions conducted with the percent change in livestock numbers over time indicated that grazing pressure (PU) was the dominant factor affecting livestock populations in all ecological zones.

A simulation model was developed to simulate the effects of grazing pressure and winter disasters on livestock population dynamics in Mongolia. The calibration results indicated that the model had higher degree of closeness between observed and predicted data on sheep and goat than cattle and horse in steppe and forest steppe ecological zone. In the desert steppe ecological zone, the models for cattle, goat, horse, and sheep over-predicted livestock numbers on average. Moreover, the camels model in the desert steppe generally under-predicted the population over time. Model verification results indicated that the simulation model generally had good correlative trend for sheep, cattle, and horses in the forest steppe and steppe when compared to goat and camel. However, the accuracy of the predictions was generally low in the forest steppe. In the desert steppe, the model generally overestimated cattle, sheep, goats, and horses and underestimated camels.

The testing of the hypothesis that an integrated model that included effects of grazing pressure, temperate, and snow depth would improve predictions compared to models including these variables alone, indicated that the integrated simulation model better corresponds to livestock losses than examination of these thresholds individually.

This study represents the first national-level evaluation of grazing pressure in Mongolia and how grazing pressure and climate have influenced livestock densities over time. The methodologies for grazing pressure assessment could be used in developing the guidelines for livestock stocking rates to improve sustainable pasture management for local communities and national government in the future. This study is also novel in that it represents the first time a livestock population dynamics model has been developed to simulate dzud and its impact on livestock populations. The simulation would be useful for predicting livestock losses in preparing winter disasters. The prediction of livestock populations could also provide reference data on livestock losses to develop guidelines for winter disasters aid response.

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APPENDIX I

Appendix I.1

Stepwise regressions output statistics where forage availability (average kg/ha/soum) was used as the dependent variable and growing season (June to August) average temperature (˚C), annual average precipitation (mm), and average livestock density (SFU/ha) as independent variables during the 2000 to 2014 period. Data are reported by soum.

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	Grow Temp	Precipitation	SFU/ha	RSQ
Arxangai	Batcengel	6504	FA	71.64	349.72		1.80		0.46
Arxangai	Bulgan	6507	FA	96.01	936.84				0.00
Arxangai	Caxir	6543	FA	98.82	519.06		1.67		0.28
Arxangai	Cecerleg	6549	FA	66.42	656.25		1.00		0.25
Arxangai	Cenxer	6546	FA	77.09	1036.13			-103.13	0.20
Arxangai	Chuluut	6552	FA	89.88	905.23				0.00
Arxangai	Erdenemandal	6555	FA	68.89	760.15			126.80	0.21
Arxangai	Ixtamir	6513	FA	73.53	637.11		1.07		0.26
Arxangai	Jargalant	6510	FA	65.03	993.05				0.00
Arxangai	O'giinuur	6516	FA	84.15	1273.83	-59.45	1.45		0.43
Arxangai	O'lziit	6519	FA	54.94	976.31	-52.26	2.28		0.78
Arxangai	O'ndor-Ulaan	6522	FA	81.12	980.59				0.00
Arxangai	Tariat	6525	FA	77.28	619.60		1.25		0.21
Arxangai	To'vshru'ulex	6528	FA	88.77	549.36		1.25		0.27
Arxangai	Xairxan	6531	FA	65.63	667.14		0.94		0.21
Arxangai	Xangai	6534	FA	97.80	577.62		1.54		0.25
Arxangai	Xashaat	6537	FA	101.52	407.24		1.29		0.35
Arxangai	Xotont	6540	FA	92.61	611.46		1.03		0.20

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	Grow Temp	Precipit ation	SFU/ha	RSQ
Bayan-O'lgii	Altai	8304	FA	52.05	930.25	-45.76			0.41
Bayan-O'lgii	Altanco'gc	8307	FA	52.08	192.25		1.50		0.37
Bayan-O'lgii	Bayannuur	8310	FA	32.67	212.07		1.16		0.55
Bayan-O'lgii	Bugat	8313	FA	75.68	441.57				0.00
Bayan-O'lgii	Bulgan	8316	FA	42.13	192.16	16.39	0.72		0.47
Bayan-O'lgii	Buyant	8319	FA	69.47	890.33	-50.24			0.27
Bayan-O'lgii	Cengel	8340	FA	47.20	426.09		0.97		0.29
Bayan-O'lgii	Delu'un	8322	FA	61.38	455.63				0.00
Bayan-O'lgii	Nogoonnuur	8325	FA	58.49	264.81		1.14		0.23
Bayan-O'lgii	Sagsai	8328	FA	43.57	759.02	-35.20	1.09		0.55
Bayan-O'lgii	Tolbo	8331	FA	64.94	447.56				0.00
Bayan-O'lgii	Ulaanxus	8334	FA	59.24	377.81		1.05		0.25
Bayanxongor	Baacagaan	6404	FA	39.21	590.64	-24.37			0.34
Bayanxongor	Bayan-O'ndor	6419	FA	14.16	96.90		0.29		0.39
Bayanxongor	Bayan-Ovoo	6416	FA	61.35	166.11		1.32		0.58
Bayanxongor	Bayanbulag	6407	FA	65.31	205.12		2.52		0.71
Bayanxongor	Bayancagaan	6422	FA	44.86	625.78	-26.85			0.36
Bayanxongor	Bayangovi	6410	FA	30.37	405.86	-15.76	0.44		0.52
Bayanxongor	Bayanlig	6413	FA	14.55	232.18	-7.00	0.34		0.62
Bayanxongor	Bo'mbogor	6428	FA	44.12	126.30		1.34		0.69
Bayanxongor	Bogd	6425	FA	36.89	146.93		0.70		0.41
Bayanxongor	Buucagaan	6431	FA	32.95	567.54	-27.01	0.79		0.73
Bayanxongor	Erdenecogt	6458	FA	69.06	685.18		0.72		0.24
Bayanxongor	Galuut	6434	FA	65.76	525.91		0.86		0.33
Bayanxongor	Gurvanbulag	6437	FA	97.67	1310.58			-1597.56	0.48
Bayanxongor	Jargalant	6440	FA	77.07	1624.67	-36.13		-1045.68	0.48
Bayanxongor	Jinst	6443	FA	41.23	92.56		0.80		0.44
Bayanxongor	O'lziit	6449	FA	58.33	220.06		1.28		0.63
Bayanxongor	Shinejinst	6455	FA	16.03	98.48		0.29		0.42
Bayanxongor	Xu'reemaral	6452	FA	48.36	155.08		1.67		0.66
Bayanxongor	Zag	6446	FA	82.00	230.06		1.99		0.55
Bulgan	Bayan agt	6304	FA	58.98	1377.23	-28.27			0.22
Bulgan	Bayannuur	6307	FA	103.52	504.33		1.32		0.35
Bulgan	Bu'regxangai	6313	FA	79.26	381.04		1.74		0.48
Bulgan	Bugat	6310	FA	90.16	880.35				0.00
Bulgan	Dashinchilen	6319	FA	114.28	478.88		1.34		0.33
Bulgan	Gurvanbulag	6316	FA	96.02	316.99		1.62		0.46
Bulgan	Mogod	6322	FA	79.38	1196.49	-51.10	1.54		0.51

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	Grow Temp	Precipitation	SFU/ha	RSQ
Bulgan	Orxon	6325	FA	61.55	561.77		1.29		0.43
Bulgan	Rashaant	6328	FA	90.08	559.54		0.90		0.40
Bulgan	Saixan	6331	FA	61.61	1422.69	-36.01			0.26
Bulgan	Selenge	6334	FA	91.57	671.22				0.00
Bulgan	Teshig	6337	FA	62.42	1371.61			-1700.60	0.82
Bulgan	Xangal	6340	FA	93.38	327.09		1.58		0.29
Bulgan	Xishig-O'ndor	6343	FA	86.35	328.38		1.98		0.52
Bulgan	Xutag-O'ndor	6346	FA	74.96	948.75				0.00
Darxan-Uul	Xongor	4507	FA	44.32	547.31		1.24	-95.25	0.67
Dornod	Bayan-Uul	2110	FA	89.61	1795.41	-57.62			0.38
Dornod	Bayandun	2104	FA	93.88	661.06		0.87		0.34
Dornod	Bayantu'men	2107	FA	113.93	453.00		1.54		0.46
Dornod	Bulgan	2113	FA	153.74	397.96		2.01		0.44
Dornod	Cagaan-Ovoo	2134	FA	93.90	503.67		1.40		0.53
Dornod	Choibalsan	2137	FA	99.94	464.10		1.54		0.52
Dornod	Chuluunxoroot	2140	FA	107.74	485.19		1.46		0.43
Dornod	Dashbalbar	2119	FA	105.05	530.02		1.29		0.45
Dornod	Gurvanzagal	2116	FA	103.05	503.44		1.48		0.48
Dornod	Matad	2122	FA	138.08	271.93		2.18		0.43
Dornod	Sergelen	2125	FA	112.69	476.80		1.52		0.48
Dornod	Xalx gol	2128	FA	67.16	797.34				0.00
Dornod	Xo'lonbuir	2131	FA	130.15	451.71		1.71		0.45
Dornogovi	Airag	4404	FA	112.76	286.40				0.00
Dornogovi	Altanshiree	4407	FA	92.08	103.46		1.70		0.39
Dornogovi	Dalanjargalan	4410	FA	119.81	344.58				0.00
Dornogovi	Delgerex	4413	FA	87.85	117.59		1.81		0.55
Dornogovi	Erdene	4440	FA	39.40	78.34		1.42		0.56
Dornogovi	Ix xet	4419	FA	120.89	42.76		2.27		0.35
Dornogovi	Mandax	4422	FA	29.61	105.52		1.36	-885.45	0.66
Dornogovi	O'rgon	4425	FA	62.58	86.92		1.53		0.53
Dornogovi	Sainshand	4401	FA	40.28	95.91		0.90		0.45
Dornogovi	Saixandulaan	4428	FA	66.43	77.25		1.26		0.34
Dornogovi	Ulaanbadrax	4431	FA	40.73	875.10	-32.43	0.83		0.57
Dornogovi	Xatanbulag	4434	FA	47.15	71.97		0.89		0.47
Dornogovi	Xo'vsgol	4437	FA	37.14	143.23		1.17	-553.97	0.63
Dundgovi	Adaacag	4804	FA	78.33	134.65		2.35		0.49
Dundgovi	Bayanjargalan	4807	FA	71.05	279.63				0.00
Dundgovi	Cagaandelger	4840	FA	90.25	1199.78	-42.26			0.22

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	Grow Temp	Precipitation	SFU/ha	RSQ
Dundgovi	Delgercogt	4819	FA	74.51	225.79		1.55		0.32
Dundgovi	Delgerxangai	4816	FA	21.08	44.18		1.43		0.88
Dundgovi	Deren	4822	FA	60.12	424.60		1.58	-419.08	0.67
Dundgovi	Erdenedalai	4843	FA	58.18	88.60		2.44		0.73
Dundgovi	Govi-Ugtaal	4810	FA	87.58	201.90		1.32		0.21
Dundgovi	Gurvansaixan	4813	FA	55.16	103.76		1.21		0.39
Dundgovi	Luus	4825	FA	37.67	260.36		1.47	-288.11	0.77
Dundgovi	O'lziit	4828	FA	16.57	677.09	-18.45	0.36	-1236.79	0.84
Dundgovi	O'ndorshil	4831	FA	68.43	198.23				0.00
Dundgovi	Saintsagaan	4801	FA	53.46	310.28		1.33	-188.84	0.62
Dundgovi	Saixan-Ovoo	4834	FA	46.61	47.73		1.92		0.81
Dundgovi	Xuld	4837	FA	32.08	33.37		1.77		0.77
Govi-Altai	Altai	8204	FA	18.51	123.96				0.00
Govi-Altai	Bayan-Uul	8207	FA	30.12	110.00		1.55	-184.81	0.81
Govi-Altai	Biger	8210	FA	39.79	238.17		1.14	-289.17	0.50
Govi-Altai	Bugat	8213	FA	21.13	105.94		0.76		0.44
Govi-Altai	Ceel	8243	FA	34.44	191.38		0.89	-270.39	0.57
Govi-Altai	Chandmani	8246	FA	61.92	247.32				0.00
Govi-Altai	Cogt	8240	FA	20.45	217.34			-536.16	0.34
Govi-Altai	Darvi	8216	FA	43.78	101.61		1.50		0.54
Govi-Altai	Delger	8219	FA	31.16	73.24		1.57		0.76
Govi-Altai	Erdene	8252	FA	14.85	150.59			-512.61	0.23
Govi-Altai	Jargalan	8222	FA	40.72	113.03		1.47		0.65
Govi-Altai	Sharga	8249	FA	27.83	82.18		1.06		0.66
Govi-Altai	Taishir	8225	FA	44.65	123.56		1.31		0.62
Govi-Altai	To'grog	8231	FA	24.06	151.79		0.97	-212.97	0.74
Govi-Altai	Tonkhil	8228	FA	26.03	159.84		0.95		0.55
Govi-Altai	Xaliun	8234	FA	32.97	252.82		1.01	-264.62	0.71
Govi-Altai	Xo'xmorit	8237	FA	20.40	90.86		0.93	-215.54	0.73
Govi-Altai	Yeso'nbulag	8201	FA	46.45	159.42		1.35		0.60
Govisu'mber	Bayantal	4204	FA	110.73	1528.03	-57.73			0.28
Govisu'mber	Shiveegovi	4207	FA	77.84	1158.39	-43.51			0.32
Govisu'mber	Su'mber	4201	FA	104.95	1617.71	-62.10			0.35
O'mnogovi	Bayan-Ovoo	4607	FA	23.97	58.44		0.70		0.59
O'mnogovi	Bayandalai	4604	FA	32.05	100.75		0.84		0.43
O'mnogovi	Bulgan	4610	FA	37.44	70.74		1.12		0.56
O'mnogovi	Cogt-Cecii	4643	FA	39.47	30.35		1.53		0.64
O'mnogovi	Cogt-Ovoo	4640	FA	25.19	55.79		1.20		0.72
O'mnogovi	Gurvantes	4613	FA	16.48	94.45		0.43		0.63

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	Grow Temp	Precipit ation	SFU/ha	RSQ
O'mnogovi	Mandal-Ovoo	4616	FA	23.03	59.83		0.77		0.64
O'mnogovi	Manlai	4619	FA	24.81	31.60		1.41		0.76
O'mnogovi	Nomgon	4625	FA	22.15	46.39		0.66		0.58
O'mnogovi	Noyon	4622	FA	23.64	69.91		0.90		0.47
O'mnogovi	Sevrei	4628	FA	26.60	94.20		0.80		0.53
O'mnogovi	Xanbogd	4631	FA	35.71	56.92		0.71		0.47
O'mnogovi	Xanxongor	4634	FA	45.19	64.84		1.30		0.54
O'mnogovi	Xu'rmen	4637	FA	18.80	302.47	-9.58	0.54		0.59
O'vorxangai	Baruunbayan-Ulaan	6204	FA	36.40	681.57	-24.28			0.32
O'vorxangai	Bat-O'lzii	6207	FA	59.94	762.40		0.60		0.22
O'vorxangai	Bayan-O'ndor	6213	FA	99.13	527.67				0.00
O'vorxangai	Bayangol	6210	FA	82.34	173.44		1.31		0.45
O'vorxangai	Bogd	6216	FA	31.15	132.07		0.59		0.37
O'vorxangai	Bu'rd	6219	FA	102.78	712.83				0.00
O'vorxangai	Guchin-Us	6222	FA	43.98	839.76	-30.51			0.30
O'vorxangai	Nariinteel	6231	FA	58.41	254.87		1.00		0.52
O'vorxangai	O'lziit	6234	FA	74.99	433.49		0.69		0.27
O'vorxangai	Sant	6237	FA	70.55	152.45		1.47		0.59
O'vorxangai	Taragt	6240	FA	71.97	273.70		1.15		0.55
O'vorxangai	To'grog	6243	FA	45.48	113.60		0.77		0.45
O'vorxangai	Uyanga	6246	FA	61.44	614.06		0.88		0.42
O'vorxangai	Xairxandulaan	6249	FA	60.62	1075.42	-42.25	0.59		0.60
O'vorxangai	Xarxorin	6252	FA	77.66	1601.49	-71.48	0.90		0.49
O'vorxangai	Xujirt	6255	FA	80.88	601.44		0.92		0.32
O'vorxangai	Yeso'nzu'il	6225	FA	80.05	643.10				0.00
O'vorxangai	Zu'unbayan-Ulaan	6228	FA	74.38	512.10		0.84		0.34
Selenge	Altanbulag	4304	FA	87.96	729.71			-310.08	0.26
Selenge	Baruunbu'ren	4307	FA	50.88	353.03		2.12	-150.77	0.71
Selenge	Bayangol	4310	FA	43.60	521.70		1.47	-87.29	0.75
Selenge	Cagaannuur	4346	FA	88.95	693.39				0.00
Selenge	Javxlant	4316	FA	86.69	836.58				0.00
Selenge	Mandal	4322	FA	36.65	144.69	25.91	1.00	-223.79	0.83
Selenge	Orxon	4325	FA	62.52	439.01		1.91	-84.81	0.72
Selenge	Orxontuul	4328	FA	61.56	436.10		1.69		0.66
Selenge	Saixan	4331	FA	74.00	473.41		1.34		0.52
Selenge	Sant	4334	FA	54.02	363.66		1.53		0.68
Selenge	Shaamar	4349	FA	88.17	1030.41			-235.29	0.26
Selenge	Tu'shig	4337	FA	76.32	598.75			-193.26	0.22

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	Grow Temp	Precipitation	SFU/ha	RSQ
Selenge	Xu'der	4340	FA	30.60	272.99			-71.14	0.73
Selenge	Xushaat	4343	FA	59.49	280.43		1.34		0.43
Selenge	Yero'o	4313	FA	40.08	384.37			-75.30	0.55
Selenge	Zu'unburen	4319	FA	69.65	484.59		1.64	-216.97	0.52
Su'xbaatar	Asgat	2204	FA	138.96	231.54		2.70		0.54
Su'xbaatar	Baruun-Urt	2201	FA	124.41	432.09		3.50	-748.81	0.66
Su'xbaatar	Bayandelger	2207	FA	81.87	198.79		1.57		0.58
Su'xbaatar	Dariganga	2210	FA	93.85	371.83		1.95		0.56
Su'xbaatar	Erdenecagaan	2237	FA	118.31	1215.84		2.24	-3641.71	0.54
Su'xbaatar	Mo'nxxaan	2213	FA	115.22	454.81		2.67	-522.04	0.67
Su'xbaatar	Naran	2216	FA	95.04	320.07		1.69		0.46
Su'xbaatar	Ongon	2219	FA	92.56	226.07		1.79		0.54
Su'xbaatar	Tu'mencogt	2228	FA	142.35	2152.95	-70.94			0.39
Su'xbaatar	Tu'vshinshiree	2225	FA	90.58	25.96		2.56		0.73
Su'xbaatar	Uulbayan	2231	FA	136.88	50.19		2.74		0.58
Su'xbaatar	Xalzan	2234	FA	114.91	619.85		2.84	-1071.63	0.64
To'v	Altanbulag	4103	FA	99.82	698.50				0.00
To'v	Argalant	4107	FA	93.54	480.70		1.35		0.21
To'v	Arxust	4110	FA	77.97	397.69		1.84		0.42
To'v	Batsu'mber	4113	FA	75.80	747.88				0.00
To'v	Bayan	4116	FA	82.35	317.29		1.85		0.37
To'v	Bayan-O'njuul	4125	FA	69.63	213.95		3.60	-392.03	0.69
To'v	Bayancagaan	4131	FA	73.87	203.61		2.10		0.38
To'v	Bayancogt	4134	FA	88.17	470.29		1.26		0.29
To'v	Bayandelger	4119	FA	68.86	575.46		1.42		0.35
To'v	Bayanjargalan	4122	FA	123.55	1909.63	-74.59			0.33
To'v	Bayanxangai	4128	FA	91.03	376.51		1.63		0.33
To'v	Bornuur	4140	FA	62.26	764.91				0.00
To'v	Bu'ren	4143	FA	102.11	540.08		1.89	-309.71	0.41
To'v	Ceel	4173	FA	64.32	430.64		2.32	-150.39	0.67
To'v	Delgerxaan	4146	FA	106.46	602.99				0.00
To'v	Erdene	4176	FA	54.91	958.13			-471.34	0.57
To'v	Erdenesant	4179	FA	123.16	768.76				0.00
To'v	Jargalant	4149	FA	54.01	517.39		1.62	-111.91	0.70
To'v	Lu'n	4155	FA	82.91	487.14		1.19		0.31
To'v	Mo'ngonmorit	4158	FA	48.45	905.91			-614.92	0.65
To'v	O'ndorshireet	4161	FA	105.77	496.27		1.02		0.23
To'v	Sergelen	4167	FA	54.24	1435.38	-45.89	1.00	-478.45	0.64

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	Grow Temp	Precipit ation	SFU/ha	RSQ
To'v	Ugtaalcaidam	4170	FA	67.74	402.85		2.64	-216.07	0.66
To'v	Zaamar	4152	FA	101.07	338.41		1.82		0.39
Ulaanbaatar	Baganuur	1101	FA	51.33	531.47		0.98		0.32
Ulaanbaatar	Bayanzu'rx	1110	FA	68.48	786.02				0.00
Ulaanbaatar	Nalaix	1113	FA	62.72	1413.94	-38.97			0.38
Ulaanbaatar	Songinoxairxan	1116	FA	62.45	705.83				0.00
Uvs	Baruunturuun	8504	FA	46.16	1450.51	-46.80		-726.67	0.65
Uvs	Bo'xmoron	8507	FA	36.57	595.77			-573.34	0.37
Uvs	Cagaanxairxan	8555	FA	48.42	359.25				0.00
Uvs	Davst	8510	FA	38.79	955.14	-29.13		-514.03	0.47
Uvs	Malchin	8522	FA	50.49	204.76		1.53		0.54
Uvs	Naranbulag	8525	FA	38.04	177.22		1.35		0.67
Uvs	O'lgii	8528	FA	33.25	193.17		1.41	-220.92	0.80
Uvs	O'mnogovi	8531	FA	38.06	275.89		0.89		0.52
Uvs	O'ndorxangai	8534	FA	62.86	558.83				0.00
Uvs	Sagil	8537	FA	50.00	417.04		0.58		0.22
Uvs	Tarialan	8540	FA	57.81	426.01		0.83		0.30
Uvs	Tes	8546	FA	42.95	241.23		1.60		0.61
Uvs	Tu'rgen	8543	FA	60.91	515.02		0.93		0.33
Uvs	Xovd	8549	FA	40.76	298.77		0.92		0.42
Uvs	Xyargas	8552	FA	49.88	1596.09	-43.87		-554.94	0.60
Uvs	Zavxan	8513	FA	17.47	154.43		0.41	-385.51	0.65
Uvs	Zu'ungovi	8516	FA	46.08	1282.12	-40.06		-544.71	0.68
Uvs	Zu'unxangai	8519	FA	100.98	682.67				0.00
Xentii	Batnorov	2304	FA	89.22	2063.45	-77.02			0.59
Xentii	Batshireet	2307	FA	62.89	1031.65			-580.46	0.22
Xentii	Bayan-Adraga	2310	FA	77.88	1538.95	-44.91			0.32
Xentii	Bayan-Ovoo	2316	FA	118.31	2174.27	-78.01			0.51
Xentii	Bayanmo'nx	2313	FA	121.16	2359.38	-94.93			0.46
Xentii	Bayanxutag	2319	FA	89.65	302.49		3.03	-402.58	0.74
Xentii	Binder	2322	FA	59.52	1586.28	-46.24			0.39
Xentii	Cenxermandal	2349	FA	59.33	1486.12	-40.49			0.40
Xentii	Dadal	2328	FA	78.32	841.46		0.45		0.31
Xentii	Darxan	2331	FA	111.06	1865.05	-71.32			0.36
Xentii	Delgerxaan	2334	FA	82.92	1644.20	-59.39			0.41
Xentii	Galshir	2325	FA	108.93	11.54		2.91		0.64
Xentii	Jargaltxaan	2337	FA	90.92	1969.01	-77.86			0.48
Xentii	Mo'ron	2340	FA	85.05	262.88		2.01		0.59

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	Grow Temp	Precipit ation	SFU/ha	RSQ
Xentii	Norovlin	2343	FA	74.88	1602.54	-46.37			0.43
Xentii	O'mnodelger	2346	FA	65.60	839.70				0.00
Xentii	Xerlen	2301	FA	83.44	2177.16	-87.14			0.61
Xo'vsgol	Alag-Erdene	6704	FA	65.89	977.96				0.00
Xo'vsgol	Arbulag	6707	FA	89.42	538.29		1.15		0.21
Xo'vsgol	Bayanzu'rx	6710	FA	57.20	1016.08				0.00
Xo'vsgol	Bu'rentogtox	6713	FA	68.85	468.03		1.42		0.37
Xo'vsgol	Cagaan-U'ur	6755	FA	60.23	1379.33			-3141.07	0.72
Xo'vsgol	Cagaan-Uul	6752	FA	74.20	454.59		1.88		0.48
Xo'vsgol	Cagaannuur	6749	FA	30.59	400.44	31.33	0.55		0.75
Xo'vsgol	Cecerleg	6758	FA	57.77	720.28		1.06		0.43
Xo'vsgol	Chandmani-O'ndor	6761	FA	63.62	1602.08			-1573.79	0.54
Xo'vsgol	Erdenebulgan	6767	FA	54.61	1509.51			-1503.50	0.81
Xo'vsgol	Galt	6716	FA	57.85	459.83		1.58		0.48
Xo'vsgol	Ix-Uul	6722	FA	65.45	1363.24	-29.57			0.21
Xo'vsgol	Jargalant	6719	FA	54.63	710.61		1.36	-113.61	0.50
Xo'vsgol	Rashaant	6725	FA	71.77	1478.51	-36.95			0.21
Xo'vsgol	Renchinlxu'mbe	6728	FA	48.35	307.07	34.40	0.80		0.59
Xo'vsgol	Shine-Ider	6764	FA	77.21	535.41		1.49		0.33
Xo'vsgol	Tarialan	6731	FA	62.68	1276.57			-357.89	0.36
Xo'vsgol	To'morbulag	6737	FA	66.45	519.35		1.48		0.38
Xo'vsgol	Tosoncengel	6734	FA	71.57	460.24		1.62		0.38
Xo'vsgol	Tu'nel	6740	FA	74.39	960.77				0.00
Xo'vsgol	Ulaan uul	6743	FA	48.67	1114.76			-1030.49	0.44
Xo'vsgol	Xanx	6746	FA	34.88	662.20			-340.82	0.31
Xovd	Altai	8404	FA	17.25	132.51		0.74		0.62
Xovd	Bulgan	8407	FA	17.69	81.91	6.71	0.62	-139.34	0.73
Xovd	Buyant	8410	FA	32.21	555.04	-18.71	0.55		0.48
Xovd	Ceceg	8443	FA	42.48	323.37		0.98		0.35
Xovd	Chandmani	8446	FA	45.50	774.19	-29.81	1.40		0.63
Xovd	Darvi	8413	FA	55.26	134.68		1.90		0.49
Xovd	Do'rgon	8416	FA	16.54	489.71	-14.66	0.91	-289.86	0.86
Xovd	Duut	8419	FA	73.11	309.71		1.03		0.21
Xovd	Erdenebu'ren	8449	FA	39.52	223.56		1.07		0.46
Xovd	Manxan	8425	FA	46.57	1101.22	-40.00			0.45
Xovd	Mo'nxxairxan	8428	FA	51.20	652.58			-556.20	0.37
Xovd	Mo'st	8431	FA	46.17	256.35		1.12		0.39

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	Grow Temp	Precipit ation	SFU/ha	RSQ
Xovd	Myangad	8434	FA	38.32	225.23		1.14		0.56
Xovd	U'yench	8437	FA	22.95	164.17		0.75		0.51
Xovd	Xovd	8440	FA	41.43	663.10	-27.82	1.02		0.58
Xovd	Zereg	8422	FA	58.19	247.98		1.26		0.30
Zavxan	Aldarxaan	8104	FA	41.93	499.33		1.23	-271.19	0.74
Zavxan	Bayantes	8110	FA	42.70	1713.11	-62.44		-653.98	0.77
Zavxan	Bayanxairxan	8113	FA	67.74	1842.95	-69.84	0.73	-562.55	0.67
Zavxan	Cagaanchuluu t	8158	FA	60.66	-56.47	29.64	1.95	-377.31	0.79
Zavxan	Cagaanxairxa n	8155	FA	55.33	498.88		1.27	-392.28	0.65
Zavxan	Cecen-Uul	8161	FA	43.95	426.91		0.92	-194.70	0.53
Zavxan	Do'rvoljin	8116	FA	23.40	144.67		1.04	-343.60	0.70
Zavxan	Erdenexairxan	8167	FA	36.90	303.53		1.37	-251.53	0.75
Zavxan	Ider	8122	FA	50.01	556.06		1.75		0.66
Zavxan	Ix-Uul	8125	FA	58.10	642.70		1.38		0.46
Zavxan	No'mrog	8128	FA	41.54	1147.18	-44.41	1.27	-232.33	0.83
Zavxan	Otgon	8131	FA	69.41	349.60		2.14		0.57
Zavxan	Santmargac	8134	FA	52.46	369.61		0.98	-253.06	0.49
Zavxan	Shilu'ustei	8164	FA	45.45	336.82		1.64	-377.68	0.82
Zavxan	Songino	8137	FA	110.01	614.00				0.00
Zavxan	Telmen	8146	FA	33.63	1016.21	-40.85	1.60	-176.97	0.90
Zavxan	Tes	8149	FA	78.69	2059.94	-73.47	0.71	-333.88	0.69
Zavxan	Tosoncengel	8140	FA	52.04	678.24		1.25		0.49
Zavxan	Tu'devtei	8143	FA	88.82	529.69		0.85		0.23
Zavxan	Urgamal	8152	FA	26.03	262.90		0.60	-370.18	0.62
Zavxan	Yaruu	8170	FA	40.42	323.14		1.78		0.76
Zavxan	Zavxanmandal	8119	FA	60.44	248.16		1.31	-371.85	0.46

Appendix I.2

Stepwise regressions output statistics where yearly change in livestock numbers was used as the dependent variable; percent use (PU) from the previous year, winter season (January to March) average temperature (˚C) for the current year, and average annual precipitation (mm) from the previous year were used as independent variables during the 2000 to 2014 period. Data are presented by soum.

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	PU	Precipit ation	Winter Temp	RSQ
Arxangai	Batcengel	6504	SFU	12.39	-6.84	-0.64	0.18		0.52
Arxangai	Bulgan	6507	SFU	11.29	-36.28		0.16		0.29
Arxangai	Caxir	6543	SFU	12.98	3.37				0.00
Arxangai	Cecerleg	6549	SFU	13.95	3.20				0.00
Arxangai	Cenxer	6546	SFU	19.20	4.55				0.00
Arxangai	Chuluut	6552	SFU	8.30	4.57				0.00
Arxangai	Erdenemandal	6555	SFU	14.18	60.99	-1.16			0.40
Arxangai	Ixtamir	6513	SFU	11.03	-38.32		0.16		0.27
Arxangai	Jargalant	6510	SFU	13.65	2.61				0.00
Arxangai	O'giinuur	6516	SFU	19.10	2.64				0.00
Arxangai	O'lziit	6519	SFU	12.94	-26.69	-0.58	0.27		0.53
Arxangai	O'ndor-Ulaan	6522	SFU	10.42	2.96				0.00
Arxangai	Tariat	6525	SFU	14.59	2.41				0.00
Arxangai	To'vshru'ulex	6528	SFU	18.65	69.44	-1.24			0.53
Arxangai	Xairxan	6531	SFU	12.11	4.94				0.00
Arxangai	Xangai	6534	SFU	11.54	2.73				0.00
Arxangai	Xashaat	6537	SFU	12.91	-23.88		0.13		0.26
Arxangai	Xotont	6540	SFU	15.66	83.11	-1.08		8.19	0.68
Bayan-O'lgii	Altai	8304	SFU	6.60	28.55			4.22	0.37
Bayan-O'lgii	Altanco'gc	8307	SFU	10.95	62.22	-1.02			0.72
Bayan-O'lgii	Bayannuur	8310	SFU	10.04	50.80	-0.69			0.51
Bayan-O'lgii	Bugat	8313	SFU	7.45	55.97	-1.07			0.75

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	PU	Precipit ation	Winter Temp	RSQ
Bayan-O'lgii	Bulgan	8316	SFU	13.39	53.50	-2.12			0.45
Bayan-O'lgii	Buyant	8319	SFU	6.60	78.61	-1.42			0.77
Bayan-O'lgii	Cengel	8340	SFU	8.24	6.63		0.16	5.04	0.52
Bayan-O'lgii	Delu'un	8322	SFU	4.98	86.33	-1.65		4.82	0.86
Bayan-O'lgii	Nogoonnuur	8325	SFU	6.75	54.10	-1.54			0.68
Bayan-O'lgii	Sagsai	8328	SFU	6.79	99.37	-2.35		4.79	0.62
Bayan-O'lgii	Tolbo	8331	SFU	9.27	74.48	-1.82			0.47
Bayan-O'lgii	Ulaanxus	8334	SFU	7.10	70.19	-1.75		4.22	0.65
Bayanxongor	Baacagaan	6404	SFU	24.31	51.70	-0.88			0.48
Bayanxongor	Bayan-O'ndor	6419	SFU	16.20	64.01	-3.00			0.64
Bayanxongor	Bayan-Ovoo	6416	SFU	20.66	-31.01		0.23		0.28
Bayanxongor	Bayanbulag	6407	SFU	11.37	33.24	-1.09			0.55
Bayanxongor	Bayancagaan	6422	SFU	18.36	63.62	-1.37			0.73
Bayanxongor	Bayangovi	6410	SFU	26.05	54.65	-0.98			0.51
Bayanxongor	Bayanlig	6413	SFU	17.15	27.14	-1.09	0.22		0.59
Bayanxongor	Bo'mbogor	6428	SFU	28.17	39.81	-0.73			0.24
Bayanxongor	Bogd	6425	SFU	16.81	57.71	-0.83			0.62
Bayanxongor	Buucagaan	6431	SFU	13.85	99.37	-1.33		7.96	0.79
Bayanxongor	Erdenecogt	6458	SFU	14.22	5.06				0.00
Bayanxongor	Galuut	6434	SFU	13.20	3.05				0.00
Bayanxongor	Gurvanbulag	6437	SFU	6.73	70.79	-1.56		4.05	0.79
Bayanxongor	Jargalant	6440	SFU	8.26	35.52	-1.33			0.42
Bayanxongor	Jinst	6443	SFU	20.55	59.50	-1.29			0.67
Bayanxongor	O'lziit	6449	SFU	22.64	40.48	-0.63			0.25
Bayanxongor	Shinejinst	6455	SFU	18.39	33.98	-2.47	0.27		0.69
Bayanxongor	Xu'reemaral	6452	SFU	14.96	54.52	-1.38			0.57
Bayanxongor	Zag	6446	SFU	9.70	34.15	-0.76			0.46
Bulgan	Bayan agt	6304	SFU	7.53	-23.27	-1.16	0.26		0.63
Bulgan	Bayannuur	6307	SFU	27.72	8.90				0.00
Bulgan	Bu'regxangai	6313	SFU	16.78	4.68				0.00
Bulgan	Bugat	6310	SFU	14.39	2.76				0.00
Bulgan	Dashinchilen	6319	SFU	19.13	5.34				0.00
Bulgan	Gurvanbulag	6316	SFU	12.72	2.36	-0.52	0.17		0.52
Bulgan	Mogod	6322	SFU	8.79	-25.49	-0.72	0.26		0.70
Bulgan	Orxon	6325	SFU	14.22	4.47				0.00
Bulgan	Rashaant	6328	SFU	13.19	12.09				0.00
Bulgan	Saixan	6331	SFU	14.19	2.96				0.00
Bulgan	Selenge	6334	SFU	15.67	4.41				0.00
Bulgan	Teshig	6337	SFU	9.20	-42.94		0.15		0.24

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	PU	Precipitation	Winter Temp	RSQ
Bulgan	Xangal	6340	SFU	14.94	3.60				0.00
Bulgan	Xishig-O'ndor	6343	SFU	10.18	-9.01	-0.68	0.18		0.52
Bulgan	Xutag-O'ndor	6346	SFU	7.53	12.30			4.69	0.32
Darxan-Uul	Xongor	4507	SFU	19.21	4.68				0.00
Dornod	Bayan-Uul	2110	SFU	5.99	2.08				0.00
Dornod	Bayandun	2104	SFU	7.26	1.72				0.00
Dornod	Bayantu'men	2107	SFU	10.38	-2.68			6.02	0.28
Dornod	Bulgan	2113	SFU	8.26	4.39				0.00
Dornod	Cagaan-Ovoo	2134	SFU	10.20	3.02			6.18	0.28
Dornod	Choibalsan	2137	SFU	9.79	-1.73			6.20	0.30
Dornod	Chuluunxoroot	2140	SFU	7.60	8.52				0.00
Dornod	Dashbalbar	2119	SFU	4.10	-8.29	0.87			0.25
Dornod	Gurvanzagal	2116	SFU	8.66	3.10			5.02	0.28
Dornod	Matad	2122	SFU	5.11	3.56				0.00
Dornod	Sergelen	2125	SFU	12.50	0.09			7.27	0.30
Dornod	Xalx gol	2128	SFU	12.12	3.72				0.00
Dornod	Xo'lonbuir	2131	SFU	7.04	3.32				0.00
Dornogovi	Airag	4404	SFU	15.02	-30.32		0.29		0.32
Dornogovi	Altanshiree	4407	SFU	15.40	33.76	-1.58			0.32
Dornogovi	Dalanjargalan	4410	SFU	15.34	43.09	-1.10			0.29
Dornogovi	Delgerex	4413	SFU	14.75	3.83				0.00
Dornogovi	Erdene	4440	SFU	14.04	3.15	-1.41	0.26		0.60
Dornogovi	Ix xet	4419	SFU	11.74	-27.21		0.20		0.33
Dornogovi	Mandax	4422	SFU	9.43	-32.51		0.33		0.53
Dornogovi	O'rgon	4425	SFU	15.22	36.12	-1.70			0.41
Dornogovi	Sainshand	4401	SFU	17.72	58.02	-0.60			0.57
Dornogovi	Saixandulaan	4428	SFU	11.88	2.96	-1.07	0.25		0.65
Dornogovi	Ulaanbadrax	4431	SFU	12.97	-26.03		0.24		0.26
Dornogovi	Xatanbulag	4434	SFU	10.30	-27.36		0.20		0.49
Dornogovi	Xo'vsgol	4437	SFU	11.65	-45.99		0.36		0.56
Dundgovi	Adaacag	4804	SFU	13.82	36.52	-0.67			0.45
Dundgovi	Bayanjargalan	4807	SFU	8.83	-2.37	-0.46	0.20		0.58
Dundgovi	Cagaandelger	4840	SFU	15.61	51.59	-2.41		7.83	0.64
Dundgovi	Delgercogt	4819	SFU	15.08	27.08	-0.81		9.03	0.51
Dundgovi	Delgerxangai	4816	SFU	9.39	34.21	-1.48		5.31	0.89
Dundgovi	Deren	4822	SFU	15.21	27.80	-0.83		11.22	0.55
Dundgovi	Erdenedalai	4843	SFU	9.75	53.14	-1.00			0.77
Dundgovi	Govi-Ugtaal	4810	SFU	11.97	35.78	-0.62			0.44
Dundgovi	Gurvansaixan	4813	SFU	9.42	24.02	-0.64		4.53	0.68

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	PU	Precipitation	Winter Temp	RSQ
Dundgovi	Luus	4825	SFU	10.28	22.80	-0.66		6.84	0.75
Dundgovi	O'lziit	4828	SFU	10.26	16.37	-1.53		6.19	0.66
Dundgovi	O'ndorshil	4831	SFU	8.25	-10.59	-0.35	0.29		0.73
Dundgovi	Saintsagaan	4801	SFU	10.61	28.99	-0.47		6.73	0.73
Dundgovi	Saixan-Ovoo	4834	SFU	5.36	81.12	-1.32	-0.15		0.97
Dundgovi	Xuld	4837	SFU	11.12	48.61	-0.93			0.65
Govi-Altai	Altai	8204	SFU	12.30	47.51	-3.39			0.65
Govi-Altai	Bayan-Uul	8207	SFU	15.46	66.36	-1.32			0.72
Govi-Altai	Biger	8210	SFU	15.87	38.99	-0.76			0.38
Govi-Altai	Bugat	8213	SFU	24.22	57.19	-1.91			0.39
Govi-Altai	Ceel	8243	SFU	15.62	53.29	-1.24			0.65
Govi-Altai	Chandmani	8246	SFU	22.89	50.21	-1.30			0.47
Govi-Altai	Cogt	8240	SFU	16.65	55.73	-2.16			0.53
Govi-Altai	Darvi	8216	SFU	16.59	52.47	-0.81			0.50
Govi-Altai	Delger	8219	SFU	22.57	47.33	-1.18			0.42
Govi-Altai	Erdene	8252	SFU	18.32	36.18	-3.30	0.38		0.56
Govi-Altai	Jargalan	8222	SFU	18.20	49.30	-0.97			0.57
Govi-Altai	Sharga	8249	SFU	15.39	54.65	-1.25			0.57
Govi-Altai	Taishir	8225	SFU	19.64	54.30	-1.85			0.60
Govi-Altai	To'grog	8231	SFU	16.70	37.24	-0.88			0.32
Govi-Altai	Tonkhil	8228	SFU	13.94	34.64	-0.88			0.32
Govi-Altai	Xaliun	8234	SFU	19.03	46.02	-0.99			0.42
Govi-Altai	Xo'xmorit	8237	SFU	21.96	57.88	-1.24			0.55
Govi-Altai	Yeso'nbulag	8201	SFU	25.77	51.32	-0.79			0.40
Govisu'mber	Bayantal	4204	SFU	30.73	14.27				0.00
Govisu'mber	Shiveegovi	4207	SFU	15.97	-40.31		0.37		0.45
Govisu'mber	Su'mber	4201	SFU	17.47	-51.23		0.43		0.46
O'mnogovi	Bayan-Ovoo	4607	SFU	10.12	46.16	-1.77			0.74
O'mnogovi	Bayandalai	4604	SFU	10.25	50.81	-1.76			0.73
O'mnogovi	Bulgan	4610	SFU	12.62	50.50	-1.40			0.71
O'mnogovi	Cogt-Cecii	4643	SFU	10.99	47.26	-1.56			0.81
O'mnogovi	Cogt-Ovoo	4640	SFU	12.31	44.94	-1.45			0.67
O'mnogovi	Gurvantes	4613	SFU	10.74	33.42	-2.66	0.15		0.76
O'mnogovi	Mandal-Ovoo	4616	SFU	12.86	47.09	-0.71			0.58
O'mnogovi	Manlai	4619	SFU	10.18	34.42	-1.14			0.48
O'mnogovi	Nomgon	4625	SFU	11.13	46.13	-1.41			0.68
O'mnogovi	Noyon	4622	SFU	11.83	14.54	-1.14	0.28		0.60
O'mnogovi	Sevrei	4628	SFU	7.64	80.08	-1.19		-6.46	0.79
O'mnogovi	Xanbogd	4631	SFU	10.96	4.61				0.00

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	PU	Precipit ation	Winter Temp	RSQ
O'mnogovi	Xanxongor	4634	SFU	10.58	49.45	-1.71			0.81
O'mnogovi	Xu'rmen	4637	SFU	15.74	49.11	-1.95			0.58
O'vorxangai	Baruunbayan-Ulaan	6204	SFU	15.74	58.24	-0.93			0.60
O'vorxangai	Bat-O'lzii	6207	SFU	17.71	53.48	-1.10			0.32
O'vorxangai	Bayan-O'ndor	6213	SFU	16.14	7.36				0.00
O'vorxangai	Bayangol	6210	SFU	6.28	58.23	-0.67			0.94
O'vorxangai	Bogd	6216	SFU	13.00	48.01	-0.90			0.51
O'vorxangai	Bu'rd	6219	SFU	12.68	-3.26		0.08		0.21
O'vorxangai	Guchin-Us	6222	SFU	15.02	51.42	-0.96			0.42
O'vorxangai	Nariinteel	6231	SFU	17.35	40.81	-0.68			0.37
O'vorxangai	O'lziit	6234	SFU	15.80	49.53	-0.73			0.31
O'vorxangai	Sant	6237	SFU	11.90	59.87	-0.67			0.79
O'vorxangai	Taragt	6240	SFU	21.26	65.94	-1.02			0.54
O'vorxangai	To'grog	6243	SFU	10.49	60.99	-1.35			0.84
O'vorxangai	Uyanga	6246	SFU	17.55	57.31	-1.02			0.44
O'vorxangai	Xairxandulaan	6249	SFU	18.91	48.31	-1.24			0.34
O'vorxangai	Xarxorin	6252	SFU	16.95	6.52				0.00
O'vorxangai	Xujirt	6255	SFU	14.12	64.15	-0.84			0.59
O'vorxangai	Yeso'nzu'il	6225	SFU	15.19	46.09	-0.89			0.24
O'vorxangai	Zu'unbayan-Ulaan	6228	SFU	13.19	71.74	-1.76			0.75
Selenge	Altanbulag	4304	SFU	17.00	5.47				0.00
Selenge	Baruunbu'ren	4307	SFU	14.42	16.51			8.36	0.30
Selenge	Bayangol	4310	SFU	14.47	14.15			7.17	0.25
Selenge	Cagaannuur	4346	SFU	14.01	-68.72		0.24		0.27
Selenge	Javxlant	4316	SFU	14.42	23.52			11.73	0.42
Selenge	Mandal	4322	SFU	15.48	4.76				0.00
Selenge	Orxon	4325	SFU	23.60	7.86				0.00
Selenge	Orxontuul	4328	SFU	27.31	7.98				0.00
Selenge	Saixan	4331	SFU	13.39	13.38			5.78	0.24
Selenge	Sant	4334	SFU	15.20	7.68				0.00
Selenge	Shaamar	4349	SFU	12.82	2.42				0.00
Selenge	Tu'shig	4337	SFU	152.82	217.07			104.40	0.34
Selenge	Xu'der	4340	SFU	40.02	15.80				0.00
Selenge	Xushaat	4343	SFU	26.58	31.91			20.69	0.46
Selenge	Yero'o	4313	SFU	33.42	81.14			21.92	0.26
Selenge	Zu'unburen	4319	SFU	18.26	7.57				0.00
Su'xbaatar	Asgat	2204	SFU	5.57	26.67	-1.64			0.77
Su'xbaatar	Baruun-Urt	2201	SFU	8.52	24.50	-0.77			0.46

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	PU	Precipitation	Winter Temp	RSQ
Su'xbaatar	Bayandelger	2207	SFU	11.14	31.77	-0.66			0.28
Su'xbaatar	Dariganga	2210	SFU	8.98	29.98	-1.10			0.27
Su'xbaatar	Erdenecagaan	2237	SFU	3.59	11.94	-0.87			0.49
Su'xbaatar	Mo'nxxaan	2213	SFU	9.11	40.68	-1.57			0.73
Su'xbaatar	Naran	2216	SFU	10.15	2.45				0.00
Su'xbaatar	Ongon	2219	SFU	7.90	28.35	-0.83			0.36
Su'xbaatar	Tu'mencogt	2228	SFU	10.16	31.61	-0.91			0.65
Su'xbaatar	Tu'vshinshiree	2225	SFU	12.88	29.57	-0.55			0.27
Su'xbaatar	Uulbayan	2231	SFU	8.33	39.12	-1.06			0.71
Su'xbaatar	Xalzan	2234	SFU	8.61	42.81	-1.57			0.66
To'v	Altanbulag	4103	SFU	16.67	4.68				0.00
To'v	Argalant	4107	SFU	18.84	6.86				0.00
To'v	Arxust	4110	SFU	20.45	103.22	-1.64		11.38	0.41
To'v	Batsu'mber	4113	SFU	11.65	39.61	-0.73			0.34
To'v	Bayan	4116	SFU	22.34	49.75	-1.92			0.23
To'v	Bayan-O'njuul	4125	SFU	15.34	5.48				0.00
To'v	Bayancagaan	4131	SFU	21.12	61.87	-2.96			0.38
To'v	Bayancogt	4134	SFU	15.49	12.66			9.09	0.27
To'v	Bayandelger	4119	SFU	8.00	6.35				0.00
To'v	Bayanjargalan	4122	SFU	20.07	4.15				0.00
To'v	Bayanxangai	4128	SFU	11.68	9.03			8.30	0.31
To'v	Bornuur	4140	SFU	14.98	5.63				0.00
To'v	Bu'ren	4143	SFU	11.42	3.97	-0.57	0.17		0.48
To'v	Ceel	4173	SFU	22.18	6.53				0.00
To'v	Delgerxaan	4146	SFU	16.20	-10.64		0.13		0.24
To'v	Erdene	4176	SFU	11.02	5.63				0.00
To'v	Erdenesant	4179	SFU	14.40	-8.84		0.10		0.23
To'v	Jargalant	4149	SFU	16.69	14.03			8.21	0.26
To'v	Lu'n	4155	SFU	15.00	4.07				0.00
To'v	Mo'ngonmorit	4158	SFU	17.08	6.42				0.00
To'v	O'ndorshireet	4161	SFU	13.75	-18.59		0.13		0.23
To'v	Sergelen	4167	SFU	20.71	43.87	-2.00			0.22
To'v	Ugtaalcaidam	4170	SFU	15.81	10.62			8.36	0.26
To'v	Zaamar	4152	SFU	20.97	6.01				0.00
Ulaanbaatar	Baganuur	1101	SFU	9.55	4.00				0.00
Ulaanbaatar	Bayanzu'rx	1110	SFU	10.31	3.34				0.00
Ulaanbaatar	Nalaix	1113	SFU	9.64	3.84				0.00
Ulaanbaatar	Songinoxairxan	1116	SFU	9.55	3.62				0.00
Uvs	Baruunturuun	8504	SFU	19.68	4.70				0.00

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	PU	Precipitation	Winter Temp	RSQ
Uvs	Bo'xmoron	8507	SFU	10.13	36.59	-1.26			0.29
Uvs	Cagaanxairxan	8555	SFU	14.82	38.80	-1.07			0.34
Uvs	Davst	8510	SFU	7.31	34.02	-1.03			0.47
Uvs	Malchin	8522	SFU	11.14	31.58	-0.88			0.23
Uvs	Naranbulag	8525	SFU	9.92	44.68	-1.04			0.55
Uvs	O'lgii	8528	SFU	13.18	54.54	-0.85			0.69
Uvs	O'mnogovi	8531	SFU	15.42	43.88	-0.74			0.38
Uvs	O'ndorxangai	8534	SFU	13.56	33.61	-1.00			0.27
Uvs	Sagil	8537	SFU	9.74	34.06	-0.96			0.32
Uvs	Tarialan	8540	SFU	11.66	53.78	-2.15			0.51
Uvs	Tes	8546	SFU	7.58	-19.19		0.13		0.26
Uvs	Tu'rgen	8543	SFU	9.99	48.65	-1.64			0.51
Uvs	Xovd	8549	SFU	13.29	37.18	-0.86			0.31
Uvs	Xyargas	8552	SFU	13.24	3.40				0.00
Uvs	Zavxan	8513	SFU	12.79	55.54	-0.81			0.68
Uvs	Zu'ungovi	8516	SFU	15.00	36.45	-0.83			0.39
Uvs	Zu'unxangai	8519	SFU	13.88	31.38	-0.84			0.27
Xentii	Batnorov	2304	SFU	7.95	3.85				0.00
Xentii	Batshireet	2307	SFU	11.12	4.03				0.00
Xentii	Bayan-Adraga	2310	SFU	9.25	20.15			5.82	0.35
Xentii	Bayan-Ovoo	2316	SFU	11.61	3.26				0.00
Xentii	Bayanmo'nx	2313	SFU	11.53	-58.40		0.35		0.60
Xentii	Bayanxutag	2319	SFU	11.79	-26.84		0.15		0.34
Xentii	Binder	2322	SFU	7.96	2.63				0.00
Xentii	Cenxermandal	2349	SFU	8.69	4.63				0.00
Xentii	Dadal	2328	SFU	6.64	0.71				0.00
Xentii	Darxan	2331	SFU	12.83	41.93	-1.16			0.42
Xentii	Delgerxaan	2334	SFU	9.60	63.52	-1.59		6.98	0.61
Xentii	Galshir	2325	SFU	10.05	30.90	-1.00			0.52
Xentii	Jargaltxaan	2337	SFU	5.84	20.49	-0.48			0.41
Xentii	Mo'ron	2340	SFU	10.60	36.15	-0.65			0.52
Xentii	Norovlin	2343	SFU	7.75	8.40			4.64	0.28
Xentii	O'mnodelger	2346	SFU	7.28	5.87				0.00
Xentii	Xerlen	2301	SFU	11.39	-22.61		0.13		0.35
Xo'vsgol	Alag-Erdene	6704	SFU	10.42	1.17				0.00
Xo'vsgol	Arbulag	6707	SFU	10.89	49.08	-1.32			0.58
Xo'vsgol	Bayanzu'rx	6710	SFU	14.04	2.07				0.00
Xo'vsgol	Bu'rentogtox	6713	SFU	15.45	52.62	-1.37			0.43
Xo'vsgol	Cagaan-U'ur	6755	SFU	8.49	1.08				0.00

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	PU	Precipitation	Winter Temp	RSQ
Xo'vsgol	Cagaan-Uul	6752	SFU	16.54	49.55	-1.79			0.49
Xo'vsgol	Cagaannuur	6749	SFU	8.19	55.38			6.17	0.23
Xo'vsgol	Cecerleg	6758	SFU	15.96	14.21	-3.13	0.20		0.55
Xo'vsgol	Chandmani-O'ndor	6761	SFU	6.90	0.16				0.00
Xo'vsgol	Erdenebulgan	6767	SFU	7.50	2.06				0.00
Xo'vsgol	Galt	6716	SFU	12.90	43.79	-0.97			0.22
Xo'vsgol	Ix-Uul	6722	SFU	7.00	3.23				0.00
Xo'vsgol	Jargalant	6719	SFU	16.96	5.25				0.00
Xo'vsgol	Rashaant	6725	SFU	8.35	1.73				0.00
Xo'vsgol	Renchinlxu'mbe	6728	SFU	4.95	31.02			3.66	0.25
Xo'vsgol	Shine-Ider	6764	SFU	11.83	58.44	-1.25			0.52
Xo'vsgol	Tarialan	6731	SFU	7.15	-31.75		0.12		0.32
Xo'vsgol	To'morbulag	6737	SFU	12.11	46.21	-1.06			0.31
Xo'vsgol	Tosoncengel	6734	SFU	9.51	3.11				0.00
Xo'vsgol	Tu'nel	6740	SFU	11.71	40.87	-1.09			0.28
Xo'vsgol	Ulaan uul	6743	SFU	8.52	2.17				0.00
Xo'vsgol	Xanx	6746	SFU	8.77	2.80				0.00
Xovd	Altai	8404	SFU	17.26	41.77	-1.72			0.42
Xovd	Bulgan	8407	SFU	10.82	54.23	-0.90			0.60
Xovd	Buyant	8410	SFU	12.79	-19.45		0.19		0.25
Xovd	Ceceg	8443	SFU	13.30	0.83				0.00
Xovd	Chandmani	8446	SFU	14.69	57.80	-0.84			0.63
Xovd	Darvi	8413	SFU	20.45	47.11	-1.34			0.37
Xovd	Do'rgon	8416	SFU	14.77	45.09	-0.70			0.43
Xovd	Duut	8419	SFU	15.46	41.93	-0.86			0.39
Xovd	Erdenebu'ren	8449	SFU	12.13	53.31	-0.77			0.56
Xovd	Manxan	8425	SFU	12.99	46.05	-0.67			0.52
Xovd	Mo'nxxairxan	8428	SFU	10.87	34.58	-0.76			0.40
Xovd	Mo'st	8431	SFU	14.83	1.72				0.00
Xovd	Myangad	8434	SFU	9.85	51.70	-0.74			0.58
Xovd	U'yench	8437	SFU	12.21	43.59	-1.28			0.43
Xovd	Xovd	8440	SFU	11.13	60.11	-0.92			0.55
Xovd	Zereg	8422	SFU	16.95	40.26	-0.57			0.31
Zavxan	Aldarxaan	8104	SFU	18.36	44.42	-1.34			0.36
Zavxan	Bayantes	8110	SFU	14.28	5.08				0.00
Zavxan	Bayanxairxan	8113	SFU	13.02	4.35				0.00
Zavxan	Cagaanchuluut	8158	SFU	16.27	31.80	-0.77			0.51
Zavxan	Cagaanxairxan	8155	SFU	15.43	38.42	-1.63			0.48

Aimag	Soum	soum code	Dependent Variable	RMSE	Intercept	PU	Precipitation	Winter Temp	RSQ
Zavxan	Cecen-Uul	8161	SFU	15.58	5.61				0.00
Zavxan	Do'rvoljin	8116	SFU	10.56	36.60	-0.94		5.14	0.68
Zavxan	Erdenexairxan	8167	SFU	19.13	33.53	-0.90			0.25
Zavxan	Ider	8122	SFU	18.73	46.19	-2.77			0.36
Zavxan	Ix-Uul	8125	SFU	16.13	2.88				0.00
Zavxan	No'mrog	8128	SFU	22.85	38.03	-1.75			0.23
Zavxan	Otgon	8131	SFU	13.94	34.26	-1.33			0.40
Zavxan	Santmargac	8134	SFU	9.06	31.52	-0.36			0.57
Zavxan	Shilu'ustei	8164	SFU	17.06	39.42	-1.07			0.52
Zavxan	Songino	8137	SFU	20.99	33.72	-1.04			0.26
Zavxan	Telmen	8146	SFU	14.88	48.39	-1.75			0.51
Zavxan	Tes	8149	SFU	7.00	23.36	-0.39	0.08		0.62
Zavxan	Tosoncengel	8140	SFU	16.66	48.30	-2.81			0.40
Zavxan	Tu'devtei	8143	SFU	24.75	6.58				0.00
Zavxan	Urgamal	8152	SFU	16.39	35.49	-0.54			0.28
Zavxan	Yaruu	8170	SFU	23.04	44.97	-2.38			0.31
Zavxan	Zavxanmandal	8119	SFU	12.34	31.59	-0.74			0.54