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Rangeland vegetation dynamics in the Altai mountain region of Mongolia, Russia, Kazakhstan and China: effects of climate, topography, and socio-political context for livestock herding practices

Liza V Iegorova[1], **James P Gibbs**[1,8], **Giorgos Mountrakis**[2], **Guillaume Bastille-Rousseau**[3], **Mikhail Yu Paltsyn**[1], **Atay Ayatkhan**[4], **Leonid V Baylagasov**[5], **Yury V Robertus**[6] and **Andrey V Chelyshev**[7]

[1] Department of Environmental and Forest Biology, State University of New York College of Environmental Science and Forestry, Syracuse, NY 13210, United States of America
[2] Department of Environmental Resources Engineering, State University of New York College of Environmental Science and Forestry, Syracuse, NY 13210, United States of America
[3] Colorado State University, Department of Fish, Wildlife, and Conservation Biology, Fort Collins, CO 80523, United States of America
[4] Protected Area Administration of Mongol Altai, Bayan-Olgii, Mongolia
[5] Gorno-Altaisk State University, Gorno-Altaisk, Altai Republic, Russia
[6] Regional Institute of Ecology of the Altai Republic, Maima, Altai Republic, Russia
[7] Katon-Karagay National Park, Katon-Karagay, Kazakhstan
[8] Author to whom any correspondence should be addressed.

E-mail: jpgibbs@esf.edu

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Supplementary material for this article is available online

Abstract

Discriminating between climate- and human-induced variation in rangeland quality poses a major challenge for developing policy to sustain herder livelihoods and alleviate herder poverty. We contrasted changes in rangeland vegetation cover across a region—the Altai Mountains of central Asia (China, Kazakhstan, Russia and Mongolia)—that juxtaposes strongly contrasting social, political and economic conditions across a community of herders of shared cultural background (all of Kazakh origin). Our analysis focused on a satellite-derived vegetation index (Normalized Difference Vegetation Index—NDVI) from the Advanced Very High Resolution Radiometer sensor during the period 1982–2013, which included the breakup of the Soviet Union in 1990 and heralded a transition away from pervasive state control on herding practices in many parts of the region. Grassland cover increased with decreasing elevation and increasing precipitation. Grassland also decreased under increased livestock density but was largely unresponsive to the dramatic changes that occurred in the sociopolitical context for grazing practices. Average NDVI values and duration of growing season were greater after the Soviet Union's collapse across the region, trends that precipitation and temperature data indicate were most likely driven by a changing climate. We conclude that rangeland policy development to assure sustainability of herder livelihoods in the Altai Mountain region should focus on climate change adaptation measures rather than modifying herders' grazing practices.

1. Introduction

Rangelands occupy approximately 50% of the world's land surface area and include grasslands, shrublands, woodlands, savannas, steppes, deserts, and tundra (Allen-Diaz *et al* 1995, Mannetje 2002). Rangelands provide multiple, often underestimated ecological functions and associated ecosystem services that benefit millions of people primarily via livestock production (Allen-Diaz *et al* 1995, Campbell *et al* 2000, Mannetje 2002, Johnson *et al* 2006, Endicott 2012). Yet, rangelands worldwide are subject to widespread degradation (Bedunah and Angerer 2012, Mansour *et al* 2012) with increasing human populations and livestock densities associated with overgrazing, conversion to croplands, improper land management practices, and climate change-associated desertification among the main causes (Han *et al* 2008, Harris 2010).

Climate is a major determinant of rangeland vegetation dynamics (Propastin *et al* 2008, Kariyeva and Van Leeuwen 2011, Dubovyk *et al* 2016). Precipitation patterns and temperature gradients are frequently identified as the primary drivers of inter-annual variability both on a seasonal basis and on longer time frames associated with climate cycles (Propastin *et al* 2008, Kariyeva and Van Leeuwen 2011, Dubovyk *et al* 2016). Other abiotic factors such as topography, soil, and surficial hydrological characteristics also have a profound effect on grassland productivity, although unlike climate their effects are relatively constant within a time scale of a few decades (Paudel and Andersen 2010).

Different forms of land tenure and herding practices are also known to be important drivers of global land-cover changes, but their impact on pastureland sustainability are poorly known (Bedunah *et al* 2006, Sankey *et al* 2009, Squires 2009, Endicott 2012, Prishchepov *et al* 2012). A lack of understanding of the relative contributions of abiotic, climatic and human activities on grassland dynamics is a major impediment to decision-makers seeking to develop policy to sustain herder livelihoods and alleviate herder poverty (Bedunah *et al* 2006, Bedunah and Angerer 2012). Contrasting rangeland dynamics under altered social, economic, and political systems (both over time and space) could elucidate primary drivers of rangeland dynamics and their interactions (Fernandez-Gimenez 2011, Prishchepov *et al* 2012).

The Altai Mountains provide a useful geographic focus to evaluate questions of interacting effects of topography, climate, and socio-political systems on rangeland dynamics. The region occurs at the border zone of Russia, Mongolia, China, and Kazakhstan and covers a vast area of mostly grassland ecosystems where grazing remains the dominant form of land use (Bedunah *et al* 2006, Endicott 2012, Benson and Svanberg 2016). Much of the region except in China has seen rapid transformation of the social, political, and economic system associated with collapse of the Soviet Union followed by abrupt but divergent transitions from state-command to market-driven economies in a region that is otherwise comparable ecologically and culturally in terms of herder societies (Fernandez-Gimenez 2011, Endicott 2012).

Together these strong and simultaneous socioeconomic changes among four countries have created a long-term, large-scale 'quasi-experiment' to examine the role of social, economic and political systems in concert with environmental factors in driving the dynamics of rangelands. To this end, we contrasted rangeland dynamics from 1982 to 2013 (a period that bracketed the collapse of the Soviet Union in 1991) among the adjacent China, Russia, Mongolia and Kazakhstan portions of the Altai Mountains to examine how environmental factors have influenced dynamics of rangeland vegetation cover. Our specific objectives were to: (1) evaluate changes in vegetation cover over three decades; (2) examine how environmental factors (climate and topography) have influenced dynamics of rangeland vegetation cover; (3) identify the role, if any, of country-specific social and political factors in mediating these changes; and (4) inform development of policy to sustain herder livelihoods and alleviate herder poverty in the broader region, where policies for sustainable rangeland management are largely non-existent yet where herding-based livelihoods predominate.

2. Methods

2.1. Study area

The study area occupied nearly 83 000 km^2 of the Altai mountain region (figure 1). Located in the middle of Eurasia, the region is characterized by a continental climate with short and cool summer (average July temperatures do not exceed +15 °C) and extremely cold winters (average temperatures −15° to −35 °C, minimum to −60 °C) (Kokorin *et al* 2001, Batima 2006, Kokorin 2011). The four countries that comprise this region—Russia, China, Kazakhstan and Mongolia—provide striking contrasts over time and space in systems governing livestock grazing. The characteristic feature of traditional grazing management system in the region has been seasonal vertical-horizontal movement between pastures (Baylagasov 2011, Endicott 2012). During the Soviet era, transhumant grazing systems were curtailed and rangeland management became more centrally controlled with provision of heavy subsidies such as veterinary care, winter shelters for livestock, hay mowing equipment, hydraulic wells, state-managed delivery of emergency fodder, and improved transportation (Bedunah *et al* 2006, Fernandez-Gimenez 2006, Endicott 2012, Benson and Svanberg 2016, Mirzabaev *et al* 2016, Eddy *et al* 2017). After the collapse of the Soviet Union centralized planning systems in many but not all parts of the region were dismantled and government subsidies disappeared (Bedunah *et al* 2006, Fernandez-Gimenez 2006, Endicott 2012). Russia and Kazakhstan were constituent republics of the Soviet Union, whereas Mongolia was never a fully integrated part of the Soviet Union (Lattimore 1956, Sharma 2016). Therefore, subsequent transitions of herding systems from state-command to market-driven varied among the three former Soviet States in the region. Livestock numbers (especially goats) increased in Mongolia (figure 2) due to high demand for cashmere wool on Chinese market (Endicott 2012, Rao *et al* 2015), but dropped significantly in Russia and then recovered 2000–2015 (Baylagasov 2011). Livestock numbers in Kazakhstan

Figure 1. Study area in the Altai Mountains where interacting effects of socio-political systems, climate, and topography on rangeland dynamics were evaluated 1982–2013. Map boundaries indicate exact limits of area of inference. Administrative boundaries within countries for which livestock data were extracted (figure 2) are indicated by white lines.

collapsed due to the loss of Soviet markets and have never recovered (figure 2) (Endicott 2012). In contrast, the communist regime in China transformed into the contemporary communist-capitalist state with state-controlled rangeland management yet persisting (Ho 2000, Benson and Svanberg 2016). Between 1949 and 1989 livestock numbers tripled in China's sector of the Altai Mountain region and continue to increase although livestock numbers may now be stabilizing (Bedunah *et al* 2006, Han *et al* 2008) (figure 2). In this quasi-experimental assessment, China was used as a 'control' because the communist regime in China, distinct from the Soviet Union, did not collapse as rapidly and state-controlled rangeland management has persisted to the present.

2.2. Datasets

2.2.1. Vegetation cover response variable

We contrasted rangeland vegetation cover among countries using Normalized Difference Vegetation Index (NDVI) as a proxy (Weiss *et al* 2001, Kawamura *et al* 2005a, Pettorelli *et al* 2005, Reeves and Baggett 2014) based on AVHRR satellite images from 1980s to the present (table 1). NDVI is one of the most widely used vegetation indices, and has been incorporated in monitoring rangeland degradation in various parts of the world (Geerken and Ilaiwi 2004, Wessels *et al* 2004, 2007, Paudel and Andersen 2010, Li *et al* 2013). MODIS-derived vegetation indices (EVI and NDVI) accurately reflect on-the-ground conditions of the Mongolian steppe ecosystems, and exhibit a strong correlation with percentage of vegetation cover (Paltsyn *et al* 2017). Numerous studies have shown a strong linear relationship between NDVI and the amount of photosynthetically active radiation (PAR) absorbed by plants, with the relationship often used to estimate net primary productivity based of NDVI (Yu *et al* 2003, Wessels *et al* 2004, Pettorelli *et al* 2005, Bat-oyun *et al* 2010).

This study used the GIMMS NDVI3g dataset (3g.v1), a global time-series NDVI product which at this time covers the period from 1981 to 2015 (Fensholt and Proud 2012, Yengoh *et al* 2015). The dataset was calibrated to remove the effects of satellite shift, sensor degradation, solar angle and view zenith angle, stratospheric aerosols from the El Chichon (1982) and Mt. Pinatubo (1991) volcanic eruptions, and other non-vegetation effects (Fensholt and Proud 2012, Pinzon and Tucker 2014, Yengoh *et al* 2015) although some noise may still be present due to cloud cover and poor atmospheric conditions (Zhou *et al* 2001, Chen *et al* 2004, Tucker *et al* 2005, Beck *et al* 2011, Geng *et al* 2014, Pinzon and Tucker 2014, Ding *et al* 2015). The NDVI data were spatially smoothed using a median filter with a window size of three ('medianFilter', library: FBN) (Agnelli *et al* 2009) in R (Version 3.2.2, www.r-project.org, accessed 01 October 2015) to further reduce residual noise caused by cloud contamination and poor atmospheric conditions (McKellip *et al* 2005, Hird and McDermid 2009, Geng *et al* 2014). All the layers were reprojected to WGS84 (World Geodetic System 1984) geographic coordinate system and resampled to a common resolution of 8 km using a bilinear interpolation for continuous data and

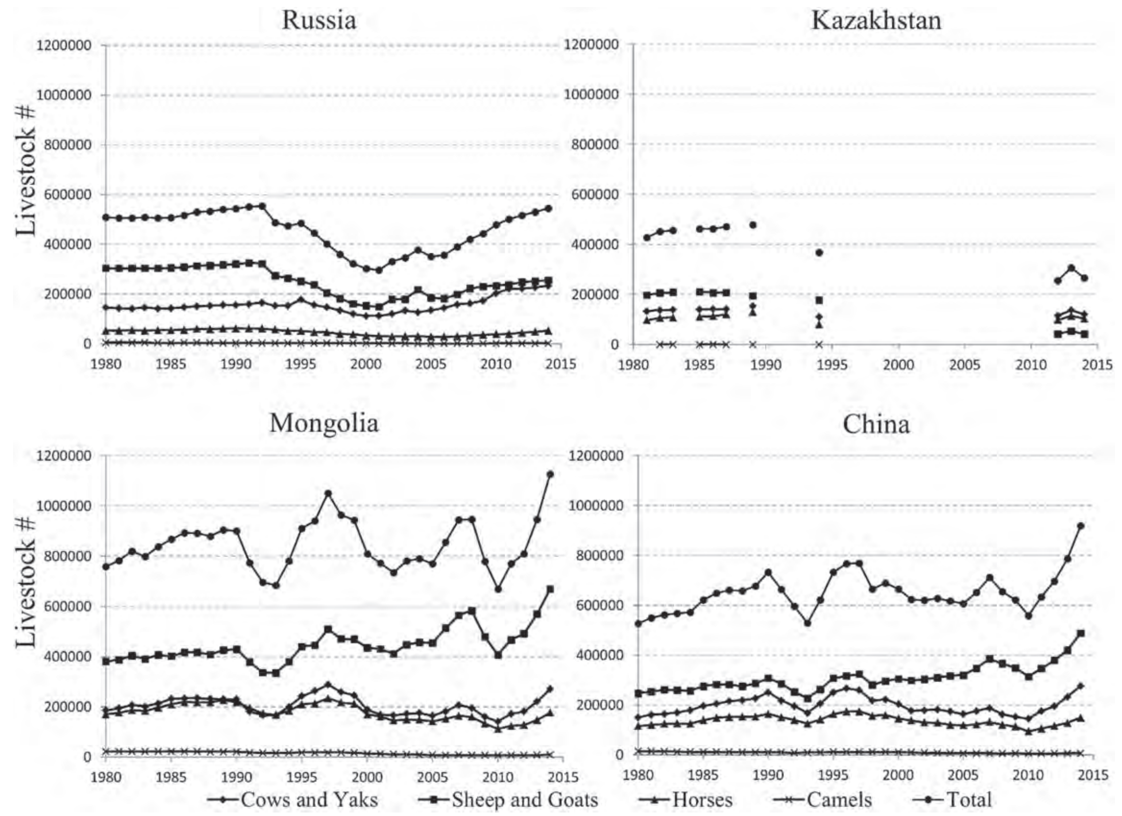

Figure 2. Livestock numbers (sheep units) (1. Livestock numbers were converted to sheep units (SU) per km^2 based on the standard body weight: 1 sheep = 1 SU, 1 goat = 1 SU, 1 horse = 7 SU, 1 cattle/yak = 6 SU, 1 camel = 5 SU) in the Altai Mountain region of central Asia, 1980–2014 (2. Republican Statistics data on the number of livestock in the settlements of Altai Republic in 1991–2012, Russia, 3. Annual reports of agricultural organizations of Kosh-Agach District (1980–2014), Russia, 4. Annual reports on the livestock census 1991–2002, Russia, 5. Statistical Bulletin 'Key parameters of functioning of agro-industrial complex of Altai Republic, 1993–1996', Russia, 6. Results of All Russia livestock census 1991, Russia, 7. Annual statistician bulletin 'Agriculture of Altai Republic' (2002–2014), Russia, 8. Statistical Reports of Bayan-Olgii Aimag (1980–2014), Mongolia, 9. Statistical Archive of Eastern Kazakhstan Region, Ust-Kamenogorsk, Fund #41, Records #8, 18, 32, 334, Kazakhstan, 10. Statistical data from the regional department of agricultural and agroindustrial management (1980–1991), China, 11. Statistical data from the regional department of agroindustry and animal husbandry (1991–2015), China). Livestock data were assembled by administrative unit within country (see figure 1) for Mongolia at the *somon* level (i.e. district, second level administrative subdivision) (Bugat, Nogoonnuur, Tsagaannuur, Tsengel, Ulaankhus), at the *kolhoz* level (a form of a collective farm) for Russia (Dzhazator settlement, Kuray and Chagan-Uzun settlements, Beltir settlement, Mukhor-Tarkhata settlement, Ortolyk settlement, Telengit-Sortogoy settlement, Tobeler settlement, Kokory settlement, Kazakh and Tashanta settlements), at the county level for China (Altay, Burchin, Burultoqay, Qaba), and for Katon-Karagay district in Kazakhstan.

Table 1. Data sources used for analysis of interacting effects of socio-political and environmental factors on rangeland dynamics in 1982–2013 in the Altai Mountains in central Asia.

Data	Type	Satellite	Source	Spatial resolution	Temporal resolution	Units
NDVI	continuous	AVHRR	NASA NEX[a]/GIMMS[b]	8 km	bimonthly	VI
Elevation	continuous	—	GLOBE/NOAA[c]	1 km	—	meters
Precipitation	continuous	—	GPCC[d]	0.5°	monthly	mm
Temperature	continuous	—	U. Delaware[e]	0.5°	monthly	°C
Land cover type	categorical	MODIS	Reverb[f]	500 m	yearly	—
Country	categorical	—	DIVA-GIS[g]	—	—	—

[a] NASA Earth Exchange (https://nex.nasa.gov/).
[b] Global Inventory Monitoring and Modeling System project.
[c] Global Land One-kilometer Base Elevation of National Oceanic and Atmospheric Administration (http://ngdc.noaa.gov/mgg/topo/globe.html).
[d] GPCC Global Precipitation Climatology Centre monthly precipitation dataset V7 (http://esrl.noaa.gov/psd/data/gridded/data.gpcc.html).
[e] Air Temperature V4.01, Willmott & Matsuura, University of Delaware (http://esrl.noaa.gov/psd/data/gridded/data.UDel_AirT_Precip.html).
[f] http://reverb.echo.nasa.gov/.
[g] http://diva-gis.org/.

majority algorithm for categorical data. NDVI time series 1982–2013 were used in this analysis. The MODIS Land Cover Type product (MCD12Q1 V051 for 2001, IGBP [Type 1] classification) was used to select only the pixels that were grassland or could potentially transition to a grassland or vice versa within the 32 year long period (grasslands, open shrubland, woody savannas, savannas cropland, cropland/natural vegetation mosaic, barren sparsely vegetated) to ensure a focus on rangeland throughout the study (270 pixels in China, 292 in Kazakhstan, 357 in Mongolia, and 483 in Russia, or 96.3% of the total area, figure 1). For each year, we calculated maximum and mean NDVI, as well as mean temperature and precipitation values, for the growing season (May–September).

2.2.2. Explanatory variables

A suite of parameters were assembled to explain NDVI variation (table 1). Climatic factors (temperature and precipitation) were included because they play a key role in driving vegetation cover dynamics in central Asia (Yu *et al* 2003, Propastin *et al* 2008, Lioubimtseva and Henebry 2009, Kariyeva and Van Leeuwen 2011, Dubovyk *et al* 2016). Elevation was also included because plant growth in montane grassland ecosystems is strongly influenced by altitude and indirectly influenced via temperature that decreases with increasing elevation (Propastin *et al* 2008, Kariyeva and Van Leeuwen 2011, Dubovyk *et al* 2016). Year was included to account for interaction between rangeland dynamics and the transition of political systems associated with the fall of the Soviet Union (Bennington and Thayne 1994, Prishchepov *et al* 2012). Lastly, country was included as the proxy for socio-political context for herder livelihoods on the basis of the following predictions: (1) NDVI would increase in Russian and Kazakhstan after the collapse of the Soviet Union due to reduction in livestock numbers and elimination of pastoral nomadic herding; (2) NDVI would decrease in Mongolia because of the more intensive use of rangelands and an increasing number of livestock, and (3) NDVI would not change in China given the stability of the social-political system there or would possibly increase due to evident rises livestock numbers over the study period (figure 2, supplementary materials S1 is available online at stacks.iop.org/erl/14/104017/mmedia).

To assess the role of livestock densities in rangeland dynamics, livestock data were assembled by adminstraive unit within each country (see figure 2 for units and data sources). Total livestock for all areas was converted to sheep units (SU) per km^2 based on the standard body weight: 1 sheep = 1 SU, 1 goat = 1 SU, 1 horse = 7 SU, 1 cattle/yak = 6 SU, 1 camel = 5 SU (Kawamura *et al* 2005b, Lise *et al* 2006, Wang *et al* 2007, Paudel and Andersen 2010, Bhatt *et al* 2013). Kazakhstan was omitted from this analysis because livestock data was only available on large-scale, district level.

Table 2. Parameter estimates (β) with associated standard errors (SE) and 95% confidence intervals (CI) for the best model describing the mean NDVI dynamics in the Altai Mountains in central Asia from 1982 to 2013 as a function of elevation and precipitation (formulated as continuous, standardized variables), country (4 categories: Russia, China, Kazakhstan and Mongolia), year (32 categories: 1982–2013), and pixel ID, pixel ID being a random factor (i.e. random intercept) and all other variables were treated as fixed effects. Marginal R^2 representing the variance explained by fixed factors = 0.51 with conditional R^2, interpreted as variance explained by both fixed and random factors, =0.97.

Variable	β	SE	95% CI	
Elevation	−0.0460	0.0040	−0.0539	−0.0381
Elevation^2	−0.0307	0.0026	−0.0357	−0.0257
Precipitation	0.0028	0.0006	0.0015	0.0040
China	0.5575	0.0082	0.5415	0.5735
Kazakhstan	0.6326	0.0078	0.6174	0.6479
Mongolia	0.3647	0.0074	0.3503	0.3790
Russia	0.4970	0.0058	0.4856	0.5084

2.3. Data analysis

We developed linear mixed models to analyze NDVI time-series as a function of environmental and socio-political factors as well as the relationship between the change in NDVI values and livestock numbers. We also assessed changes in growing season phenology by contrasting Julian dates of the beginning and end of each growing season by country over the study period.

2.3.1. The role of environmental and social-political on rangeland dynamics

We used linear mixed models (without intercept term) with a Gaussian distribution in R ('lmer' function, 'lme4' package) (Bates *et al* 2015) to partition variation in NDVI in the region as a function of elevation, precipitation, temperature, interaction of country and year, and with pixel ID as a random factor (i.e. random intercept), with all other variables treated as fixed effects. Continuous variables were standardized to facilitate interpretation of parameters estimates (Schielzeth 2010). A threshold-based filter was applied to check for multicollinearity and predictors with variance inflation factor (VIF) of 5 or higher were considered problematic and were omitted from the analysis (Graham 2003, Dormann *et al* 2013). Model selection was performed using Akaike's information Criterion corrected for sample size (AICc) (Burnham and Anderson 2002, Bolker 2008, Zuur *et al* 2009). To assess the goodness-of-fit of the best model we calculated conditional and marginal R^2 (Nakagawa and Schielzeth 2013). We tested for the presence of spatial autocorrelation in the residuals of regression models by building correlograms in R ('correlog' function, 'ncf' package) (Koenig and Knops 1998, Zuur *et al* 2009).

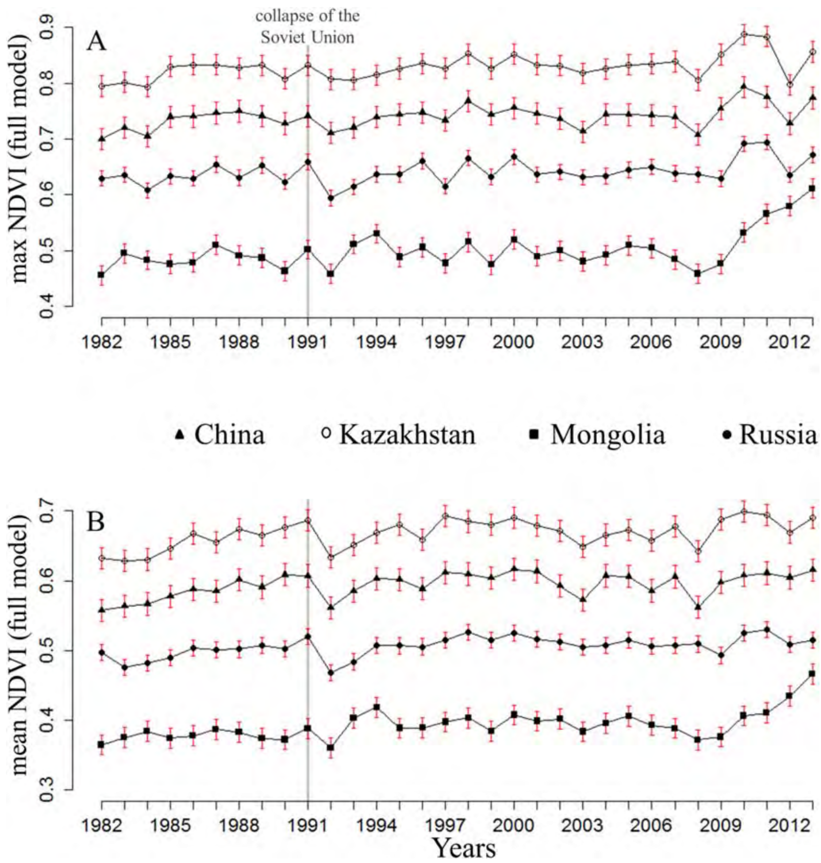

Figure 3. Full model effects for change in maximum (a) and mean (b) NDVI in the Altai Mountains 1982–2013. Mean and maximum NDVI were estimated as a function of elevation and precipitation (formulated as continuous variables standardized to zero mean and one unit standard deviation), country (4 categories: Russia, China, Kazakhstan and Mongolia), year (32 categories: one per year), and pixel ID (being a random factor, i.e. random intercept); all other variables treated as fixed effects. Error bars indicate upper and lower limit of the 95% confidence interval.

2.3.2. Effects of livestock densities on rangeland dynamics

To examine the impact of livestock densities on rangeland dynamics we removed linear trend from NDVI time-series in R ('detrend' function, 'pracma' package) (Borchers 2015) and calculated the change ratio in relation to the previous year for NDVI, precipitation, temperature and livestock. The change ratios were calculated as

$$\Delta X_t = \ln(X_t / X_{t-1}),$$

where X are the two values in one year (t) and the year immediately preceding it ($t - 1$) (Loh *et al* 2005). We fit the full linear mixed model to estimate ΔNDVI_t in three countries as a function of elevation, $\Delta \text{precipitation}_t$, $\Delta \text{temperature}_t$, Δlivestock, interaction of country and year, and pixel ID, pixel ID being a random factor (i.e. random intercept) and all other variables were treated as fixed effects. To examine whether an increase or decrease in livestock numbers in a given year influenced NDVI values the subsequent year we used $\Delta \text{livestock}_{t-1}$ in the first model, and $\Delta \text{livestock}_{t+1}$ in the second model to understand if an increase or decrease in vegetation cover during the previous year might influence what number of animals herders chose to graze.

2.3.3. Growing season phenology

To investigate the changes in the start, end and duration of the growing season we interpolated NDVI time series to 1 d temporal resolution using a cubic smoothing spline (Tang and Oki 2007, Cong *et al* 2012, Lin *et al* 2013) in R ('spline' function, 'stats' package) (R Core Team 2016). For each pixel we identified the beginning of the growing season defined as the date when the rate of change in NDVI between two consecutive (NDVI_{t+1}–NDVI_t) days reached its first local maximum value after January 30th, and the end of the growing season as the date when the rate of change in NDVI between two consecutive (NDVI_{t+1}–NDVI_t) days reached its first local minimum value after August 31st (Ding *et al* 2015). We then averaged values for the start, end and length of the growing season for Soviet Union era (1985–1991) and post-Soviet times (1995–2013). Data from 1982 to 1984 and 1992 to 1994 was removed due to the stratospheric aerosol effect of El Chichon (1982) and Mt. Pinatubo (1991) volcanic eruptions (Myneni *et al* 1997, Tucker *et al* 2001). Paired t-tests using pixel as the replicate were used to contrast start, end and the length of the growing season between the two eras within each country.

Table 3. Parameter estimates with associated standard errors and 95% confidence intervals for the model describing role of livestock densities in rangeland dynamics in the Altai Mountains in central Asia from 1982 to 2013. Change variables (Δ) were calculated as the natural logarithm of the ratio between the current year's value and the previous year's value. An increase in livestock numbers the previous year was associated with decrease in NDVI values in the current year, whereas there was no relationship between NDVI and herd density in the subsequent year. Marginal R^2 (R^2m) and conditional R^2 (R^2c) explained in table 2.

Variable	β	SE	95% CI	
A. Effect of livestock density on change in NDVI				
Elevation	0.02	0.02	−0.02	0.06
Elevation^2	−0.05	0.01	−0.08	−0.03
ΔPrecipitation$_t$	0.34	0.07	0.21	0.46
ΔTemperature$_t$	0.69	0.21	0.28	1.10
China	4.27	0.16	3.96	4.57
Mongolia	3.53	0.09	3.34	3.71
Russia	4.06	0.12	3.83	4.29
ΔLivestock$_{t-1}$	−0.39	0.18	−0.75	−0.04
$R^2{}_m = 0.10$ $R^2{}_c = 0.20$				
Random effect Variance: 0.1447				
B. Effect of NDVI on herd density in subsequent year				
Elevation	0.0045	0.0012	0.0021	0.0069
Elevation^2	0.0004	0.0007	−0.0009	0.0018
ΔPrecipitation$_t$	0.0106	0.0060	−0.0011	0.0222
ΔTemperature$_t$	−0.138	0.0200	−0.1770	−0.099
China	0.0270	0.0168	−0.0059	0.0598
Mongolia	0.0419	0.0112	0.0200	0.0638
Russia	−0.0415	0.0100	−0.0608	−0.0219
ΔNDVI	−0.0010	0.0008	−0.0026	0.0005
$R^2{}_m = 0.09$ $R^2{}_c = 0.19$				
Random effect Variance: 0.1464				

3. Results

3.1. The role of social-political and environmental factors in the dynamics of rangelands' vegetation cover

Analysis of the 32 year long (1982–2013) GIMMS NDVI3g data series using linear mixed models revealed that the full model (including elevation, precipitation, country, and year) was by far the top-ranked model (AICc weights > 0.99, table 2, S1) (temperature was omitted from the models due to multi-collinearity, with VIF = 13.02). The marginal R^2 (variance explained by fixed factors) for the full model was 0.51 and the conditional R^2 (variance explained by both fixed and random factors) was 0.97. There was no detectable spatial autocorrelation in model residuals at any lag distance. The full model indicated that, on average, NDVI was highest in Kazakhstan and lowest in Mongolia (table 2) with a drop in mean and maximum NDVI values in all four countries the year following the collapse of Soviet Union in 1991 (on average NDVI declined from 1991 to 1992 by 10.0% in Russian, 7.7% in Kazakhstan, 7.5% in Chinese, and 7.1% in Mongolian sectors of the study area) followed by an extended period of stability to 2008 in all countries and then increase in NDVI to the present (figure 3). In terms of biophysical variables, NDVI increased with elevation up to 1500 m but thereafter declined. NDVI increased with increasing precipitation during the growing season, rising by 5.58×10^{-4} for each 1 mm increase in precipitation (table 2).

3.2. The role of livestock in rangeland dynamics

Increased precipitation and temperature was associated with higher NDVI values, whereas an increase in livestock numbers over the previous year was associated with decrease in NDVI values in the current year (table 3(A)). Our models revealed no apparent relationship between increase or decrease in NDVI the previous year and the number of animals on the pasture during the current year (table 3(B)), that is, herders did not appear to be tracking the previous year's vegetation cover in decision-making on livestock stocking in the current year.

3.3. Dynamics of growing season phenology

Differences in start, end and the length of the growing season during the Soviet Union era and post-Soviet era indicated that the growing season startearlier during the post-Soviet era in Mongolia, China, and Kazakhstan (with no difference in Russia) while ending later and lasting longer during the post-Soviet era in all four countries (table 4). Trends in averaged May–September NDVI values by country during 1985–1991, 1992–1994 and 1995–2013 indicated a positive significant effect of year and divergent effects of country, but no significant interaction between country and year (supplementary materials S3).

4. Discussion

Our analysis of changes in vegetation cover in the Altai Mountains in central Asia based on AVHRR NDVI time series for 1982–2013 revealed a long-term positive trend in the NDVI time series in all four countries in the study area albeit interrupted by a short episode of decline in mean and maximum NDVI values immediately following the collapse of Soviet Union in 1991. Abiotic factors (precipitation, temperature, topography) were the primary drivers of NDVI dynamics and dominated any potential effects of social, political and economic drivers of herding practices in this region. These outcomes contradicted our expectation of sharp and divergent transitions in rangeland quality and dynamics after the Soviet Union collapse amongst the four political units that comprise the region given their distinct trajectories since the end of the Soviet era.

Climate clearly played a dominant role in rangeland dynamics in the Altai Mountain region, with average NDVI values higher after the Soviet Union collapse in all four countries, an effect seemingly

Table 4. Comparison based on paired t-tests of the mean start, end and length of the growing season between Soviet Union (1985–1991) and post-Soviet (1995–2013) eras in the Altai Mountains of central Asia.

	Start date				End date				Length (days)			
	Mean (±SD)				Mean (±SD)				Mean (±SD)			
Country	Before	After	*t*	*P*	Before	After	*t*	*P*	Before	After	*t*	*P*
Russia	18 May (±17)	17 May (±13)	1.71	0.088	2 October (±10)	7 October (±11)	−9.27	0.0001	137 (±23)	143 (±20)	−7.9	0.0001
Mongolia	20 May (±18)	18 May (±12)	2.83	0.005	1 October (±11)	3 October (±10)	−4.55	0.0001	134 (±26)	139 (±20)	−4.6	0.0001
China	8 May (±13)	8 May (±14)	2.04	0.042	7 October (±12)	15 October (±12)	−10.78	0.0001	152 (±20)	161 (±22)	−8.1	0.0001
Kazakhstan	10 May (±12)	9 May (±12)	2.64	0.009	7 October (±11)	14 October (±11)	−10.65	0.0001	150 (±16)	158 (±19)	−9.5	0.0001

driven by climate change. Central Asia is exhibiting one of the strongest warming signals on the planet and climate scenarios project a continued increase in temperature (Yu *et al* 2003, Lioubimtseva and Henebry 2009). Mongolia is a case in point. The Mongolia study area segment was at the upper end of the elevational gradient for the high elevation grassland ecosystems in the Altai region, and herders there dramatically increased the number of livestock during the study period coincident with a strong increase in NDVI values. Coupled with this increase in temperature and precipitation, we observed an expanding growing season, likely contributing to the increase observed in NDVI in this region of perennial grasslands. Our findings are consistent with other studies that suggest increase in growing season NDVI in this region driven by warmer temperatures (Myneni *et al* 1997, Tucker *et al* 2001, Zhou *et al* 2001, Propastin *et al* 2008, Dubovyk *et al* 2016).

It is important to note that the sharp decline observed in NDVI values throughout all four countries from 1991 to 1992 following the collapse of the Soviet Union coincided with a short-term global-scale change in climate associated with the Mt. Pinatubo eruption. Immediate, short-term impacts of socio-political change on rangeland dynamics during this transitional period in this region (figure 3) may therefore have been masked by Mt Pinatubo-induced climate disruption whereas over the longer-term, environmental factors were the primary drivers in NDVI dynamics in the region (Tucker *et al* 2001, Yu *et al* 2003, Julien *et al* 2006, Propastin *et al* 2008, Lioubimtseva and Henebry 2009, Kariyeva and Van Leeuwen 2011, Pinzon and Tucker 2014, Dubovyk *et al* 2016, de Beurs *et al* 2018).

Independent of the influence of climate, the strong upward tendency in NDVI forces reconciliation of the notion that increasing herd sizes occurring across much (but not all) of the region degrade rangeland. In both the countries (Russia and Mongolia) where relationships between NDVI and livestock were measured, NDVI has increased strongly coincident with increasing herd sizes over the last decade. Traditional theory conceptualizes rangelands as equilibrium systems regulated by animal density-dependent feedback, whereas an alternative view is of rangelands as non-equilibrium systems where abiotic factors are limiting (Ellis and Swift 1988, Fernandez-Gimenez and Allen-Diaz 1999). More recent studies suggest that grassland ecosystems can exhibit characteristics of both equilibrium and non-equilibrium systems at the same time (Fernandez-Gimenez and Allen-Diaz 1999). Our study suggests that the Altai Mountain region is governed mostly by abiotic factors with minor (modification by livestock grazing pressures and herding practices. Similarly, Hilker *et al* (2014) demonstrated that for the north and north east of Mongolia precipitation is one of the main drivers in NDVI dynamics although in Central and Southern Mongolia precipitation contributed less than 10% to NDVI dynamics and a negative trend in inter-annual NDVI values attributed over the last 10 years to an increase in livestock numbers. Annual precipitation also correlates positively with Leaf Area Index (LAI) with an apparent increasing trend of LAI in Chinese part of Altai Mountain region in 1981–2011 (Fang *et al* 2013). An analysis of NDVI residual trends not explained by precipitation indicated elevated livestock density in Mongolia could depress NDVI (John *et al* 2016).

In the context of our study, whereas the Soviet era changed grazing philosophy for a few decades, after the collapse of the Soviet system when regional markets were lost due to high transportation cost, localized markets reemerged along with the traditional knowledge of maintaining rangeland health and resiliency (Retzer and Reudenbach 2005, Fernandez-Gimenez 2006, Johnson *et al* 2006, Endicott 2012). Many herders have returned to former, more transhumant herding approaches. The expanded movement among pastures among contemporary herders may have allowed vegetation to recover during the season leading to apparently increasing grassland productivity coinciding with increasing total herd biomass.

5. Conclusion

Much of central Asia where livestock herding represents the dominant livelihood lacks any coherent grazing policy to sustain herder livelihoods and alleviate herder poverty, with China being a notable exception (Fernandez-Gimenez 2000, 2011, Endicott 2012). Our study calls into question whether modifying grazing practices should be the primary focus of decision-makers for developing sustainable grassland use in this region. Climate is clearly changing in the region (Yu *et al* 2003, Lioubimtseva and Henebry 2009, Kokorin 2011). The revitalization of herding communities and former herding practices in some regions may have enabled a simultaneous increase in both livestock numbers and grassland cover, for example, in western Mongolia (figure 3) where traditional intra- and inter-community relationships have reassembled following the collapse of the Soviet Union (Fernandez-Gimenez 2011, 2000, Endicott 2012). Traditional herding practices may ultimately be the most important buffer for herder livelihoods in the region as the climate continues to change and extreme weather events (especially dzuds) are expected to become more common (Fernandez-Gimenez 2000, 2011). In contrast, China is still attempting to settle herding communities based on the policy framework that urban life is superior to rural life, a policy that has led to the limitation and elimination of herder mobility and to pasture degradation (Bedunah *et al* 2006, Endicott 2012, Benson and Svanberg 2016). Our analysis of a continuous and field-validated (Paltsyn *et al* 2017) index of vegetation cover spanning a 32 year long period implies that assuring sustainability of herder livelihoods and habitat quality for rangeland-associated wild species in this globally significant ecoregion should focus more on climate change adaptation (mostly focusing on developing decision-making frameworks for responding to precipitation and vegetation growth variability, altering strategies of livestock management, modifying household financial capital, and monitoring the status of pasture degradation, Wang *et al* 2013) than modifying local grazing systems, of which traditional grazing practices are apparently more closely associated with rangeland resilience.

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ORCID iDs

James P Gibbs https://orcid.org/0000-0002-0529-9705
Giorgos Mountrakis https://orcid.org/0000-0001-5958-8134

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