Geospatial Assessment of Grazing Regime Shifts and Socio-political Changes in a Mongolian Rangeland

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ABSTRACT

Drastic changes have occurred in Mongolia's grazing land management over the last two decades, but their effects on rangelands are ambiguous. Temporal trends in Mongolia's rangeland condition have not been well documented relative to the effects of long-term management changes. This study examined changes in grazing land use and rangeland biomass associated with the transition from the socialist collective to the current management systems in the Tsahiriin tal area of northern Mongolia. Grazing lands in Tsahiriin tal that were formerly managed by the socialist collective are now used by numerous nomadic households with their privately-owned herds, although the lands remain publicly owned. Grazing pressure has more than tripled and herd distribution has changed from a few, spatially-clustered large herds of sheep to numerous smaller herds of multiple species. Landsat image-derived Normalized Difference Vegetation Index (NDVI) estimates suggest that rangeland biomass significantly decreased (p-value <0.001) from the collective to the post-collective periods. The observed decrease was significantly correlated with changes in the grazing management system and increased stocking density (p-values < 0.001), even when potential climate-induced changes were considered. Furthermore, field- and SPOT satellite imagery-based rangeland assessments in 2007 and 2008 indicate that current rangeland biomass is low. Spatial pattern analyses show that the low biomass is uniform throughout the study site. The observed decrease in rangeland biomass might be further accelerated, if current grazing land use continues with no formal rangeland management institution or organized, well-structured efforts by the local herding households.

KEYWORDS: grassland biomass, remote sensing, GPS, GIS, NDVI

INTRODUCTION

Extensive livestock production has been Mongolia's major industry for centuries. Mongolia is one of the most heavily grazed places in the world (Asner et al., 2005). Mongolia's livestock population continually increased throughout the 20th century, despite dramatic transitions from feudal to socialist and then democratic socio-political systems (Sankey et al., 2006), and pulses of large-scale animal losses due to severe winters and drought (Angerer et al., 2008; Tachiri et al., 2008). Most notably, the livestock population more than doubled after Mongolia became a democratic country in 1992 and began its transition into market economy (Mearns, 2004; Bohannon, 2008). The trend of increasing livestock population currently continues (Figure 1a). In the year 2007 alone, Mongolia's livestock population increased 15 percent and reached over 40 million animals (Mongolian Statistics Book, 2007). During the same time period, the total number of herding households in Mongolia also doubled (Mearns, 2004) and is currently increasing again after a short period of decline associated with increasing migration of herders to urban areas as a result of large-scale animal losses (Figure 1b) (Mongolian Statistics Book, 2007). In addition, the herding households make their own decisions regarding how many and what type of animals to herd. Mongolia has no regulatory limit on the number of animals each household can own. Taken together, these conditions make Mongolia's rangelands potentially susceptible to overgrazing.

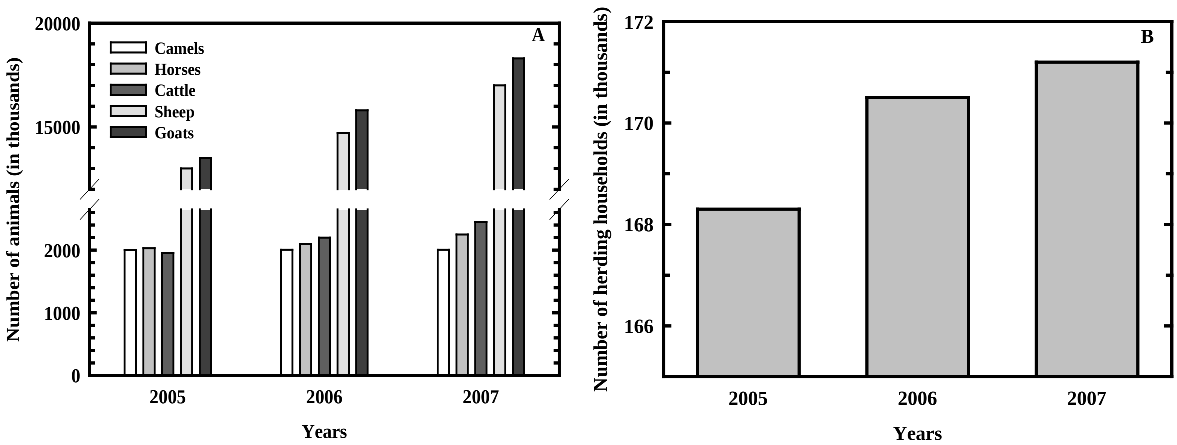

Figure 1. Livestock numbers (A) and numbers of herding households (B) from the last three years in Mongolia as examples of increasing numbers of animals and herding households since 1992 (adapted from the Mongolian Statistics Book, December 2007)

The current condition of Mongolia's rangelands and trends since the disbandment of the socialist collectives has attracted recent attention (Havstad et al., 2008), yet these issues remain largely unstudied, especially at local scales. The few nationwide studies of rangeland productivity in Mongolia (Purevdorj et al., 1998, Kogan et al., 2004, Bayarjargal et al., 2006, Erdenetuya and Khudulmur, 2008) have thus far focused on current rangeland condition only, without the analysis of long-term changes. Rangeland assessments relative to grazing land use changes are necessary to understand the recent trends in Mongolia's rangeland productivity. Moreover, some national-scale rangeland studies in Mongolia continue to suggest that rangelands are currently healthy and can support even further increase in the livestock population (Tserendash, 2008). Such recommendations are based on blurred national averages that lack the detailed documentation of correlation between grazing management changes and rangeland condition. Site-specific studies with quantified geospatial data on grazing intensity and rangeland productivity are necessary to complement national-scale studies.

This study analyzed a typical northern Mongolian rangeland using field methods and geospatial analysis tools. The objectives were to: 1) document changes in grazing land use from the collective period (pre-1992) to the post-collective period (1992-present) using GPS mapping, 2) evaluate the effects of the observed land use changes on rangeland biomass using Landsat satellite imagery acquired during the collective and post-collective periods, and 3) assess current rangeland biomass and its spatial distribution using field data and Satellite Pour l'Observation de la Terre (SPOT) satellite imagery. The decade of 1980 (1981-1990) was selected to represent the collective period and the current decade of 2000 (2001-2008) was selected to represent the post-collective period. These decades were chosen due to: 1) the absence of major socio-political and economic regime shifts during the decades, 2) the presence of a major regime shift between these decades during the decade of 1990, and 3) the availability of satellite imagery during the peak of the growing seasons (digital images prior to 1980 were not available).

The northern Mongolian rangeland examined in this study is called the Tsahiriiin tal valley. It was selected because it provides a rare opportunity with natural pastoral boundaries that limit the extent of movement by grazing animals during the typically 3-month summer season. Pasture land is publicly owned in Mongolia and not fenced or delineated for individual household use, which allows free range for all animals. Spatial boundaries in Mongolian pasture use have been described as “fuzzy, permeable, and overlapping” (Mearns, 2004 (pp 139)) and can change from year to year depending on precipitation and forage growth. This makes it difficult to delineate replicated study area boundaries in much of Mongolia’s rangelands. In this study, randomly-generated 100 point locations are used as the replicated sampling unit.

Grazing Regime Changes in Mongolia

Mongolian socialist livestock collectives were established in the 1960s and herders were paid monthly salary by the government to herd the state-owned livestock. The livestock collectives followed the traditional seasonal pastoral land use pattern. The herds grazed near rivers, lakes, and springs in the summer season for access to water and used pastures far from water in the winter months due to the availability of snow as a water source (Fernendez-Gimenez, 2002). The collectives provided well-funded infrastructure including transportation for moving camps, development of wells and water tanks in waterless pastures, supplemental feed supplies, veterinary services, travelling stores with household goods and supplies (Fernandez-Gimenez, 1999). This allowed, at a nationwide and coarser scale, better distribution of grazing land use including the use of pastures more distant from water sources and community centers. Each county had one collective with evenly distributed, large herds of a fixed size which did not vary between years or among households. Managers of the collectives made decisions regarding the timing and location of all herd movements, and coordinated all nomadic herders (Mearns, 2004). Each herd consisted of a single animal species, although a limited number of privately-owned animals of other species were allowed.

Collectives were dismantled and all formerly state-owned animals were privatized after the first democratic election in 1992 and subsequent *pastoral economic liberalization* (Fernandez-Gimenez, 1999). Although pasture land remained, and still is, publicly owned, there was no longer a state institution to formally regulate pasture use (Mearns, 2004). Herders were left to regulate their own pasture use and to pay for all expenses as the infrastructure and salary collectives provided were no longer available (Fernandez-Gimenez, 2002). At the same time, economic conditions in urban areas declined and many formerly non-herding state employees moved to the countryside to become herders with animals they acquired through privatization (FAO Crop and Grassland Service, 2008). Most herders now own a mix of cattle (includes yaks), sheep, goats, and horses, which are four of the five species of livestock traditionally found in Mongolia (with the fifth being camel) (Sankey et al., 2006).

Geospatial Tools for Rangeland Assessment

Remote sensing satellite images have been commonly used to study rangelands. Different image classification approaches and band ratios have been used to assess rangeland conditions through estimates of biomass, productivity, or vegetative ground cover (Jensen, 1996). The relative abundance of total green vegetation can be estimated using Normalized Difference Vegetation Index (NDVI) (Jensen, 1996, Montandon and Small, 2008). This index is calculated using the spectral properties of vegetation reflectance in the red (R) and near-infrared (NIR) wavelengths (Rouse et al., 1974). Green vegetation typically has low reflectance in the red portion (630 - 690 nm) of the electromagnetic spectrum due to scattering and the absorption of radiation by chlorophyll pigments, but high reflectance of the near-infrared portion of the spectrum (760 - 900 nm) by leaf mesophyll (Jensen, 1996). NDVI is expressed as (Rouse et al., 1974):

$$NDVI = \frac{NIR\ band - R\ band}{NIR\ band + R\ band} \qquad \text{(Eq. 1)}$$

NDVI values range between -1 and 1. Higher values represent greater amounts of photosynthetic vegetation (Jensen, 1996). In semi-arid grasslands, NDVI has been successfully correlated with field-based measurements of grassland biomass and some of the previously published correlation coefficients (R^2) have ranged between 0.74-0.96 (Anderson et al., 1993, Fukuo et al., 2001, Wylie et al., 2002, Zha et al., 2003, Kensuke et al., 2005). In Mongolia, several coarse-scale studies have estimated the nationwide or regional rangeland productivity using NDVI (Purevdorj et al., 1998, Bayarjargal et al., 2000, Yu et al., 2003, Yu et al., 2004, Bayarjargal et al., 2006, Erdenetuya and Khudulmur, 2008, Tachiri et al., 2008, Iwasaki, 2009). NDVI has not been commonly used for land use and land cover change detection purposes in Mongolia, although NDVI has been widely used for change detection purpose in other regions of the world (e.g., Jin and Sader, 2005, Cakir et al., 2006, Numata et al., 2007, Karnieli et al., 2008).

In addition to remote sensing, accurate GPS-based mapping of nomadic herding household distribution along with field-based vegetation and soil measurements can provide baseline data for analysis of spatial patterns of grazing use and rangeland conditions. Such spatial analysis can be used to determine whether rangelands are deteriorating or degrading (Koppel et al., 2002, Pearson, 2002, Zhong Su et al., 2006, Kefi et al., 2007, Roder et al., 2008). GPS mapping-based analyses of nomadic grazing management have not been common in Mongolia, although spatial pattern analyses of fine-scale vegetation and soil distribution have been performed (Zemmrich et al., 2007: Sasaki et al., 2008). Such geospatial analyses are crucially important in understanding rangeland health in spatially-dynamic nomadic grazing systems.

METHODS

Regional Setting and Study Area

The Tsahiriin tal valley is within Renchinlhumbe county of Khuvsgul province in northwestern Mongolia (Figure 2) and was within the Renchinlhumbe collective territory. Tsahiriin tal is approximately 5 km x 6 km in dimension (~30,000 m^2). It is at approximately 1650 m elevation and experiences extreme continental climate with cold winters, short summers, and a summer-wet, winter-dry annual precipitation pattern. Mean annual precipitation is less than 300 mm with more than half of the yearly total falling during the months of June-August. Monthly average temperatures range from less than -30 Cº in winter to close to 15 Cº in summer. Common plant species are *Poa pratensis* L., *Artemisia mongolica* (Fisch. ex Bess) Nakai, *Artemisia frigida* Willd., *Potentilla acaulis* L., and *Stipa krylovii* Roshev. The valley floor within Tsahiriin tal consists of relic alluvial channels, terraces, and plains, as well as areas with closed depressions and hummocky rises. Soil parent materials are predominantly alluvial and lacustrine sediments. Ten to twenty meters of topographic relief spans the highest landscape positions (terraces, plains, and hummocks) to the lowest (channels and depressions). Soils associated with the alluvial features include calcareous grassland soils with organic-rich surface horizons in the more well-drained positions, and similar soils with more strongly developed subsurface clay-rich horizons in the lower (and sometimes wetter) landscape positions. These soils include Typic Calcicryolls and Ustic (or Oxyaquic) Argicryolls, respectively, as classified by the United States soil classification system (Soil Survey Staff, 1998). Soils associated with the hummock/depression features include frost-churned (cryoturbated) permafrost and weakly developed non-permafrost soils. These soils are classified as Aquic Haploturbels and Ustic Eutrocryepts (Soil Survey Staff, 1998).

Tsahiriin tal is bordered to the north and south by bedrock-controlled hills with exposed limestone outcrops and herbaceous vegetation on the southerly aspects, and Siberian larch (*Larix sibirica*) forests on the northerly aspects (Figure 2). The Hogiin gol river and the Tsagaan nuur lake border the valley on the west and east, respectively. The valley is used as summer pasture only. *Gers* (traditional Mongolian tents used by herders) are located beyond the natural borders of Tsahiriin tal during the summer. However, animals from these *gers* cannot normally graze into the Tsahiriin tal valley, just as animals do not often graze out of the valley. Tsahiriin tal, therefore, encompasses an area for which stocking density can be quantified. Although a greater geographic extent might be more desirable, grazing boundaries at such scales are not feasible to determine, which makes it difficult to estimate grazing effects.

Field Methods

To assess current rangeland biomass, two seasons of field work were completed during the month of July in 2007 and 2008. Prior to field work, 100 random points were generated across the Tsahiriin tal area using Hawth's tool in ESRI® ArcMap™ 9.2 software [ESRI Inc, 1999-2006]. The same set of points were visited each year by navigating with a Trimble GeoXT GPS receiver with ± 3 m real-time horizontal accuracy. At each point, estimates of percent cover of litter, herbaceous cover, bare soil, and rock (coarse fragments > 75 mm) were made within a 10 m by 10 m plot centered on the point and aligned in the cardinal directions. Point-intercept method was used along two, 10 m line transects that were oriented perpendicular to each other and intersected at the center of the plot at 5 m along each transect. Observations were recorded at every 20 cm along each 10 m line, beginning at 10 cm and ending at 990 cm, to indicate the cover type at the point. This resulted in 100 point measurements for each plot. All herbaceous plants within a 0.44 m^2 cable hoop randomly tossed within each quadrant of each plot were clipped and weighed to estimate average standing plant biomass (henceforth referred to as biomass) for each plot. A total of 108 bags of biomass samples were randomly selected from the set of all samples across the study site. These samples were dried to estimate the weight difference between wet and dry biomass samples. On average, 49.96 % (SD±5.02) of the weight was lost during drying. This difference was subtracted from all wet weights to convert the wet biomass estimates to dry biomass estimates. At each plot, a soil profile was described to evaluate the surface and first subsurface horizon thickness, color, and structure.

Topography was classified into one of three possible classes at each plot: convex (water-shedding), level, or concave (water-collecting).

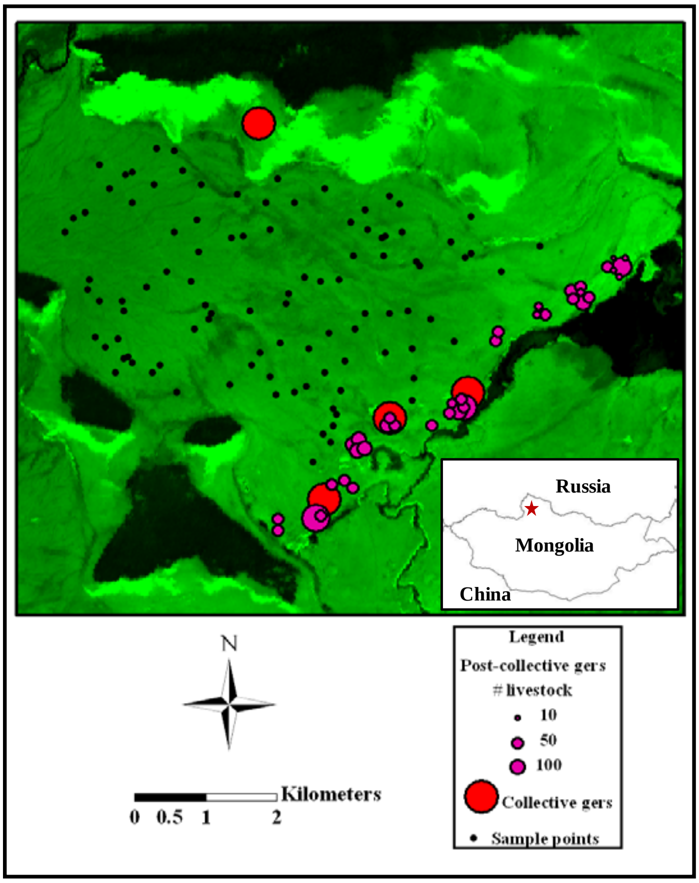

Figure 2. The documented *ger* or household distribution during the collective and post-collective periods at the Tsahiriin tal study site in Mongolia (inset).

The location of the households currently camped in the Tsahiriin tal valley and their grazing distribution was documented by mapping the summer camps or *gers* in the summer of 2007 using a Trimble GeoXT GPS receiver. The name of each household was acquired during mapping. Their livestock numbers were then obtained from local government tax records. In the summer of 2008, a collective-period veterinarian from Tsahiriin tal was interviewed regarding the herd size and distribution during the collective period (Maruush, July 15, 2008, personal communication). A map of the collective-period household locations with associated herd sizes was produced with the veterinarian's assistance.

Image Analysis

Landsat-4 Thematic Mapper (one image) and Landsat-5 Thematic Mapper (five images) images from the peak of six different growing seasons were acquired to assess changes in rangeland biomass (objective 2). Three of the images represent the collective period (dated July 23, 1986; August 17, 1989; and July 19, 1990) and three represent the post-collective period (dated August 9, 2001; July 20, 2002; and July 17, 2007). In addition, SPOT-4 satellite imagery (acquired on August 8, 2007) and SPOT-5 imagery (acquired on August 9, 2008) were used to assess current rangeland biomass (objective 3). All images were corrected for atmospheric effects using Idrisi's ATMOSC module (based on Chavez (1996) cos(t) model) and were projected in UTM Zone 47 North with WGS 1984 datum. Each image was co-registered to a georectified SPOT-4 image with 20 m x 20 m resolution (root mean squared error ranged between 0.43 - 0.96 meters) using ArcMap 9.2 software. All images were then subset to the Tsahiriin tal area. NDVI was estimated in each image subset using ENVI software (ENVI Version 4.3, ITT Industries Inc, 2006, Boulder, CO). NDVI values at the 100 random points were then extracted for statistical analysis.

GIS Data Sets

A shapefile of the 100 random points was created using ArcMap 9.2 software and each point was assigned attributes of: field-based estimates of biomass and percent cover of green vegetation in 2007 and 2008, SPOT image-derived NDVI values from 2007 and 2008, and Landsat image-derived NDVI values from 1986, 1989, 1990, 2001, 2002, and 2007. In addition, attributes describing the current stocking density as well as the collective-period stocking density were created using the *ger* maps from the two periods. Stocking density attributes were derived by generating six concentric buffer rings around each *ger*. The buffer rings were each 1 km wide and increased in circumference with increasing distance from each *ger*. The ring closest to each *ger* (i.e. the innermost ring) was classified as having the greatest stocking density, while the remaining rings were classified with decreasing stocking density as distance from the *ger* increased. The assumption that stocking density was greatest within the rings closest to the *gers* and decreased with increasing distance away from the *gers* was made, because all animals, except for horses, are brought to camp every night for milking, shelter, and protection from predators. Animals also spend a portion of each morning grazing adjacent to the camp, before herders herd them to farther reaches of the valley for the day. Next, the area of each buffer ring was calculated and the number of animals owned by each household was divided by this area to estimate the animal density per square km within each buffer ring. The concentric buffer rings radiating away from each *ger* eventually overlap with other buffers from the neighboring *gers.* Therefore, the animal densities from all overlapping buffer rings of all neighboring *gers* were added to estimate the total animal density per square km throughout the entire Tsahiriin tal valley. The resulting zonal attributes were converted to a raster format with 28.5 m resolution. The estimated stocking density at the 100 random points were then extracted for statistical analysis.

STATISTICAL ANALYSIS

Collective versus Post-collective Change Analysis

The 1986, 1989, and 1990 Landsat NDVI values at each sample point were averaged to produce a mean value for the collective period at each point location. Means were similarly calculated for the post-collective period using the 2001, 2002, and 2007 Landsat NDVI values. The mean NDVI values at the 100 sample locations from the two periods were then compared using analysis of variance (ANOVA) test (SPSS 14.0 for Windows, 2005) to assess changes in rangeland biomass between the collective and post-collective periods. In addition, a simple regression model was developed using all Landsat NDVI values from the six growing seasons as a response variable and the grazing management systems from the two periods as a categorical predictor variable. A separate regression model was also developed using all Landsat NDVI values as a response variable and the estimated stocking densities at the 100 random locations during the two periods as a predictor variable.

A climate dataset from our study region since 1980 indicates that mean annual temperatures have increased from 1980-present, albeit with substantial inter-annual variability (Figure 3a), while total annual precipitation has fluctuated without a substantial positive or negative trend during the same time period (Figure 3b). The increasing temperatures and fluctuating precipitation probably had some effects on the observed Landsat NDVI values in addition to the effects of grazing management changes. Propastin et al. (2007) report strong positive correlation between AVHRR NDVI data and temperature and precipitation at all scales in Central Asian rangelands in Kazakhstan. We acquired AVHRR Pathfinder NDVI time-series data (NOAA/NASA EOS-WEBSTER) from August of 1982-2002 (with 1995, 1996, and 1997 missing). We selected a 1225 km^2 area (35 km x 35 km pixel) centered over the study site from each year to construct an annual NDVI time-series dataset for the peak of the growing season from 1982-2002 (Figure 3c). A linear regression trendline was fit to the AVHRR Pathfinder NDVI dataset (R^2=0.10). The regression slope indicated a 0.0019 increase in NDVI per year (Figure 3c), which was assumed to reflect changes in NDVI due to climate effects. The observed Landsat NDVI values from the six years were adjusted to remove the climate-related trend (i.e., regression slope) observed in the AVHRR time-series. The adjusted NDVI values were then averaged to produce an adjusted mean value for the collective and post-collective periods at each point location. These adjusted mean values from the two periods were again compared using an ANOVA test (SPSS 14.0 for Windows, 2005) to examine the effects of grazing management changes.

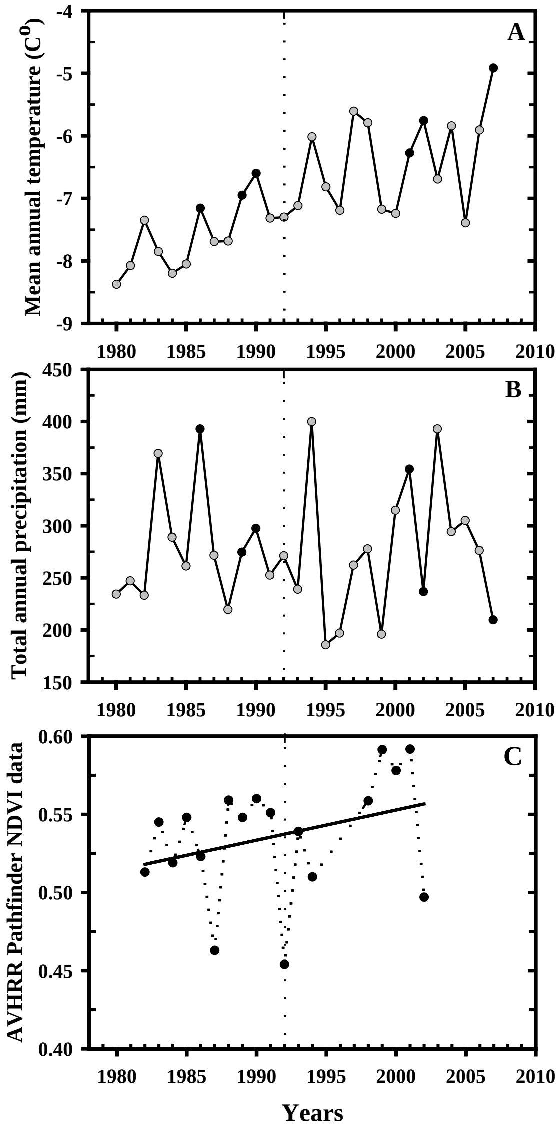

Figure 3. Mean annual temperatures (A) and total annual precipitation (B) in 1980-2007 for Renchinlhumbe county, Khuvsgul province, Mongolia. The six years selected for this study are marked with black circles. Dashed line marks the regime shift in 1992 from collective to post-collective periods. The AVHRR NDVI time-series data from the study region beyond the Tsahiriin tal valley and its long-term trend (C) was used to adjust the Landsat NDVI values for potential climate-induced effects.

Current Rangeland Biomass

We used field-based biomass estimates and SPOT NDVI estimates individually as the response variables to represent rangeland biomass in separate regression models. Field-based biomass estimates were predicted as a function of stocking density, topographic classes, and surface soil horizon thickness. SPOT NDVI values were predicted as a function of the same predictor variables using separate linear regression models. Field-based biomass estimates from 2007 and 2008 were not strongly correlated with SPOT NDVI estimates (*p*-value = 0.432 in 2007 and *p*-value <0.0001 and adjusted R^2=0.13 in 2008). Field-based and image-based estimates, therefore, could not be used to predict one another.

Exploratory spatial pattern analysis was performed to evaluate the spatial distribution of the field biomass estimates and SPOT NDVI values. Field biomass measurements and SPOT NDVI estimates from 2007 and 2008 were examined using Moran's *I* to determine whether their distribution was spatially clustered, random, or uniform. Moran's *I* index was estimated using the Euclidian distance method with inverse distance relationship in ArcMap 9.2 software. A *Z*-score was also estimated to determine the statistical significance of the estimated *I*. Moran's *I* values close to -1 indicate a uniform pattern, values close to 0 indicate a random pattern, and values close to 1 indicate a clustered pattern (O'Sullivan and Unwin, 2003). Getis-Ord general *G* with a Z score (significance level of 0.01) was additionally used to determine if high and low field biomass estimates and NDVI estimates were spatially clustered across the study site. In Getis-Ord analysis, a Z score close to 0 indicates that there is no clustering, a positive Z score indicates clustering in the high values, and a negative Z score indicates clustering in the low values.

RESULTS

Changes in Grazing Land use and Rangeland Biomass

The Tsahiriin tal valley has been used as summer pasture during the collective and post-collective periods. During the collective period, the valley was predominantly grazed by sheep with 360 Animal Units (AU) (each AU equals one cow and calf pair) for three months a year. There were four collective-owned sheep flocks herded by four households. Each herd included 450 animals of which 20-30 were goats (Table 1). The collective was dismantled in 1992. The valley is currently used by 34 households (Figure 2) for approximately three months a year and is grazed by 1191 AU consisting of cattle (includes yaks), sheep, goats, and horses (Table 1).

Table 1. Summary of livestock population in Tsahiriin tal during the collective and post-collective period

Total number	Collective period	Post-collective period
Sheep	1680	1169
Goats	120	755
Cattle	0	613
Horses	0	161
Total livestock	1800	2698
Total Animal Units	360	1191
Households	4	34

The first ANOVA model (comparing the observed NDVI values) indicated that the post-collective, observed Landsat NDVI values were significantly lower than the observed Landsat NDVI values from the collective period (p-value <0.0001) (Figure 4a). The second ANOVA model (comparing the adjusted NDVI values) indicated that the adjusted Landsat NDVI values from the post-collective period were also significantly lower than those from the collective period (p-value < 0.0001) (Figure 4b). The simple regression models both indicated statistically significant negative effects of grazing management changes and increasing stocking densities on NDVI (*p*-values <0.001), although the coefficients of determination were low (adjusted R^2 of 0.14 and 0.03, respectively).

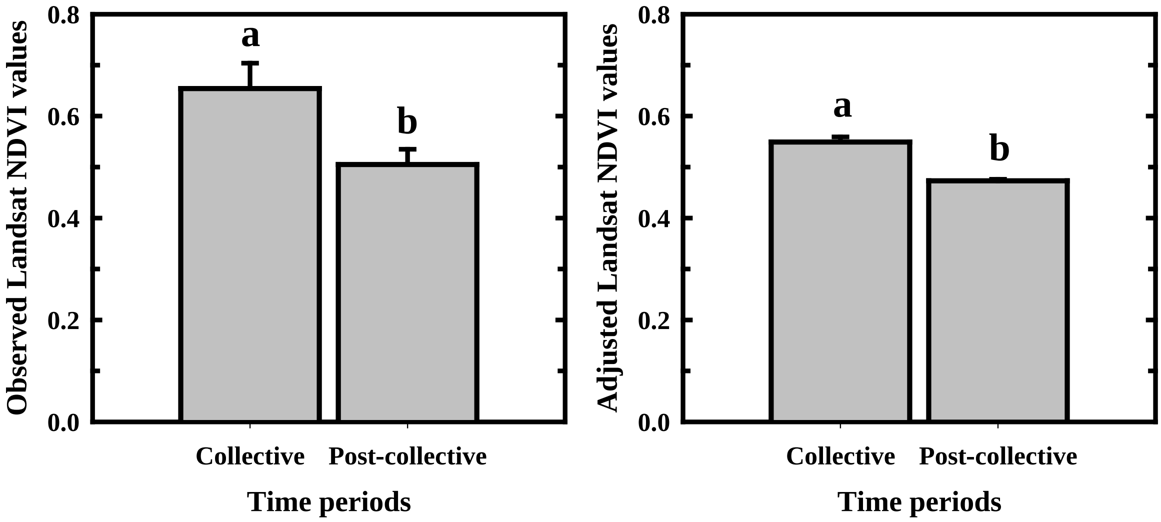

Figure 4. Estimated (A) and adjusted (B) Landsat-derived mean (with standard error) Normalized Difference Vegetation Index (NDVI) values from the collective and post-collective periods. Different letters indicate statistically significant differences at a significance level of 0.05.

Current Rangeland Biomass

Mean field-based green vegetation cover was 68 percent (SD±11.8) in 2007 and 49 percent (SD±7.6) in 2008. Field-based estimates of average dry forage was 712 kg/ha in 2007 and 605 kg/ha in 2008 in Tsahiriin tal. Field-based biomass estimates were not significantly correlated, in both years, with topography (*p*-values = 0.28 and 0.42) or thickness of the surface and first subsurface soil horizons (*p*-values = 0.283 and 0.789). In 2007, field-based biomass estimates were not significantly correlated with stocking density (*p*-value = 0.858), but the correlation was significant in 2008 (*p*-value = 0.035) with a low adjusted R^2 of 0.035. Moran's *I* for both years indicated a random spatial pattern (*I* = 0.004 and 0.017, Z-score = 0.01 and 0.10, for 2007 and 2008, respectively). The Getis-Ord general *G* index indicated no clustering in both years (0.0006 and 0.009 with a Z-score of -0.61 and 0.005, respectively).

The estimated mean SPOT NDVI values were 0.193 (SD±0.06) and 0.406 (SD±0.05) in 2007 and 2008, respectively. SPOT NDVI was not significantly correlated with topography (*p*-value = 0.650) or stocking density (*p*-value = 0.787) in 2007, but was significantly correlated with topography (*p*-value = 0.027) and stocking density (*p*-value = 0.054) in 2008 with an adjusted R^2 of 0.11. SPOT NDVI values were not correlated, in either year, to surface soil horizon thickness (*p*-value 0.098 and 0.56). Moran's *I* indicated a completely random pattern for SPOT NDVI values for both years (*I* = 0.25 with a Z-score of 0.05, and *I* = 0.0001 with a Z-score of 0.000, for 2007 and 2008, respectively). The Getis-Ord general *G* index also indicated a random pattern for SPOT NDVI values (0.0005 with a Z-score of -0.37 in 2007 and 0.004 with Z-score of 0.001 in 2008.

DISCUSSION

Grazing Land use Changes and their Effects on Rangeland Biomass

Three major changes were observed in Tsahiriin tal when the collective-period grazing land use was compared to the current grazing land use (Table 1 and Figure 2). First, during the collective period, livestock grazing was distributed in a few localized clusters of equally-sized large herds within the geographic extent of our study site, while it is now distributed more evenly throughout the valley with numerous smaller herds. The collective management maintained a small group of four households in the valley, whereas nomadic herders can now freely migrate to Tsahiriin tal resulting in a much larger number of households. Similar to other areas of Mongolia, this change in Tsahiriin tal is associated with increased number of herding households (Bedunah and Schmidt, 2004). One possible effect of this change on the rangeland might be a decrease in length of recovery time for the plants between grazing events (Voisin 1988, Savory 1999). Numerous smaller herds represent a continuous grazing system, in which plants are frequently grazed with little recovery time between grazing events. In contrast, fewer, larger herds, such as during the collective period, more closely emulate a high intensity grazing system, in which plants receive a relatively longer recovery period between more intense grazing events.

Secondly, the grazing animal species composition changed in Tsahiriin tal from herds of predominantly a single species of livestock (sheep) to four different species of livestock (cattle, sheep, goats, and horses). Although sheep remains a proportionally large component of the current herds, our livestock survey from Tsahiriin tal indicates that the number of goats is now fairly close to the number of sheep due to increased cashmere prices in Mongolia and China. Furthermore, the number of cattle has increased, which has the greatest proportional impact on the changes in total Animal Units from the collective to the post-collective period. Such changes in herd composition are known to have substantially different effects on the grazed vegetation community because different grazing animal species prefer different plant species (Vallentine, 2001). Lastly, the stocking density in the Tsahiriin tal valley has increased by over 800 Animal Units, which has more than tripled the grazing pressure from the collective period. This trend is similar to the observed patterns in other areas of Mongolia (UNEP, 2002, Bedunah and Schmidt, 2004, Bohannon, 2008) as well as the national trend over the last 15 years (Damdinsuren et al., 2008).

These changes appeared to correspond with a decrease in rangeland biomass as measured by a significant decrease in Landsat NDVI values even when potential climate-induced effects were taken into consideration. In particular, the decrease in rangeland biomass was significantly correlated with the changes in grazing management and increased stocking density in the Tsahiriin tal valley. This trend of decreased rangeland biomass might be occurring at many other locations in Mongolia where increased livestock numbers are documented (UNEP, 2002, Bedunah and Schmidt, 2004, Bohannon, 2008). Furthermore, a similar trend might have dominated across the entire country over the last two decades since the livestock population has doubled nationwide with the socio-economic and political changes (Figure 1). However, long-term trends since the collective period have not been examined at the national scale. Only the deteriorating conditions in areas surrounding major urban areas have been documented (Mearns, 2004, FAO Crop and Grassland Service, 2008), while less populated rural areas are mostly unstudied.

Current Rangeland Biomass

Tsahiriin tal had less than half of the average biomass in an ungrazed enclosure (35 years of no grazing, 17 km from Tsahiriin tal), which was sampled as a potential reference site (1,876 kg per ha), although with no formal statistical comparison because of limited sample size within the enclosure. The observed, relatively low rangeland biomass in Tsahiriin tal was not strongly correlated to any of the other local variables measured. Most importantly, current biomass was not correlated to the estimated stocking density. Rangeland biomass was expected to increase with increasing distance away from camps (Kensuke et al., 2005), where stocking density was estimated to be lower. This pattern was not found, however, which might indicate that grazing pressure was high not only near camp sites, but throughout the entire Tsahiriin tal valley. Furthermore, greater biomass was expected in the small, wet depressions and swales which were common across the study site. These water-collecting landscape positions tended to have slightly thicker soil A-horizons, suggesting that they might have historically been locations of greater biomass. However, results indicated these locations to be equally grazed relative to the others. Spatial pattern analysis also showed that the current low biomass is evenly distributed throughout the valley, with no spatial clustering of low or high biomass estimates, and no directional increase or decrease in biomass with distance from camps. Taken together, our results indicate that the drastic increase in grazing pressure might have overwhelmed the effects of other local factors resulting in uniformly heavily grazed rangelands with little variability in biomass. This lack of variability in biomass might have contributed to the low correlation between field-based biomass estimates and NDVI values. NDVI correlation with field biomass has been low (R^2 ranges 0.05-0.4) in other studies in heavily grazed areas (Numata et al., 2007, Yang et al., 2009).

The current low biomass in Tsahiriin tal is consistent with nationwide trends documented in Mongolia (Damdinsuren et al., 2008). The United Nations Environment Programme statement on Mongolia's environmental health (2002) indicates that over 70% of Mongolia's rangeland is degraded due to overgrazing. Interestingly, there are rangeland assessments which continue to suggest that Mongolian rangelands are currently healthy and can support an even greater number of animals than the current population of 65 million animals in sheep units (a conversion, used in Mongolia, of all livestock species into a single species) (Mongolian Statistics Book, 2007). Tserendash's review (2008) of Mongolian rangeland assessment, for example, indicates that it can support 86 million animals in sheep units. Results from Tsahiriin tal, however, clearly indicate that the changes in grazing pressure and grazing management since disbandment of the socialist collectives have already had significant impact on rangeland biomass.

CONCLUSIONS

Major changes in grazing land use management have had significant effects on rangeland biomass in Tsahiriin tal of northern Mongolia. Rangeland biomass has significantly decreased in the post-collective period relative to the collective period, and low biomass appears currently wide spread and predominant throughout the valley. The Tsahiriin tal rangeland biomass might further decline, if current rangeland use continues without either formal government-led management or organized, well-structured efforts by the local herding households. Some nationwide, coarse-scale rangeland assessments continue to suggest that Mongolian rangelands are healthy given the current grazing regime and can support even greater numbers of livestock than the current size. This study provides evidence from one northern Mongolian rangeland where such recommendations should not apply. Mongolian national-level rangeland management might benefit from more studies that examine local, site-specific effects on rangelands of the regime shift that has occurred with the transition from socialist to democratic socio-political systems.

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