Geospatial Assessment of Grazing Regime Shifts and Sociopolitical 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 estimates suggest that rangeland biomass significantly decreased ($P < 0.001$) from the collective to the postcollective periods. The observed decrease was significantly correlated with changes in the grazing management system and increased stocking density ($P < 0.001$), even when potential climate-induced changes were considered. Furthermore, field- and Satellite Pour l'Observation de la Terre 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.

Resumen

El manejo del pastoreo en Mongolia ha cambiado drásticamente en las últimas dos décadas, pero su influencia sobre los pastizales naturales es ambigua. La tendencia temporal en la condición de los pastizales naturales de Mongolia en relación con los efectos de largo plazo provocados por los cambios en el manejo no ha sido bien documentada. Este estudio examinó los cambios en el uso de las tierras de pastoreo y la biomasa del pastizal asociados a la transición del sistema socialista colectivo a los sistemas de manejo actuales en el área de *Tsahiriin tal* del norte de Mongolia. Las tierras de pastoreo en *Tsahiriin tal* que anteriormente eran manejadas bajo el sistema socialista colectivo ahora son utilizadas por numerosas familias nómades que poseen hatos privados; las tierras, no obstante, siguen siendo de propiedad pública. La presión de pastoreo se ha más que triplicado y la distribución de los hatos ha cambiado de unas pocas grandes majadas de ovejas espacialmente agrupadas, a numerosos hatos pequeños de múltiples especies. Estimaciones basadas en el Índice Verde Normalizado (IVN) derivado de imágenes Landsat sugieren que la biomasa de los pastizales decreció significativamente (valor de $P < 0.001$) entre la época del manejo colectivo y los períodos de manejo post- colectivos. La disminución observada estuvo significativamente correlacionada con los cambios en el sistema de pastoreo y con el incremento en la densidad del pastoreo (valores de $P < 0.001$), aun considerando potenciales cambios inducidos por el clima. Es más, mediciones en el terreno y estimaciones realizadas a partir de imágenes satelitales SPOT en 2007 y 2008 indican que la biomasa actual de los pastizales es baja. El análisis de los patrones espaciales demuestra que los niveles bajos de biomasa son uniformes a lo largo del área de estudio. La reducción observada en biomasa de pastizales podría acelerarse aun más si el uso de las tierras de pastoreo continúa sin una institución formal de manejo de pastizales o sin esfuerzos organizados y bien estructurados por parte de las familias de pastores a nivel local.

Key Words: GIS, GPS, grassland biomass, NDVI remote sensing

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 sociopolitical 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

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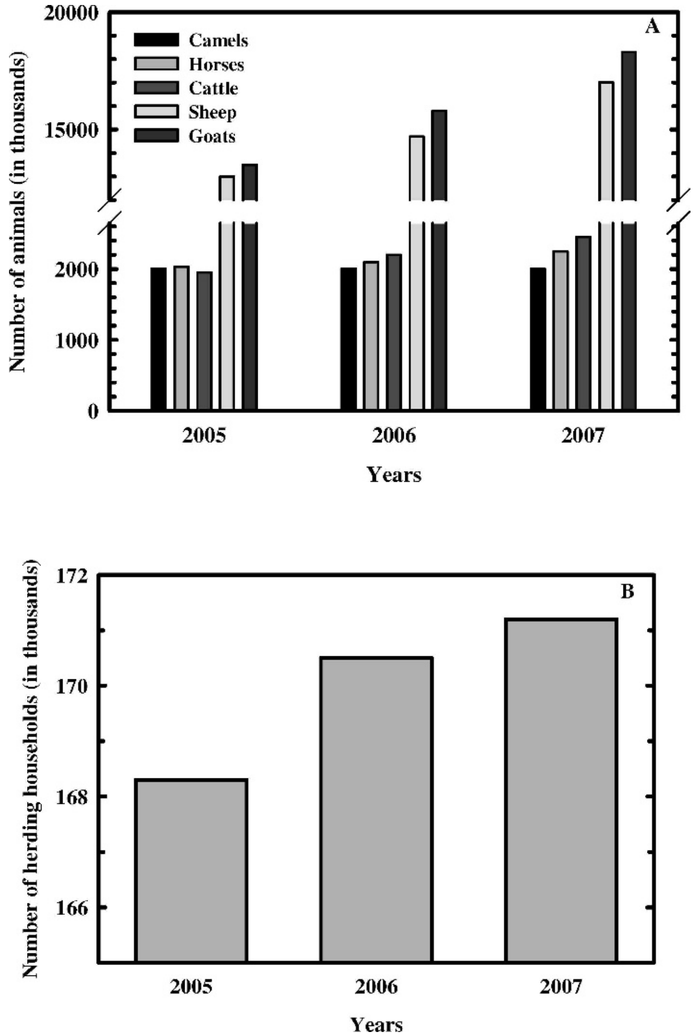

Figure 1. A, Livestock numbers and **B**, numbers of herding households from the last 3 yr in Mongolia as examples of increasing numbers of animals and herding households since 1992 (adapted from the Mongolian Statistics Office 2007).

continues (Fig. 1A). In the year 2007 alone, Mongolia's livestock population increased 15% and reached over 40 million animals (Mongolian Statistics Office 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 (Fig. 1B; Mongolian Statistics Office 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.

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 biomass 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 postcollective period (1992–present) using global positioning system (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 postcollective period. These decades were chosen because of 1) the absence of major sociopolitical 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 Tsahiriin tal Valley. It was selected because it provides a unique opportunity with natural pastoral boundaries that limit the extent of movement by grazing animals during the typically 3-mo-long 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 [p. 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 a 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 because of the availability of snow as a water source (Fernendez-Gimenez 2002). The collectives provided a well-funded infrastructure including transportation for moving camps, development of wells and water tanks in waterless pastures, supplemental feed supplies, veterinary services, and 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 nonherding state employees moved to the countryside to become herders with animals they acquired through privatization (Food and Agriculture Organization [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 the normalized-difference vegetation index (NDVI; Jensen 1996). 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 R band (630–690 nm) due to radiation absorption by chlorophyll pigments, but high reflectance in the NIR band (760–900 nm) due to scattering by leaf mesophyll (Jensen 1996). NDVI is expressed as the following (Rouse et al. 1974):

$$\mathrm{NDVI} = \frac{\mathrm{NIRband} - \mathrm{Rband}}{\mathrm{NIRband} + \mathrm{Rband}} \quad [1]$$

NDVI values range between -1 and 1. Higher values represent greater amounts of photosynthetic vegetation (Jensen 1996). In semiarid 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 and 0.96 (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, 2006; Yu et al. 2003, 2004; 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 purposes 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; Zhong Su et al. 2006; Kefi et al. 2007). 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 (Fig. 2) and was within the Renchinlhumbe collective territory. Tsahiriin tal is approximately 5×6 km in dimension ($\sim$30 000 m^2). It is at approximately 1 650 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°C in winter to close to 15°C 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 meters to 20 m 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 US soil classification system (Soil Survey Staff 1998). Soils associated with the hummock/depression features include frost-churned (cryoturbated) permafrost and weakly developed nonpermafrost 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

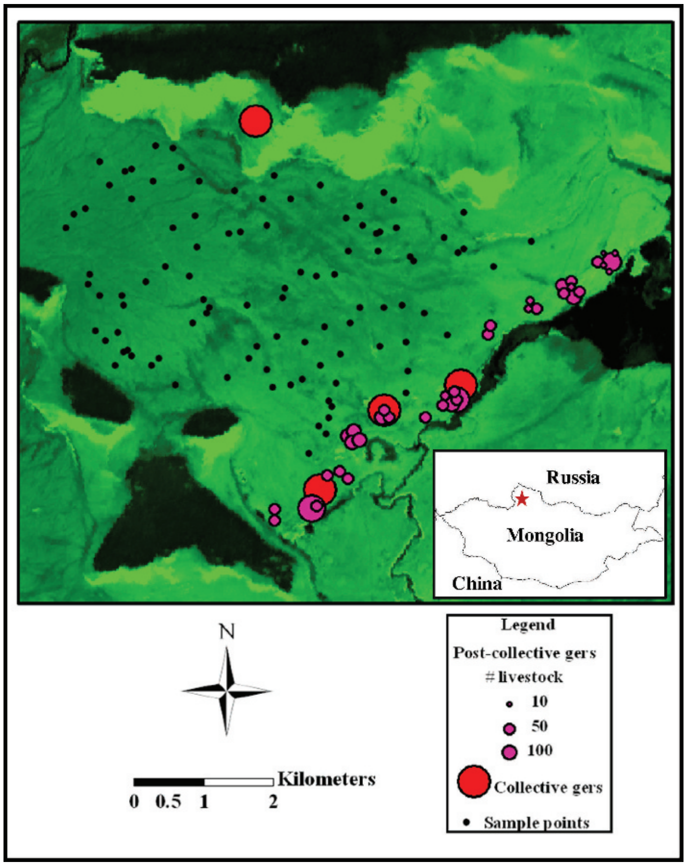

Figure 2. The documented *ger* (household) distribution during the collective and postcollective periods and study sampling locations in the Tsahiriin tal Valley. Inset shows location (star) of the study within Mongolia. The Tsahiriin tal Valley is shown in July 2007 Satellite Pour l'Observation de la Terre image green (G = 0.50–0.59 μm) and red (R = 0.61–0.68 μm) bands displayed as a GRG true color composite in 20-m resolution. The light green features in the image are rock outcrops and bare ground patches, generally located on south-facing hill slopes. The valley's grasslands are the intermediate green tones that predominate throughout the image. The darkest features are Tsagaan nuur Lake (right side of the image) and Siberian larch (*Larix sibirica*) forests, generally on north-facing hill slopes (near the top, bottom, and left edges of the image).

vegetation on the southerly aspects, and Siberian larch (*Larix sibirica* Ledeb.) forests on the northerly aspects (Fig. 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, Redlands, CA). 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 percentage of cover of litter, herbaceous cover, bare soil, and rock (coarse fragments > 75 mm) were made within a 10 × 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% (± 5.02 SD) 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).

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, personal communication, July 2008). 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 23 July 1986, 17 August 1989, and 19 July 1990) and three represent the postcollective period (dated 9 August 2001, 20 July 2002, and 17 July 2007). In addition, SPOT-4 satellite imagery (acquired on 8 August 2007) and SPOT-5 imagery (acquired on 9 August 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's [1996] COS[T] model) and were projected in Universal Transverse Mercator Zone 47 North with World Geodetic System 1984 datum. Each image was coregistered to a georectified SPOT-4 image with 20 × 20 m resolution (root mean squared error ranged between 0.43 m and 0.96 m) 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, 2006; ITT Industries Inc, Boulder, CO). NDVI values at the 100 random points were then extracted for statistical analysis.

Geographic Information Systems Data Sets

A shapefile of the 100 random points was created using ArcMap 9.2 software and each point was assigned attributes of the following: field-based estimates of biomass and percentage of 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, and 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 kilometer within each buffer ring. The concentric buffer rings radiating away from each *ger* eventually overlapped 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 kilometer throughout the entire Tsahiriin tal Valley. The resulting zonal attributes were converted to a raster format with 28.5-m resolution. The estimated stocking densities at the 100 random points were then extracted for statistical analysis.

Statistical Analysis

Collective vs. Postcollective 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 postcollective 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 an analysis of variance (ANOVA) test (SPSS 14.0 for Windows; SPSS, Chicago, IL) to assess changes in rangeland biomass between the collective and postcollective 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 data set from our study region since 1980 indicates that mean annual temperatures have increased from 1980 to present, albeit with substantial interannual variability (Fig. 3A), while total annual precipitation has fluctuated without a substantial positive or negative trend during the same time period (Fig. 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 Advanced Very High Resolution Radiometer (AVHRR) NDVI data and temperature and precipitation at all scales in the Central Asian rangelands of Kazakhstan. We acquired Pathfinder AVHRR NDVI time-series data (NOAA/NASA EOS-WEBSTER) from August of 1982 to 2002 (with 1995, 1996, and 1997 missing). We selected a 1 225-km^2 area (35×35 km pixel) centered over our study site from each year to construct an annual NDVI time-series data set for the peak of the growing season from 1982 to 2002 (Fig. 3C). A linear regression trend line was fit to the AVHRR NDVI dataset ($R^2 = 0.10$). The regression slope indicated a 0.0019 increase in NDVI per year (Fig. 3C), which was assumed to reflect changes in NDVI due to climate effects. The observed Landsat NDVI values from the 6 yr were adjusted to remove the climate-related trend (i.e., the regression slope) observed in the AVHRR NDVI time series. The adjusted Landsat NDVI values were then averaged to produce an adjusted mean value for the collective and postcollective 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) to examine the effects of grazing management changes.

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 ($P = 0.432$ in 2007 and $P < 0.0001$ 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

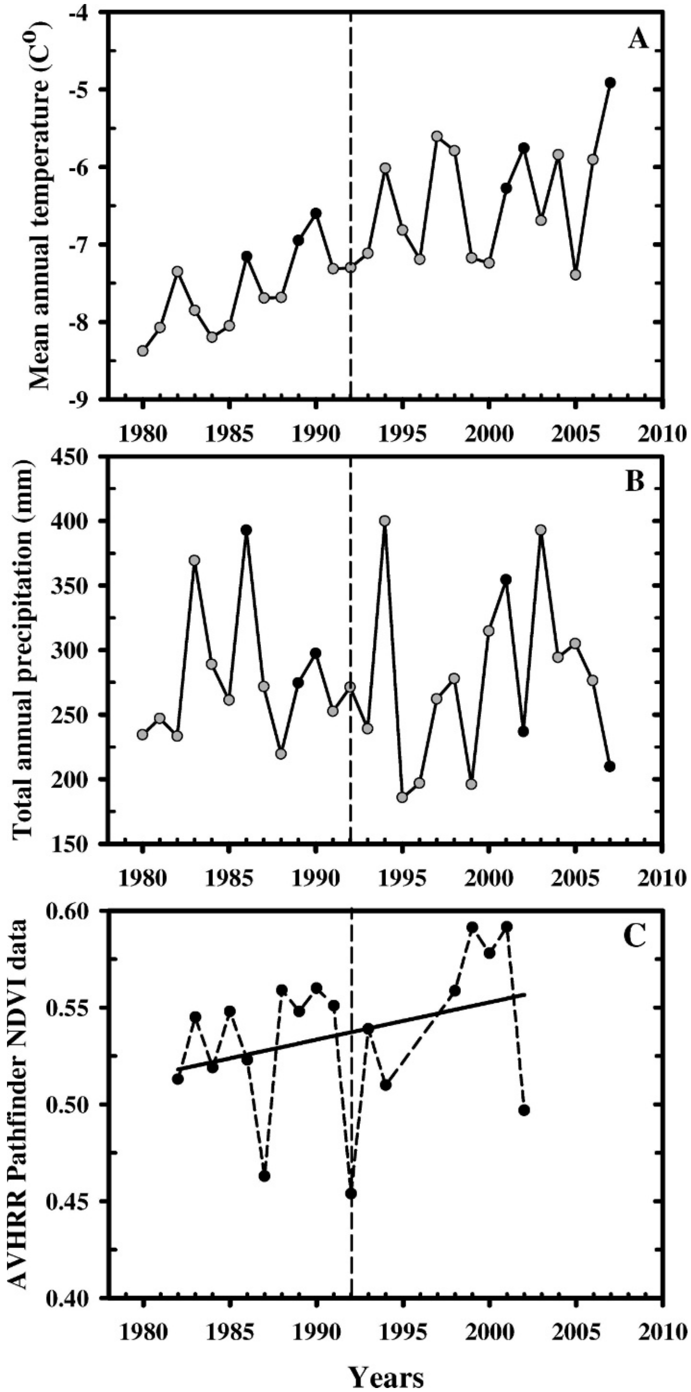

Figure 3. A, Mean annual temperatures and **B,** total annual precipitation in 1980–2007 for Renchinlhumbe County, Khuvsgul Province, Mongolia. The 6 yr selected for this study are marked with black circles. A dashed line marks the regime shift in 1992 from collective to postcollective periods. **C,** The Advanced Very High Resolution Radiometer (AVHRR) normalized-difference vegetation index (NDVI) time-series data from the study region beyond the Tsahiriin tal Valley and its long-term trend was used to adjust the Landsat NDVI values for potential climate-induced effects.

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.

Table 1. Summary of livestock population and herding households in Tsahiriin tal during the collective and postcollective period.

Total number	Collective period	Postcollective period
Sheep	1 680	1 169
Goats	120	755
Cattle	0	613
Horses	0	161
Total livestock	1 800	2 698
Total animal units	360	1 191
Households	4	34

RESULTS

Changes in Grazing Land Use and Rangeland Biomass

The Tsahiriin tal Valley has been used as summer pasture during the collective and postcollective periods. During the collective period, the valley was predominantly grazed by sheep with 360 animal units (AU; each AU equals one mature cow) for 3 mo per 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 (Fig. 2) for approximately 3 mo per year and is grazed by 1 191 AU consisting of cattle (includes yaks), sheep, goats, and horses (Table 1).

The first ANOVA model (comparing the observed NDVI values) indicated that the postcollective observed Landsat NDVI values were significantly lower than the observed Landsat NDVI values from the collective period ($P < 0.0001$; Fig. 4A). The second ANOVA model (comparing the adjusted NDVI values) indicated that the adjusted Landsat NDVI values from the postcollective period were also significantly lower than those from the collective period ($P < 0.0001$; Fig. 4B). The simple regression models both indicated statistically significant negative effects of grazing management changes and increasing stocking densities on NDVI ($P < 0.001$), although the coefficients of determination were low (adjusted R^2 of 0.14 and 0.03, respectively).

Current Rangeland Biomass

Mean field-based green vegetation cover was 68% (± 11.8 SD) in 2007 and 49% (± 7.6 SD) in 2008. Field-based estimates of average dry forage was 712 $kg \cdot ha^{-1}$ in 2007 and 605 $kg \cdot ha^{-1}$ in 2008 in Tsahiriin tal. Field-based biomass estimates were not significantly correlated, in both years, with topography ($P = 0.28$ and $P = 0.42$) or thickness of the surface and first subsurface soil horizons ($P = 0.283$ and $P = 0.789$). In 2007, field-based biomass estimates were not significantly correlated with stocking density ($P = 0.858$), but the correlation was significant in 2008 ($P = 0.035$) with a low adjusted R^2 of 0.035. Moran's I for both years indicated a random spatial pattern ($I = 0.004$ and $I = 0.017$, $Z = 0.01$ and $Z = 0.10$, for 2007 and 2008, respectively). The Getis–Ord general G index indicated no clustering in both years (0.0006 and 0.009 with Z-scores of -0.61 and 0.005, respectively).

The estimated mean SPOT NDVI values were 0.193 (± 0.06 SD) and 0.406 (± 0.05 SD) in 2007 and 2008, respectively. SPOT NDVI was not significantly correlated with topography

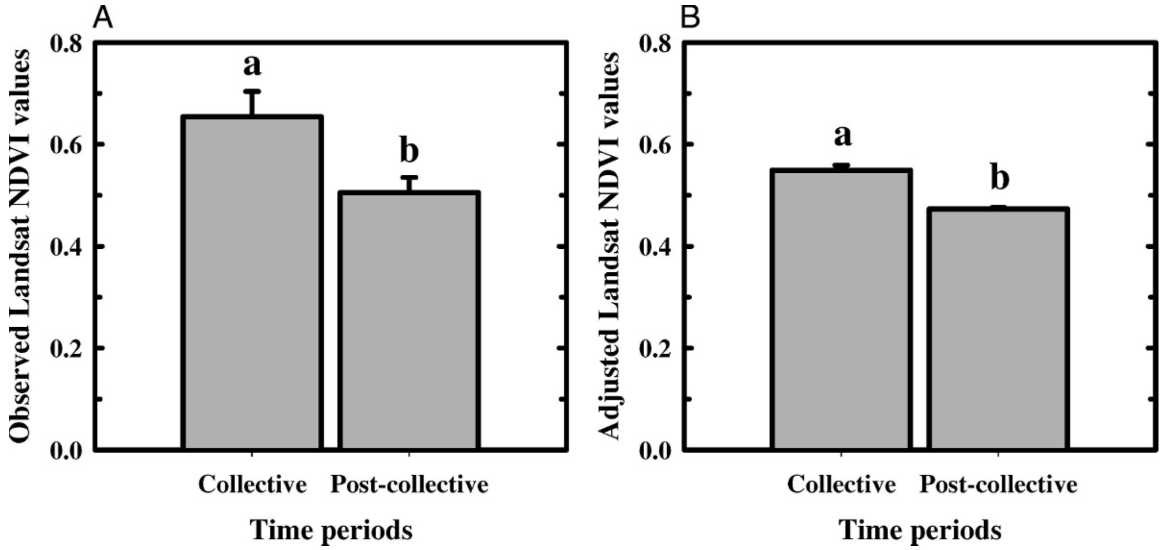

Figure 4. A, Observed and **B**, adjusted Landsat-derived mean (with standard error) normalized-difference vegetation index (NDVI) values from the collective and postcollective periods. Different letters indicate statistically significant differences at a significance level of 0.05.

($P = 0.650$) or stocking density ($P = 0.787$) in 2007, but was significantly correlated with topography ($P = 0.027$) and stocking density ($P = 0.054$) in 2008 with an adjusted R^2 of 0.11. SPOT NDVI values were not correlated, in either year, to surface soil horizon thickness ($P = 0.098$ and $P = 0.56$). 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; Fig. 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, whereas 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 remain 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 because of 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 AU from the collective to the postcollective 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 AU, 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 (United Nations Environment Programme [UNEP] 2002; Bedunah and Schmidt 2004; Bohannon 2008) as well as the national trend over the last 15 yr (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 socioeconomic and political changes (Fig. 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), whereas 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 yr of no grazing, 17 km from Tsahiriin tal), which was sampled as a potential reference site (1 876 $kg \cdot ha^{-1}$), 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 that 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 UNEP statement on Mongolia's environmental health (UNEP 2002) indicates that over 70% of Mongolia's rangeland is degraded because of overgrazing. Interestingly, there are rangeland assessments that 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 Office 2007), which equal 12 million AU. Tserendash's review (2008) of Mongolian rangeland assessment, for example, indicates that it can support 86 million animals in sheep units (17.2 million AU). 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 a significant impact on rangeland biomass.

MANAGEMENT IMPLICATIONS

Major changes in grazing land use management have had significant effects on rangeland biomass in Tsahiriin tal, northern Mongolia. Rangeland biomass has significantly decreased in the postcollective period relative to the collective period, and low biomass appears currently widespread 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 sociopolitical and economic regime shift that has occurred with the transition from socialist to democratic sociopolitical systems.

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