Integrating Herder Observations, Meteorological Data and Remote Sensing to Understand Climate Change Patterns and Impacts across an Eco-Climatic Gradient in Mongolia

M.E. Fernandez-Gimenez[1,2], J.P. Angerer[3,4], A.M. Allegretti[5], S.R. Fassnacht[5,6,7], A. Byamba[8,9], J. Chantsallkham[1], R. Reid[5], N.B.H. Venable[10]

[1]Forest & Rangeland Stewardship, Colorado State University, Fort Collins CO 80523-1472, USA [2]<maria.fernandez-gimenez@colostate.edu>
[3]Texas A&M University, Blackland Research and Extension Center, 720 E. Blackland Road, Temple, TX, 76502 USA, [4]<jangerer@brc.tamus.edu>
[5]Ecosystem Science and Sustainability, Colorado State University, Fort Collins, CO 80523-1476 USA [6]<Steven.Fassnacht@colostate.edu>
[7]Cooperative Institute for Research in the Atmosphere, Fort Collins, CO 80523-1375 USA
[8]Nutag Partners, Post 28, Nomun Box 670 Ulaanbaatar 14252, Mongolia, [9]<batkhishig@nutagpartners.mn>
[10]Geosciences, Colorado State University, Fort Collins, CO 80523

ABSTRACT

Mongolia has one of the strongest climate warming signals on Earth, and over 40% of the human population depends directly or indirectly on pastoral livestock production for their livelihoods. Thus, climate-driven changes in rangeland production will likely have a major effect on pastoral livelihoods. We examined patterns of climate change and rangeland production over 20 years in three ecological zones based on meteorological records, remote sensing and herder observations. We found the strongest trends in both instrument records and herder observations in the steppe zone, where summers are getting hotter and drier, winters colder, and rangeland production is declining. Instrument records and herder observations were most consistently aligned for total annual rainfall, and consensus among herders was greatest for changes in rainfall and production and lowest for temperature changes. We found more differences in herder observations between neighboring *soums* within the same ecozone than expected, suggesting the need for more fine-scale instrument observations to detect fine-scale patterns of change that herders observe.

Keywords: local knowledge, traditional knowledge, climate change, monitoring

INTRODUCTION

Multiple studies using coarse-resolution meteorological station and interpolated data have shown significant warming trends in Mongolia over the past century (Batima et al., 2005; Dagvadorj et al., 2009; Venable et al., 2015). Trends in precipitation are more variable (Dagvadorj et al., 2009). Much less is understood about fine-scale climate changes or their impacts on the amount and timing of forage production (Marin, 2010).

A major concern for Mongolia is how climate change will alter pasture conditions. The combination of significantly increased temperature and minor changes in precipitation leads to increased evaporation, less moisture for plant growth and "pasture droughts" (Nandintsetseg and Shinoda, 2013). Remote sensing studies have demonstrated declines in greenness (Liu et al., 2013), while some long-term field studies show no change or an increase in total biomass (Khishigbayar et al., 2015). In response to predicted changes in temperature and soil moisture, the desert steppe ecoregion is expected to expand in extent, and the steppe and mountain and forest steppe are expected to contract (Angerer et al., 2008; Dagvadorj et al., 2009).

Local ecological knowledge (LEK) provides observations on climate and pasture changes that may complement and enrich instrumental records and ecological field data (Klein et al., 2014), including information at finer spatial resolutions (Marin, 2010; Klein et al., 2014). Past LEK studies on the Mongolian Plateau and Tibet have focused on herder observations of changes in streamflow (Fassnacht et al., 2011), increasing temperature and increasingly variable rainfall (Marin, 2010), and pasture condition changes (Bruegger et al., 2014; Klein et al., 2014). In some cases, herder observations were directly compared with instrument records and found to align with them (Fassnacht et al., 2011), while in others herders observed changes in precipitation not detected with instrument records (Marin, 2010; Li et al., 2014).

Objectives and Hypotheses

To better understand climate change trends and their impacts on herders, and whether coarse-resolution climate and remote sensing data identify local-level impacts observed by herders, this study examines and compares patterns of change in climate and rangeland production across an ecological gradient based on herder observations, interpolated meteorological data, and satellite imagery. Based on previous climate and LEK research in Mongolia and nearby regions, we hypothesized that both meteorological records and herder observations would detect strong warming trends, and that both satellite imagery and herders would detect declines in production/greenness over all study sites, with the greatest changes observed at higher latitudes and elevations. We expected trends in precipitation would be more varied across zones with less agreement between meteorological records and herder observations. We further expected that herder observations would be similar between *soums* in the same ecozone and that herder consensus on change would be greatest regarding temperature and production, and lower regarding rainfall amount and frequency.

STUDY SITES

Our study sites include 2 *soums* per ecozone for 3 ecozones lying in a north-south gradient from the mountain and forest steppe (Bayangol and Saikhan, Selenge *Aimag*), to the steppe (Undurshireet and Erdenesant, Tuv *Aimag*) and desert steppe (Ulziit and Undurshil, Dundgobi *Aimag*).

METHODS

Meteorological and Remote Sensing Data

We used the Global Historical Climate Network dataset for temperature (Lawrimore et al., 2011) and the Climate Prediction Center Unified Precipitation dataset for precipitation (Chen et al., 2008). Both are 0.5^{o} x 0.5^{o} resolution. We used 1993-2013 for temperature and 1993-2012 for precipitation in our analysis, and for precipitation we calculated a 5-year moving average. We used number of days without rainfall as an indicator of rainfall frequency. We used GIS to calculate average values for each pixel in the grid by year and then calculated *soum* and ecozone averages for each variable**.** We used AVHRR-

NDVI (normalized difference vegetation index) data at 8 km x 8 km resolution (Pinzon and Tucker, 2014) from 1993 to 2009 as our proxy for rangeland production (Tucker et al., 1985). We used TIMESAT software (Eklundh and Jonsson, 2009) to extract time series variables, which included small integral NDVI, an estimate of annual production that excludes residual biomass from prior years, start of season (green-up), and end of season (brown-down). We used the non-parametric Mann Kendall test to evaluate the significance of changes over time for all variables and when significant calculated the Sen's slope (Gilbert, 1987).

Herder Survey

We surveyed a spatially representative convenient sample of herders in the 6 *soums* using a closed-ended questionnaire that asked about their observations of climate and rangeland changes from 1993 to 2013. Responses were on a 5-point Likert-type scale from -2 "decreased a lot" to +2 "increased a lot". Respondents included 62 men and 47 women ranging in age from 29 to 87 years old and had lived in their area from 10 to 87 years.

To compare the direction and magnitude of herder-observed changes among ecozones, we used one-way ANOVA, with Bonferroni-corrected post-hoc comparisons. To compare herder-observed changes between *soums* within each ecozone we used t-tests. To assess the level of consensus in herder observations within and between communities and ecozones, we used the Potential for Conflict Index (PCI_2) (Vaske et al., 2010). A PCI_2 of 1 represents the least amount of consensus and the greatest variability among herder observations. A PCI_2 of 0 illustrates a distribution with 100% at one point on the response scale, indicating complete consensus among respondents (Vaske et al. 2010).

RESULTS

Changes in Climate, Production and Phenology from Meteorological and Remote Sensing Observations

Meteorological observations showed that summer temperatures increased significantly in both steppe *soums* and one desert steppe *soum* (Undurshil) over the past 20 years (Table 1). Winter temperatures decreased significantly in all mountain and forest steppe and steppe *soums*. Annual precipitation declined significantly in all steppe and desert steppe *soums*. The number of days without rainfall significantly increased in all mountain and forest steppe and steppe *soums*, indicating declining frequency of rainfall events.

Small integral NDVI decreased significantly in both steppe *soums*, and increased in one desert steppe *soum* (Undurshil). Although there were no significant changes in spring green-up times, the direction of the trends differed among zones, with a trend towards earlier green-up in the mountain and forest steppe and desert steppe and later green-up in the steppe. Brown-down in one steppe *soum* (Erdenesant) was significantly earlier over time.

Herder Observations of Change

A majority of herders in all ecological zones observed that spring temperatures are cooler than 20 years ago (Figure 1). Herders in Saikhan observed more extreme cooling than those in Bayangol ($t = -2.001$, $p = .053$). Most observed that summer temperatures have cooled but others, especially in Undurshireet (steppe), observed warmer summer temperatures in contrast to their neighbors in Erdenesant ($t = 4.078$, $p = .002$). Herders were divided in their observations of fall temperatures with about half observing cooler falls and the rest observing no change or warmer fall temperatures (Figure 1b). Again Undurshireet and Erdenesant herders differed significantly in the trends of their observations ($t = 3.321$, $p = .003$), with 75% of herders in Undurshireet observing warmer falls. Observations of winter temperatures were variable, with nearly half of all desert steppe herders observing warmer winters, and half of steppe herders and more than half of mountain and forest steppe herders observing cooler winters. Observations of winter temperature trends differed significantly between the desert steppe and each of the other zones ($F = 6.006$, $p = .003$).

Most herders observed moderate to extreme declines in rainfall amount over the past 20 years. Observed changes were greatest in the steppe and desert steppe with a substantial minority of herders in the mountain and forest steppe observing no change or a slight increase in precipitation. Mean observations differed significantly between the mountain and forest steppe and the other two zones ($F=5.449$, $p=.006$). Most herders observed an increase in the time between rainfall events (rainfall interval), but a substantial minority of herders in Bayangol (mountain and forest steppe) saw no change or a slight decrease in rainfall interval, leading to a significant difference in mean observations between the mountain and forest steppe and other zones ($F=9.696$, $p<.001$).

Across all ecological zones, herders observed moderate to substantial declines in pasture production over the past 20 years. However, herders in neighboring *soums* in the mountain and forest steppe ($t=-2.657$, $p=.013$) and steppe ($t=-2.405$, $p=.024$) differed significantly in the extent of decline observed, with Saikhan (mountain and forest steppe) and Undurshireet (steppe) observing more extreme declines. All herders observed later green-up than 20 years ago, with similar differences in the observed degree of delay between *soums* within the mountain and forest steppe ($t=2.465$, $p=.019$) and steppe ($t=2.00$, $p=.055$). A majority of herders observed earlier brown-down at the end of the growing season, but in the desert steppe, Ulziit herders observed earlier brown-down than Undurshil herders ($t=2.073$, $p=.045$).

PCI_2 analysis revealed the least consensus about changes in summer, fall and winter temperatures, and most consensus on production, green-up time, rainfall amount and rainfall frequency (Figure 1). In the steppe, there was complete consensus ($PCI_2=0$) that pasture growth decreased, green-up is later, and rainfall interval increased.

DISCUSSION

Meteorological records, satellite imagery, and herder observations all indicate that the steppe study sites are experiencing the strongest changes in climate and rangeland production, with increasingly hot and dry summers, colder winters, and declining production. These findings do not support predictions that the largest changes will be observed in the highest latitudes and elevations, i.e., the mountain and forest steppe.

Contrary to our hypothesis, we found more differences in herder observations between *soums* than between ecozones. Most within-zone differences between *soums* related to observed changes in production, phenology and spring, summer and fall temperatures, whereas differences between zones concerned rainfall and winter temperatures. Between-zone differences in herder observations mirrored instrument records for those zones. Within-zone differences between *soums* may indicate that herders are responding to real differences in local conditions not detected by coarse-resolution meteorological and remote sensing measurements.

We hypothesized that herder consensus would be greatest about temperature and rangeland production and lowest about rainfall amount, frequency and vegetation phenology. Instead, consensus was greatest about production, phenology and rainfall amount and frequency, and lowest about temperature. One explanation is that herders pay closer attention to rainfall because it is directly linked to pasture production amount and timing, on which their livelihoods depend (Marin 2010).

Across all *soums* and zones, both herders and the meteorological record observed negative trends in total rainfall amount. The greatest concordance between local observations and the instruments was in the steppe, where observations of the direction of change matched for 7 of 9 variables, and 5 of these were statistically significant in the instrument record. Mountain and forest steppe herder observations aligned with instrument records for 5 variables, of which 2 showed statistically significant trends in the instrument record. Desert steppe herder observations only aligned with one instrument record (annual rainfall), and contradicted instrument record trends in brown-down (Ulziit) and summer temperatures (Undurshil). Rather than concluding that herder observations are inaccurate, as some have done (Li et al. 2014), we suggest that finer-resolution meteorological and pasture production data are needed to explain the apparent inconsistencies. As Klein et al. (2014) showed, herder observations may contribute to understanding fine-scale variability in important climate change impacts such as phenology.

Table 1. Rate of change in temperature (degrees Celsius per year), precipitation (mm per year), greenness (NDVI) and phenology based on meteorological and remote sensing data. Changes analyzed using the Mann-Kendal test (Z-statistic) and Sen’s slope. Significant trends are highlighted, and significance is indicated as * p<0.05, ** p<0.01, *** p<0.001. All variables are from 1993-2013 except for amount of rainfall (1993-2012) and NDVI, green-up and brown-down (1993-2009).

	Forest-steppe		Steppe		Desert-steppe	
	Bayangol	Saikhan	Undurshireet	Erdenesant	Ulziit	Undurshil
spring temp	-0.015	-0.027	-0.011	-0.027	0.03	0.022
summer temp	0.04	0.028	0.084*	0.084*	0.05	0.086*
fall temp	0.104	0.108	0.097	0.081	0.029	0.051
winter temp	-0.234*	-0.266*	-0.174*	-0.218*	-0.091	-0.076
amount of rainfall	-2.085	-1.508	-4.5*	-5.417*	-2.734***	-2.199*
days between rainfall	1.778***	1.458**	1.303*	1.545***	-0.226	0.127
greenness (small integral NDVI)	-0.039	-0.028	-0.09*	-0.82*	-0.003	0.082*
green-up	-0.491	-0.494	0.554	1.215	-0.531	-2.676
brown-down	-0.045	0.141	-3.57	-0.666**	1.295	0.042

CONCLUSION AND IMPLICATIONS

Our findings suggest that herder observations are generally highly consistent within communities and that where significant changes are detected by instruments, herders are also observing these changes (i.e. steppe zone). Across all ecological zones the greatest concurrence between instrument records and herder observations was declining rainfall amount. The significant differences in herder observations within ecozones for some variables could indicate that herder observations detect changes at finer spatial resolutions than some coarse-resolution instrument measurements. The lack of instrument data at resolutions meaningful for local pasture management suggests the need to build capacity for rangeland and meteorological monitoring to track changes and communicate local impacts to higher-level decision-makers. Herder observations can complement existing instrument records and highlight areas to prioritize for fine-resolution formal monitoring. Further research is needed to document the livelihood and management impacts of the changes herders are observing.

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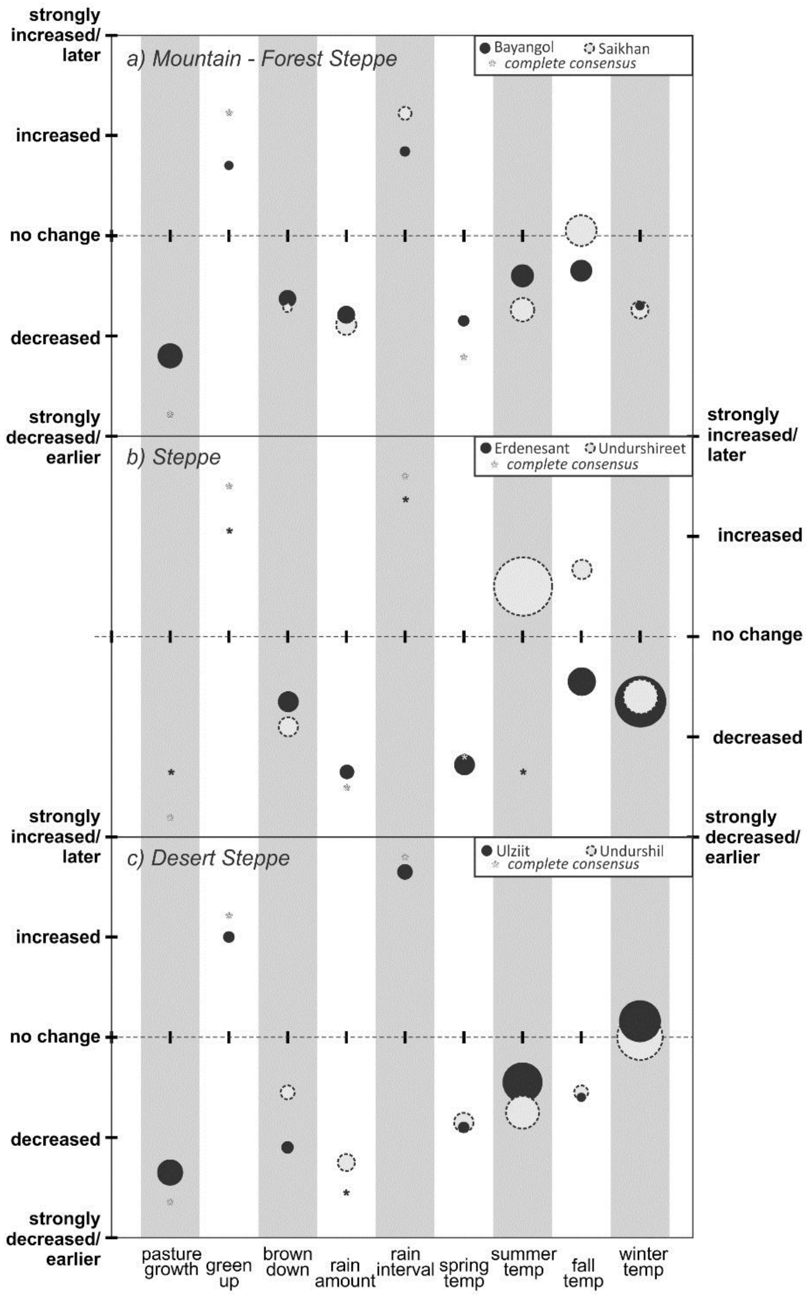

Figure 1. PCI2 results reflecting the amount of consensus regarding a given observation in the a) mountain and forest steppe, b) steppe, and c) desert steppe. A small bubble represents high consensus and a large bubble represents low consensus. Bubble centers represent the mean response.