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Integrating Traditional Ecological Knowledge and Remote Sensing for Monitoring Rangeland Dynamics in the Altai Mountain Region

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Abstract
Integrating traditional ecological knowledge (TEK) with remote sensing capabilities to monitor rangeland dynamics could lead to more acceptable, efficient, and beneficial rangeland management schemes for stakeholders of grazing systems. We contrasted pastoralists' perception of summer pasture quality in the Altai Mountains of Central Asia with normalized difference vegetation index (NDVI) metrics obtained from Terra Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor. The spatial relationship between satellite-based assessment of the grassland quality and on-the-ground evaluation by local herders was first assessed for a single year using 49, 1 × 1 km grassland blocks sampled in July 2013. Herder-derived forage value was positively and strongly (63% of variance explained) related to satellite-derived NDVI values (MODIS 1 km monthly data, MOD13A3) as well as field estimates of % vegetation cover (62% explained) and to a lesser degree to vegetation height (28% explained). Herders' multi-year perception (i.e., recall ability) was also contrasted with satellite observations of their herding areas over the period of 2006–2016 during which NDVI temporal anomaly explained >11% of variance in estimates of pasture quality recalled. Few herders in Kazakhstan could recall pasture conditions, most herders in Russia and China could but inconsistently (4 and 7% variation explained, respectively), whereas most herders in Mongolia could recall pasture conditions in strong agreement with NDVI anomaly (30% variation explained), patterns reflecting herders' regional dependence on herding as a livelihood. Corroboration of herder-derived estimates and satellite-derived vegetation indices creates opportunity for re-expression of satellite data in map form as TEK-derived indices more compatible with herder perceptions.

Keywords Traditional ecological knowledge · MODIS · NDVI · Rangelands · Herders · Altai Mountains

Introduction

Grasslands occupy >25% of the Earth's surface (Olson et al. 1983; White et al. 2000) and support >20 million households as pastures for their livestock (De Haan et al. 1997). Large-scale monitoring of grassland ecosystems has been enabled by satellite-borne remote sensing since the 1970s (Booth and Tueller 2003; Liu et al. 2005) via indices derived from grassland vegetation's spectral responses. Vegetation indexes have provided a basis for phenological monitoring, vegetation classification, and derivation of structural vegetation parameters, such as plant greenness, biomass, and leaf area index (Huete et al. 2002).

A complementary but vastly underutilized source of information for grassland assessment and monitoring are pastoralists themselves. Pastoralists' continuous interaction with the environment and their keen observation skills yield a practical understanding of grassland ecology and dynamics often referred as herders' traditional ecological knowledge (TEK) (Spooner 1973; Niamir-Fuller 1995; Fernandez-Gimenez 2000). TEK of pastoralists derives from the ability to efficiently characterize pasture quality, livestock carrying capacity, optimal timing for grazing, palatability of different plant species for livestock, protective features of landscape, seasonal forage distribution and availability, and many other dimensions of grasslands and their use (Fernandez-Gimenez 2000; Oba and Kotile 2001; Ghorbani et al. 2013; Egeru et al. 2015), which directly influences how pastoralists use the resource (Homewood and Rodgers 1989; Mills et al. 2002). Pastoralists' TEK is

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still poorly documented, however, which makes its integration into grassland research, management, and policy development problematic (Fernandez-Gimenez 2000; Oba 2012) or simply neglected (Brown 1971; Roba and Gufu 2009). Most importantly, rangeland monitoring schemes, no matter how scientifically rigorous, when disconnected from TEK often have low perceived relevance by local communities and hence limited acceptance for use in locally based decision-making often decreasing effectiveness of government programs aimed to support pastoralists (Fernandez-Gimenez 2000; Selemani et al. 2012).

Integrating TEK and remote sensing for monitoring rangeland dynamics could make monitoring and management schemes more acceptable and beneficial for all stakeholders of grazing systems including herder communities, regional decision-makers and ecologists (Robbins 2003). Over the last two decades some efforts have been made to integrate remote sensing and TEK for survey, monitoring and management of different ecosystems (Hellier, Newton and Gaona 1999; Robbins 2003; Huntington et al. 2004; Naidoo and Hill 2006; Lauera and Aswani 2008; Maynard et al. 2016; Polfus et al. 2014), but few studies were devoted to directly contrast herder knowledge and satellite-derived data upon which integration of both knowledge systems for advancing grassland research and monitoring depends (Klein et al. 2014; Egeru et al. 2015; Fernandez-Gimenez et al. 2015). Clearly the mechanics for integrating TEK and remote sensing for grassland monitoring and management require further evaluation as practical cases of integration remain rare (Sulieman and Ahmed 2013; Egeru et al. 2015; Fernandez-Gimenez et al. 2015).

Our study was focused on summer pastures over 10 years (2006–2016) in the Altai Mountains (parts of Mongolia, Russia, China, and Kazakhstan) where herder communities are heavily dependent on rangelands for their livelihoods. Most of the region lacks any coherent policy or monitoring scheme to help balance rangeland use by pastoralists and their livestock with conservation of the significant biodiversity values of the region (Maroney 2005; Bailagasov 2011; Addison et al. 2012; Naidansuren and Bayasgalan 2012; WWF 2012). To address this research gap, our study's primary objective was to elucidate the association between pastoralists' TEK and satellite-derived MODIS normalized difference vegetation index (NDVI) of grassland condition. NDVI is one of the most often used indices for monitoring of terrestrial vegetation (Huete et al. 2002) and has been applied in grasslands and rangelands research and monitoring around the world (Purevdorj et al. 1998; Akiyama and Kawamura 2007; Boone et al. 2007; Colombo et al. 2011; Ferreira et al. 2004). NDVI represents a combination of near-infrared and red bands reflecting spectral characteristics of vegetation: $NDVI = (NIR - Red)/(NIR + Red)$. NDVI offers optimal performance in mountain areas due to its low sensitivity to topography-induced uncertainty (Matsushita et al. 2007); however, the index can be affected by atmospheric conditions and soil; it also saturates in the high vegetation biomass regions (Huete and Justice, 1999). We explored the degree of corroboration provided by (1) the spatial relationship between satellite-based assessment of the grassland quality and on-the-ground evaluation by local herders employing traditional measures of forage value for livestock, and (2) the temporal relationship between NDVI and herder assessments in the context of herders' ability to reconstruct historical rangeland conditions. We tested two hypotheses critical to the concept that satellite- and herder-derived indices of rangeland quality are compatible for integration: (a) herders' estimates of grassland forage value for livestock positively correlate with satellite-derived indices across a strong spatial gradient of grassland productivity; and (b) herder's perception of summer pasture quality for a particular year positively correlates temporally with satellite-derived indices for the same pastures.

Materials and Methods

Study Area

Our study area in the Altai Mountains (47°35'–50°13' N, 85°32'–90°43' E) incorporated spatially adjacent areas of Mongolia (Ulaankhus and Nogoonnuur somons (districts) of Bayan-Olgii Aimag), Russia (Kosh-Agach district of Altai Republic), China (Altai Prefecture of Xinjiang Autonomous Region), and the Republic of Kazakhstan (Katon-Karagay district of Eastern Kazakhstan Region) (Fig. 1). This is a high mountain grassland region in the very center of the Eurasian continent traditionally used by Kazakhs and Altaians for livestock grazing. The Altai is also recognized as a UNESCO World Heritage Site (UNESCO 1992–2016) for its landscape diversity and high value for conservation of endangered species, including snow leopard (*Panthera uncia*) and Altai argali (*Ovis ammon ammon*) (Maroney 2005; Paltsyn et al. 2012).

The area is characterized by mountains, hills and intermountain depressions (elevation range: 800–4506 m). In the Mongolian and Russian parts of our study area the landscape is dominated by mountain grasslands, whereas in the Kazakhstan and China sectors coniferous forests interspersed with grasslands are more prominent. The region has a strong continental climate with a short growing season (April–August), severe winters, wide annual precipitation range (from 121 mm in Bayan-Olgii, Mongolia, to 441 mm in Katon-Karagay, Kazakhstan), and average annual temperature from −4.0° (Kosh-Agach, Russia) to 2.8 °C (Altay, China) (unpublished data from Bayan-Olgii, Kosh-Agach,

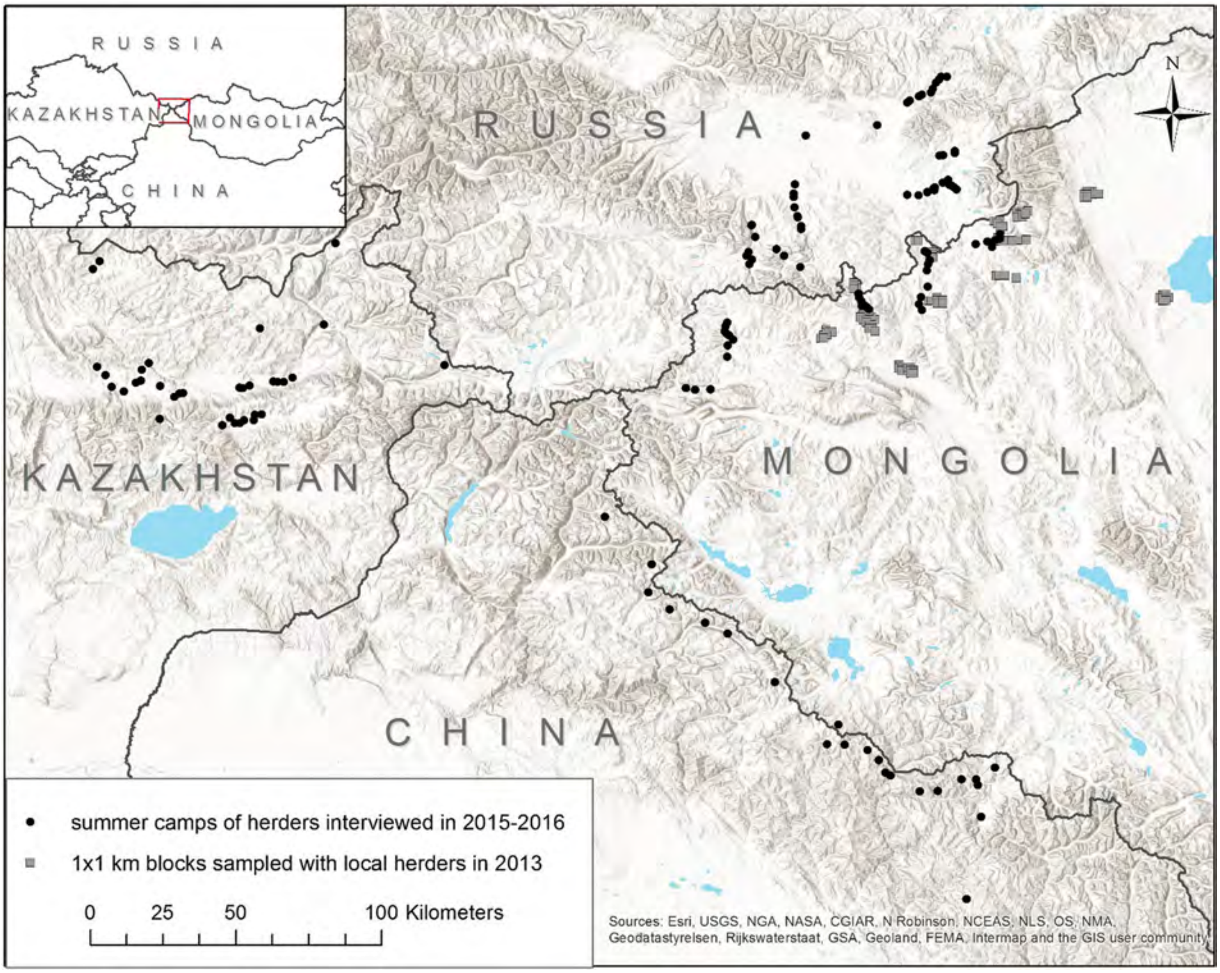

Fig. 1 Study area in the Altai Mountains, including Ulaankhus and Nogoonnuur somons of Bayan-Olgii Aimag, Mongolia; the Kosh-Agach district of Altai Republic, Russia; the Katon-Karagay district of Eastern Kazakhstan Region, Republic of Kazakhstan; and Altai prefecture of Xinjiang Autonomous Region, China. Point locations are given for 1 km^2 sampling blocks assessed in July–August 2013 (gray blocks) and also for summer camps (black dots) where herders were interviewed in 2015–2016 about summer pasture quality during 2006–2016. For this study we purposefully chose a gradient-based approach to allocate sampling effort in order to maximize the ecological contrasts present in the study region (from relatively moist high mountain pastures to arid semi-deserts) while recognizing logistical efficiencies (traveling in a sequential manner along the elevational gradient)

Katon-Karagay, and Altay meteorological stations for 2005–2014). Mean grassland productivity on summer pastures, as captured by MODIS NDVI values, varies inversely with its temporal variance such that the regions with the highest mean NDVI have the lowest annual variation (e.g., Kazakhstan segment) and vice versa (e.g., Mongolia segment, Fig. 2).

Analytical Approach

Contrasting Herder-Derived Estimates of Grassland Forage Value and Terra MODIS NDVI Data

We obtained co-located and temporally coincident estimates of rangeland condition for both MODIS-derived normalized difference vegetation index (NDVI) and herder-derived forage

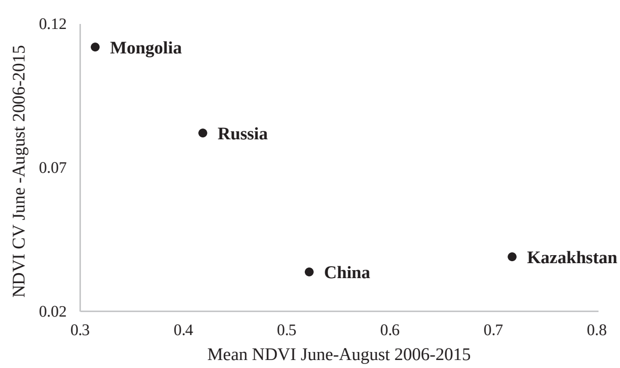

Fig. 2 Ecological contrasts among regions studied in the Altai Mountains in terms of mean NDVI and its temporal coefficient of variance (CV, June–August 2006–2015) for grasslands around summer camps (5-km-radius circular buffer) of herders interviewed about summer pasture conditions in Mongolia, Russia, China, and Kazakhstan

values at 92, 1 × 1 km blocks sampled in the Bayan-Olgii Aimag of Mongolia in 2013 (Fig. 1). We consider our sampling area representative because the region comprises the same montane landscape complex with similar ecosystems and captures the variation seen among them in terms of grassland composition and structure. NDVI is one of the most often used global-based vegetation indices for monitoring of terrestrial vegetation (Huete et al. 2002). It is widely applied in rangeland monitoring (Purevdorj et al. 1998; Akiyama and Kawamura 2007; Boone et al. 2007; Colombo et al. 2011; Ferreira et al. 2004). NDVI offers optimal performance in mountain areas due to its low sensitivity to topography-induced uncertainty (Matsushita et al. 2007).

All sampled blocks were located between 1495 and 2860 m above sea level that we purposely selected to represent the full range of grassland cover present in the region from mountain grassy tundra to dry grasslands and semi-deserts. NDVI is a frequently used index for grassland monitoring (Huete et al. 2002) and to obtain remotely sensed estimates of conditions of ground vegetation, we accessed Terra MODIS NDVI Monthly L3 Global 1 km SIN Grid V005 dataset (MOD13A3, tile h23v04) for July 2013 downloaded from the NASA's EOSDIS Reverb website (http://reverb.echo.nasa.gov/reverb/). For field sampling each MODIS tile was re-projected to WGS 1984 UTM Zone 45 projection and clipped to our study area. Coordinates of centers of every 1 × 1 km pixel in the study area were calculated in ArcGIS 10.2.2 (ESRI 2014).

Between July 18 and August 3, 2013 we sampled herder-derived forage value as well as percentage of vegetation cover, vegetation height, and percentage of grass and forbs at the same 92 sites where MODIS NDVI estimates were gathered (Fig. 1). To estimate the vegetation parameters in each sampled block a rangeland ecologist walked simultaneously with a local herder in an ever-increasing, spiral-shaped, 4800-m-long transect guided by a hand-held GPS unit achieving approximately equal sampling coverage of each block via the transect design (Fig. 3). A total of 4 herder-ecologist pairs completed the survey work. The ecologist-herder pair stopped every 25 paces along each transect to enable the herder to make a point estimate of *vegetation forage value* (0—low, 1—medium, and 2—high). At the same point the ecologist made a point measurement of *vegetation cover* (vegetation versus bare ground), *vegetation height* (none: 0 cm, low: 0.1–5.0 cm, medium: 5.1–15.0 cm, and high: >15.0 cm) and *vegetation composition* (% no vegetation, grass or forb) at the sampling point touched by a pin placed at the leading edge of the surveyor's foot. The point estimates accumulated along a given transect in each block were used to calculate (a) herder-derived forage value for a given sampling block as weighted average of points in three categories; (b) proportion of points that were vegetated among all sampled points

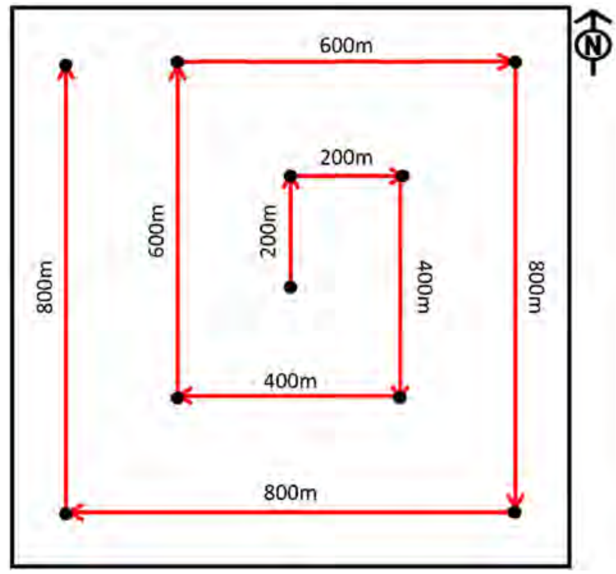

Fig. 3 Sampling design used for estimating of vegetation cover and herder-derived forage value on each of 92, 1 × 1 km blocks aligned with MODIS grid in the Sailugem area of western Mongolia portion of the Altai Mountains in July–August 2013. Black frame represents a 1 × 1 km sampling block; red lines depict segments of a 4800-m-long sampling transect and arrows the direction of movement during sampling

within a given sampling block; (c) average vegetation height as a weighted average of points in four height categories; and (d) proportion of points that were grass or forb among all sampled points within given sampling block (average $n = 215$ points per sampled block, range = 167–255 depending on stride length of surveyors).

Simple linear regressions were used to contrast the relationship (based on the coefficient of determination, R^2_{adj}) of herder-derived vegetation forage estimates to other grassland parameters measured by the ecologist and to the spatially co-located and temporally coincident Terra NDVI values. Only pixels of highest reliability (QA = 0 "Good data") (NASA LP DAAC, 2016) within the MODIS NDVI dataset were used for the regressions ($n = 49$ from sampled 92 blocks). We used the same simple linear regression approach to contrast herders' estimate of forage value with percentage of vegetation cover, vegetation height and percentage of grass and forb in the vegetation cover on the same 49 sampling blocks to understand how these vegetation parameters influence herder's estimates on the grassland forage value.

Evaluating Correspondence between Herders' Recollection of Summer Pasture Quality and Satellite-derived Indices over the Previous Decade

We compiled time series of herder recollections of rangeland quality during July–August 2015 and August 2016 through standardized interviews with 187 local herders on summer pastures throughout the Altai Mountain region: in Ulaankhus and Nogoonnuur somons of Bayan-Olgii Aimag, Mongolia ($n = 53$); Kosh-Agach district of Altai Republic, Russia ($n = 51$); Katon-Karagay district of Eastern Kazakhstan region, Kazakhstan ($n = 34$); and Altai prefecture of Xingjian, China ($n = 49$) (Fig. 1). Most herders were long-term tenants of the sites (mostly intermontane valleys) where we interviewed them: average duration of tenure at a given interview site had been 11.5 years in Kazakhstan, 14.9 years in Russia, 15.4 years in China, and 26.0 years in Mongolia. Each interview lasted 30–40 min on average and each was conducted at the herder's summer camp in the Kazakh language in Mongolia and China and in Russian in Russia and Kazakhstan without translators by local collaborators (two in Mongolia and China, three in Russia, and one person in Kazakhstan) each of whom had worked in their respective interview area for >20 years (Russia, Mongolia, and China) and >7 years in Kazakhstan. Questions were standardized among countries and interviewers trained in delivery prior to initiating surveys. During each survey herders were asked to recall an estimate of the quality their summer pasture for each year in sequence between 2006–2015 (2006–2016 in China) using the following scale: "bad", "average", and "good". Location of the herders' summer camps were recorded with a hand-held GPS unit (Fig. 1) enabling us to link the historical record of herder recollection of rangeland condition with the satellite-derived estimates for the same summer pastureland.

We extracted mean annual NDVI values for June–August (the period each year when herders locate to summer pastures) for 2006–2015 for areas <5 km from locations of each summer camp of interviewed herders using inverse distance weighted (IDW) average:

$$\mathrm{NDVI\ IDW\ mean} = \frac{\sum_{i=1}^{n} 1/d_i^2\ \mathrm{NDVI}_i}{\sum_{i=1}^{n} 1/d_i^2},$$

where d_i is a distance (meters) from pixel i center to the interviewed herder's camp. We used IDW to calculate average NDVI value for the summer pastures around the herders' camps because the herders use the sites closer to the camp more intensively then other parts of their pastures and it is likely to be reflected in their perception of the pasture quality in the particular year.

We extracted from herder interviews: (1) percentage of herders who were able to recall pasture conditions for each particular year in 2006–2015 (2006–2016 in China) and (2) average estimate from among those herders reporting of summer pasture quality for each year calculated as percentage of mean perception over the same 10 years (data not available for Kazakhstan, see Results), coded as bad = 0, average = 1, and good = 2. The Gini-Simpson index (Jost 2006) was used as a measure of level of herder agreement about estimates of the pasture quality in any given year. Simple linear and multiple regressions were used to relate herders' perception and agreement on pasture quality (both used as dependent variables) with NDVI anomaly for each year (an independent variable) calculated as percentage of the mean NDVI for a site over the same 10 years (2006–2015, 2006–2016 in China) to which herders' recollections pertained, and number of years lapsed from 2015 (2016—in case of China) (an independent variable).

Results

Contrasting Herder-Derived Estimates of Grassland Forage Value and Terra MODIS NDVI Data

Vegetation parameters across the 49, 1 × 1 km grassland blocks with highest reliability (QA = 0 "Good data" for MODIS sensor) varied as follows: % vegetation cover—from 9 to 100% (mean = 60%), average vegetation height—from 0 to 10 cm (mean = 4 cm), % grass—from 22 to 90% (mean = 55%), and percentage of forb—from 11 to 93% (mean = 44%). Average herder-derived forage value varied from 0.28 to 1.91 (mean = 1.11 with theoretical minimum = 0 and maximum = 2). Herders' estimates of forage value in July 2013 were strongly and positively correlated with % vegetation cover (>62% of variance explained, Fig. 3b) and vegetation height (>28% of variance explained, Fig. 3c) measured on those same sampling blocks. No relationship ($P > 0.05$) was observed between forage value and % grass or % forb in vegetation cover. Multiple linear regression with standardized variables indicated that percentage of vegetation cover exerted >x2 higher influence on herder perception of pasture forage value than did vegetation height (Table 1).

In terms of relationships between ground-level assessments and satellite-derived estimates, herders' estimates of forage value in July 2013 were strongly and positively correlated with Terra MODIS NDVI sampled in the same month (>63% of variance explained, Fig. 4a). Both % vegetation cover and vegetation height correlated positively with NDVI but with different degrees of variance explained (69% and 11%, respectively, Fig. 4d, e).

Evaluating Herders' Recollection of Summer Pasture Quality over 2006–2016

Over the decade-long assessment period (2006–2015 [2006–2016 for China]), 98% of interviewed herders in Mongolia and China, 86% in Russia, and only 6% in Kazakhstan could report about the pasture conditions back to 2006 (lack of herder recollection in Kazakhstan precluded further analysis of temporal patterns of herder assessments). Mean herder perception of pasture quality in a particular year measured as the percentage of mean perception of pasture quality for 10 years (2006–2015 [2006–2016 for China]) varied from 33.6% (2010) to 157.8% (2013) in Mongolia (CV = 0.408); from 84.8% (2015) to 104.5% (2012) in Russia (CV = 0.056); and from 39.3% (2015) to 132.1% (2006) in China (CV = 0.286). NDVI anomaly varied over the same period from 85.0% (2008) to 125.1% (2013) in Mongolia (CV = 0.112), from 85.4% (2008) to 115.7% (2013) in Russia (CV = 0.082), and from 91.6% (2008) to 105.4 (2016) in China (CV = 0.034) (Fig. 5a–c). Herder perceptions and satellite indices of annual variation in grassland productivity were similar insofar as NDVI anomaly explained >11% of variance in average herder score of pasture quality ($P < 0.05$, Fig. 5d, Table 2a). When data were subset separately for Mongolia, Russia, and China, NDVI anomaly explained >30% of the variance in Mongolia where this regression was nearly

Table 1 Parameters and coefficients of determinations (R^2) from multiple linear regression relating herder-derived forage value to % vegetation cover and vegetation height on 1 × 1 km blocks ($n = 49$) sampled in Sailugem Range in western Mongolia, July–August 2013

Parameter	Coefficient	Std. Err.	*t*	*P*-value
Intercept	0.000	0.081	0.00	1.000
% of Veg. Cover	0.684	0.088	7.775	<0.0001
Vegetation height	0.285	0.088	3.245	0.002

Variables standardized to permit comparison of relative contributions of each to variation in herder-derived forage value

Model $F = 51.84$; $P < 0.0001$; $R^2_{adj} = 0.679$

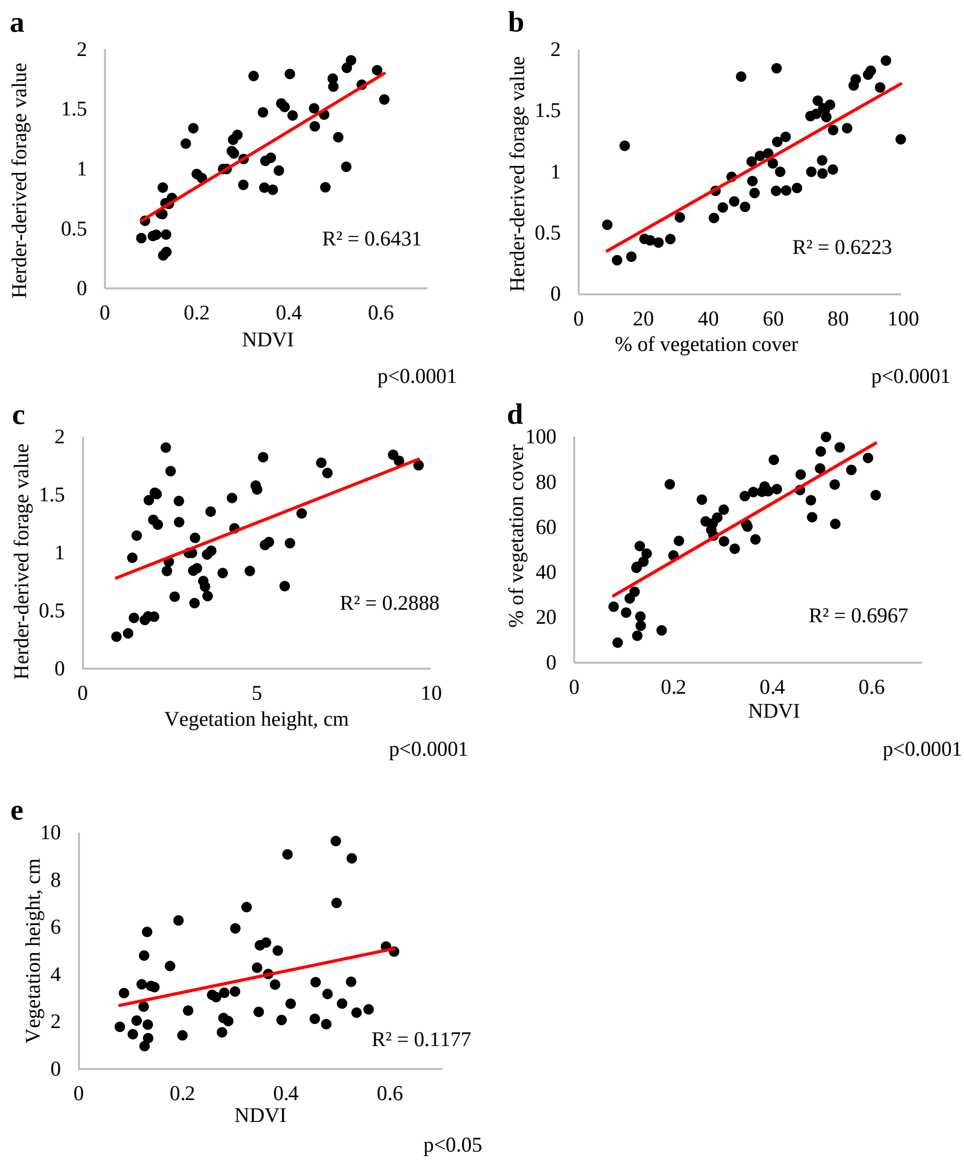

Fig. 4 Relationships among herders' estimation of forage value, Terra-derived MODIS NDVI, % vegetation cover, and vegetation height at 49 sampling sites in Sailugem Range of the western Mongolia portion of the Altai Mountains during July–August 2013

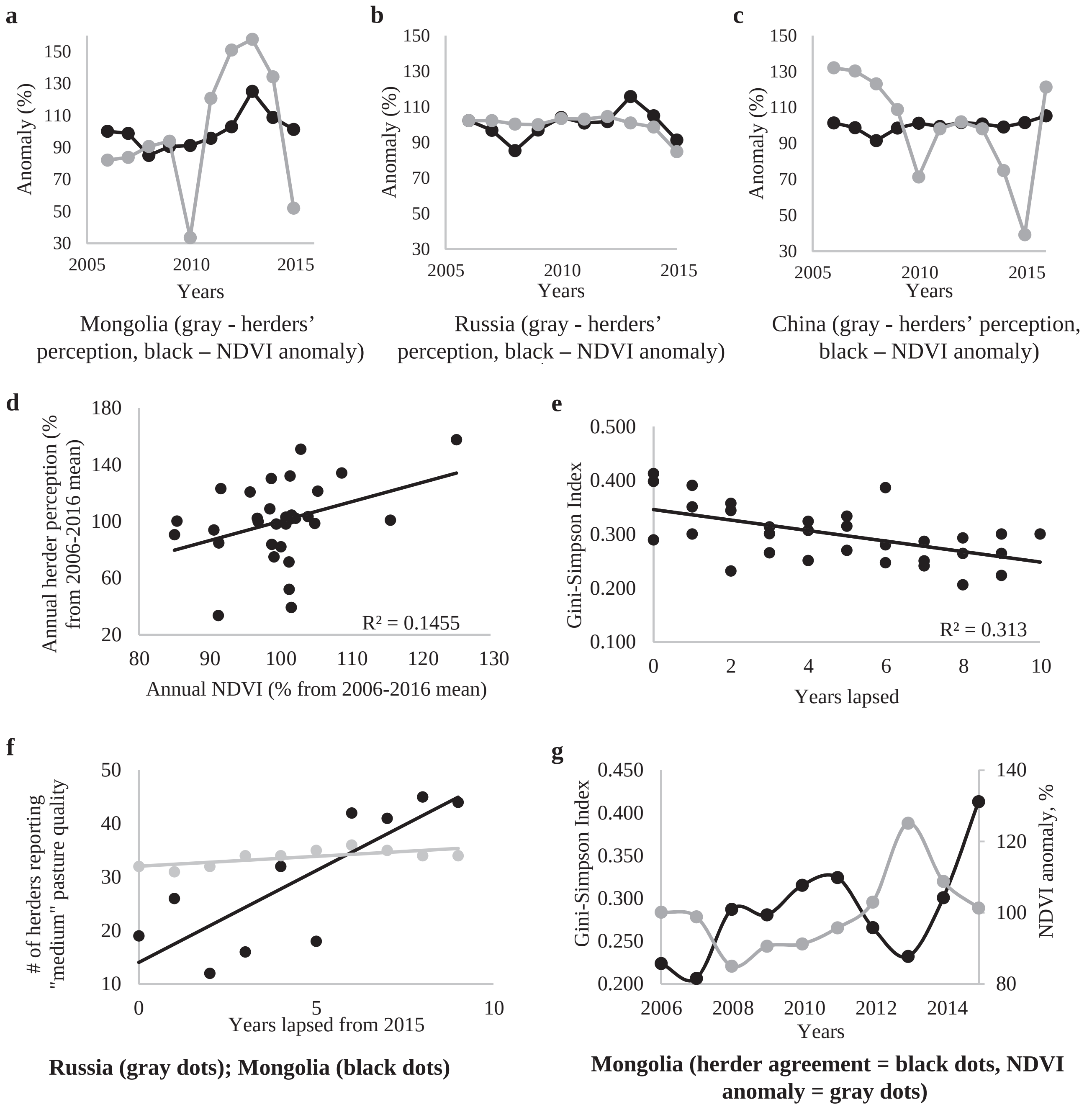

Fig. 5 Temporal patterns of herder perceptions of grassland quality and satellite-derived measures. **a**–**c** NDVI anomaly in June–August and herder's perception of summer pasture quality in the 5 km buffer zones of herder camps measured over 2006–2016 in in Altai Mountain range, Mongolia, Russia, and China. **d**–**e** Linear regressions describing relationships between **d** herder perception of pasture quality and NDVI anomaly in June–August in the 5 km buffer zones of herder camps in Mongolia, Russia, and China in 2006–2016; and **e** Gini-Simpson Index (measure of herders' agreement) and years lapsed from 2016. **f**–**g** Number of herders in Russia (gray) and Mongolia (black) reporting "medium" summer pasture quality in 2006–2015 **f**; Dynamics of Gini-Simpson Index as a measure of herder agreement (black) and NDVI anomaly in Mongolia (gray) between 2006 and 2015 **g**

significant ($P = 0.056$) (Table 2b), only ~4% of variance in the herder perception in Russia ($P = 0.280$) (Table 2c), and ~7% of variance in China ($P = 0.552$) (Table 2d). Similarly, NDVI anomaly combined with years lapsed from 2016 explained >32% of variation in herder agreement on pasture conditions (as measured by Gini-Simpson Index, Table 2e; Fig. 5e) indicating that there was more agreement among herders with more years lapsed. When data were subset separately for Mongolia, Russia, and China years lapsed remained a significant predictor of herder agreement on pasture quality for both Mongolia and Russia whereas NDVI anomaly remained so for Mongolia only (Table 2f,

Table 2 Parameters of linear regressions describing relationship between herder perception of summer pasture quality, herder agreement (Gini-Simpson Index), NDVI anomalies in June–August in the 5 km buffer zones of herder camps in Mongolia, Russia, and China portions of the Altai Mountains over the past decade (data from Kazakhstan excluded for lack of herder recall there, see Results)

Parameter	Coefficient	SE	*t*	*P*-value
Herder perception of pasture quality versus NDVI anomaly				
a. All countries ($F = 4.94$; $p = 0.034$; R^2 adj = 0.116):				
Intercept	−35.776	61.271	−0.584	0.564
NDVI anomaly	1.358	0.611	2.223	**0.034**
b. Mongolia ($F = 4.99$; $p = 0.056$; R^2 adj = 0.307):				
Intercept	−125.688	101.608	−1.237	0.251
NDVI anomaly	2.257	1.011	2.234	**0.056**
c. Russia ($F = 1.34$; $p = 0.280$; R^2 adj = 0.037):				
Intercept	74.016	22.507	3.289	0.011
NDVI anomaly	0.260	0.224	1.158	0.280
d. China ($F = 0.38$; $p = 0.552$; R^2 adj = 0.066):				
Intercept	270.853	276.617	0.979	0.353
NDVI anomaly	−1.709	2.765	−0.618	0.552
Herder agreement versus NDVI anomaly and years lapsed				
e. All countries ($F = 8.14$; $p = 0.002$; R^2 adj = 0.322):				
Intercept	0.525	0.116	4.522	0.0001
NDVI anomaly	−0.002	0.001	−1.555	0.131
Years lapsed	−0.012	0.003	−4.034	**0.0004**
f. Mongolia ($F = 18.97$; $p = 0.002$; R^2 adj = 0.800):				
Intercept	0.799	0.103	7.736	0.0001
NDVI anomaly	−1.341	0.299	−4.487	**0.003**
Years lapsed	−0.021	0.003	−5.954	**0.0006**
g. Russia ($F = 18.30$; $p = 0.002$; R^2 adj = 0.794):				
Intercept	0.334	0.115	2.911	0.023
NDVI anomaly	0.001	0.001	0.446	0.669
Years lapsed	−0.017	0.003	−5.686	**0.001**
h. China ($F = 0.16$; $p = 0.850$; R^2 adj = 0.200):				
Intercept	0.326	0.531	0.615	0.556
NDVI anomaly	−4.514E−05	0.005	−0.009	0.993
Years lapsed	−0.003	0.005	−0.495	0.634

Bold values significant *P*-values (< 0.05) and marginally significant *P*-values (0.056)

g). In case of China both predictors – NDVI anomaly and years lapsed – were not significant (Table 2h). Increased herders' agreement on the pasture quality (reduced Gini-Simpson Index) with years lapsed back from 2015 for both Russia and Mongolia was associated with herders tending to rank pasture quality to an average level of as "medium" with increasingly years lapsed (Fig. 4e). Notably, variability of Gini-Simpson Index was higher in Mongolia (CV = 0.210) than in Russia (CV = 0.187) and China (CV = 0.139) (Table 2f; Fig. 5d).

Discussion

By evaluating relationships between herder TEK and satellite-derived measures of rangeland condition over time and space we sought to understand the degree of correspondence between them and hence opportunity for integration of herders' TEK and remote sensing derived indices of rangeland quality. Our results demonstrate a relatively high level of consistency between herder-derived estimates of pasture forage values and monthly Terra MODIS NDVI datasets in western Mongolia where validation studies were conducted (Fig. 3a). This primary outcome supports our first hypothesis that satellite indices and herders' perceptions reflect in a similar manner spatial variation in grassland productivity.

NDVI is a complex index in terms of its relationship to ecological parameters measured on the ground and to those of relevance to herders. Relative composition of grass and forbs in the vegetation cover apparently had no influence on the herders' assessment of pasture forage value, whereas forage value strongly associated with percentage of vegetation cover (68% of overall variance explained) and less so with vegetation height (30%). We did not integrate plant species composition and relative palatability known to be used by Mongolian herders to estimate pasture forage quality (Fernandez-Gimenez 2000) because these parameters are unlikely to be reflected in variation in the MODIS vegetation index. Mongolian herders do rely heavily on vegetation cover to assess pasture quality (Fernandez-Gimenez 1997, 2000) with vegetation cover known to drive variation in NDVI (e.g., Purevdorj et al. 1998; Liu et al. 2005; Guo et al. 2007; Cui et al. 2012). In addition to vegetation cover, vegetation height is also used in the herders' estimates of pasture forage value (Fernandez-Gimenez 1997, 2000). Both cover and height were positively correlated with monthly MODIS NDVI data, however, magnitude of these correlations was much stronger for percentage of vegetation cover (>69% of variance explained) than for vegetation height (~12%). This was expected as optical sensors, such as MODIS, return a signal from the Earth's surface with limited ability to measure heights. Similarly, Kong et al. (2015) also found that assessment of rangeland conditions by local herders in the rangelands of South African Kalahari Duneveld was consistent with on-the-ground measurements of vegetation and bare ground cover whereas Landsat-derived NDVI, Soil Adjusted Vegetation Index (SAVI) and tasseled cap greenness poorly correlated with both herders' assessment and on-the-ground measurements due to soil parameters in that influenced performance of the vegetation indices (Kong et al. 2015).

Other cases of spatial correlations between TEK and remotely sensed indices for spatial assessment and mapping of ecosystems have been described. Naidoo and Hill (2006) found that vegetation classification of Mbaracayu Forest Reserve in Paraguay by Ache indigenous tribe was consistent with a supervised classification of Landsat 7 TM imagery of the reserve. Lauera and Aswani (2008) also described a successful case of integration of indigenous ecological knowledge of fishers from Solomon Islands and remote sensing analysis to interpret Landsat-7 ETM multispectral satellite image and produce accurate broad-scale marine habitat maps useful for management. In a related study, Pitt et al. (2012) reported on high value of local ecological knowledge (LEK) as an additional tool for remote sensing to identify isolated wetlands in South Carolina's Piedmont and Blue Ridge regions: LEK yielded discovery of 5–6x more isolated wetlands than aerial photography analysis.

Study outcomes also supported the hypothesis of temporal correlation of herders' perception of summer pasture quality with satellite-derived indices for the same pastures, albeit with some important caveats. Although herder perception of summer pasture quality in Mongolia, Russia, and China together reflected NDVI anomalies around their summer camps in 2006–2015, these correlations were weak ($R^2_{adj} = 0.12$) (Table 2a). When considered by country, herder perception of grassland quality over time was not related to NDVI anomaly in Russia and China, whereas in Mongolia it was marginally so ($P = 0.056$) and explained >30% of herders' perception variance. Notably, negative peaks of herders' perception of 2010 both in Mongolia and China and another strong drop in herder recollection of pasture quality in China in 2015 (Fig. 5a, c) were not associated with notable changes in grassland productivity as reflected by NDVI, but did coincide with *dzud* (heavy snowfall associated with unusually low temperature leading to massive livestock die-offs). *Dzud* events occurred during winters 2009–2010 and 2015–2016 both in western Mongolia and Altai prefecture of Xinjiang and resulted in a total ~10 million livestock deaths and significant economic losses for herders (Shang et al. 2012; Seaniger, 2016). No dramatic livestock decline was reported for the Russian part of our study area in 2006–2016. We speculate that herders' perception of pasture quality in Mongolia and China was influenced by and perhaps conflated with effects of *dzuds*. A similar disproportionate influence of extreme climate events with dramatic impact on their livelihood than real changes of climate conditions on rangeland assessments was found for herder communities on Qinghai–Tibet Plateau (He and Richards 2015).

The perhaps counterintuitive pattern of herders' agreement on the pasture quality increasing with more years lapsed (Table 2e; Fig. 5e) can be explained less by similarity of historical conditions than by herders tending to rank pasture quality as "medium" with increasing years lapsed (Fig. 5f). We propose that herders likely recall pasture conditions with less specificity as period of recall increases such that they collectively converge upon a "medium" assessment, a pattern expressed in our data (Fig. 5e). Mongolian herders tended to demonstrate higher agreement on years with "good" pasture quality and high mean NDVI values and have more disagreement about "bad" years with relatively low mean NDVI (Fig. 5g). Thus, it seems years 2007, 2012, and 2013 with high vegetation productivity triggered widespread agreement by majority of herders as "good" years, however, relatively low production years (2008–2010) were perceived quite differently among herder groups.

Regional-scale factors, particularly grassland productivity and its variability, also seemed to affect degree of correlation of herder perception with satellite-derived NDVI values. More specifically, mean NDVI on summer pastures and its temporal variation were inversely related among countries such that the least productive areas (Mongolia) also had the highest temporal variation in productivity while the most productive areas (Kazakhstan) had one of the lowest temporal variation (Fig. 2). Remarkably, no more than 6% of interviewed herders in Kazakhstan could recall pasture conditions back to 2006, whereas most herders in Russian and Chinese Altai recalled pasture conditions back to 2006; however, the perception of herders in Russia and China of pasture conditions was not related to NDVI anomaly. Only in Mongolian Altai with its low pasture productivity and high productivity variance was NDVI anomaly consistently related to herder assessment and agreement on pasture quality in different years. We conclude that stronger influence of vegetation productivity on socio-economic conditions of the herders' livelihoods (mainly number of livestock they depend on), which is the case in Mongolia, drives more detailed and consistent recollection of actual pasture conditions whereas in areas where dependence of livestock is less (Russia, Kazakhstan, and China) herder recall is correspondingly weaker (Table 3).

Other studies have demonstrated varying strengths of herder recall associated with regional factors. Egeru et al. (2015) in savanna grasslands of Uganda found similar, but much stronger positive correlations ($R^2 = 0.79$) between herders' perception of forage availability and monthly long-term NDVI values derived from National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA-AVHRR). Fernandez-Gimenez et al. (2015) reported on general agreement of herder perception with declining trend in rangeland production as revealed by AVHRR-NDVI Selenge and Tuv Aimags of Mongolia in 1993–2013. Klein et al. (2014) reported a long-term NDVI trend (1982–2010) toward delayed rangeland green-up on the Tibetan Plateau corresponded with herders' local observations of shifts in grassland conditions.

Table 3 Summary of rangeland conditions across the Altai Mountain study area including mean NDVI, NDVI CV, percentage of herders that could report on pasture conditions back to 2006, and significance of NDVI influence on herder perception of pasture quality and level of agreement in Mongolia, Russia, China, and Kazakhstan over previous decade

Country	Mean NDVI (2006–2016)	NDVI CV (2006–2016)	% of herders who could recall back to 2006	NDVI influence on herder perception of pasture quality	NDVI influence on herder agreement on pasture quality
Mongolia	0.314	0.112	98%	>30% variance explained, marginally significant	Significant
Russia	0.418	0.082	86%	Insignificant	Insignificant
China	0.521	0.034	98%	Insignificant	Insignificant
Kazakhstan	0.717	0.039	6%	–	–

A strength of our study is the comparative dimension across four different countries combined with large sample sized for interviews in all countries. Our interpretation of causal reasons for variation in herder perception is based primarily on ecological and, to a lesser extent, economic drivers. This said, there are social and cultural factors also at play that could complicate herder responses and our interpretations. These include the possibility of less stable site tenure by herders among countries (e.g., Kazakhstan), the degree of trust and sense obligation toward researchers in terms of propensity to collaborate, share insights, and do so honestly, and the extent to which calendar years are a useful construct for herders to organize and recall memories of rangeland conditions. We are aware of these methodological issues that could have influenced data quality and quantity yet could not identify obvious ways in which they might have operated, except perhaps a distinctly greater guardedness among herders in Kazakhstan in sharing information about herd composition and number, perhaps as a result of our perception of their greater distrust of authority figures there than in the other regions sampled.

The primary conclusion of our study is that herder-derived estimates of pasture forage value at the peak of growing season can be used as additional tool to complement widely used satellite-based methods for assessment of grasslands conditions at local level along with satellite-derived vegetation indices at least in western Mongolia. Western Mongolia, where we observed a high level of spatial and temporal correlations with MODIS NDVI and herder perceptions of rangeland quality, offers the best opportunity. Mongolian herders' decision about pasture quality were influenced greatly by vegetation cover and to a lesser degree by vegetation height. Furthermore, as was reported by Fernandez-Gimenez (1997 and 2000), Mongolian herders generally rely on vegetation cover in their traditional assessment of pasture quality; therefore, this indicator can be better understood and accepted by local communities than other grassland parameters. Given strong correlations of vegetation cover and MODIS NDVI and EVI (Paltsyn et al. 2017) this simple and consistent with traditional herders' knowledge indicator can be basic for participatory rangeland monitoring and management system in western Mongolia. Elsewhere in the Altai region, herders' perceptions of summer pasture quality are positively and significantly correlated with mean MODIS NDVI value for the pastures in June–August for the same year but the relationships are weak and strongly affected by extreme climate events (e.g., *dzuds*) not always associated with inter-annual changes in pasture productivity. Generally speaking, we determined that satellite-derived estimates conform with herder's perceptions but can be obtained at a much broader spatial scale and much more efficiently. Similarly, herders' TEK broadly validates the utility of satellite-derived indices for informing herders of trends and patterns in grassland productivity in the context of parameters of most interest to them (e.g., vegetation cover), thereby possibly facilitating their acceptance of broad-scale, satellite-based rangeland monitoring and management. By extension, given the strength of the spatial relationships we observed in western Mongolia between NDVI variation and on-the-ground TEK estimates, one pragmatic means of increasing herder acceptance of insights from satellite-derived indices of rangeland dynamics would be mapping of herder-derived estimates of pasture forage value projected on the base of the MODIS NDVI values using simple linear regressions we have established between these two parameters.

The issue of integrated monitoring of grasslands is particularly critical in Mongolia where rangelands make up roughly three-fourths of the country's land area, providing pasture for some 56 million head of livestock, and supporting livelihoods for some 26% of the country's inhabitants while generating about 13.5% of Mongolia's GDP (Erdenesan, 2016). However, an estimated 75% of Mongolia's pastureland is overgrazed and overstocked with domestic livestock such that significant degeneration caused both by anthropogenic and climate factors is a major concern for decision-makers and local communities (Stumpp et al. 2005; Naidansuren and Bayasgalan 2012; Hilker et al. 2014). Our studies suggest that decision-makers in western Mongolia responsible for environmental monitoring and grassland management as well as community-based rangeland management organizations could benefit from incorporating simple vegetation cover analysis based on NDVI and heder-derived forage value in their decision-making process that will be consistent with traditional herders' knowledge and practices. To conclude, we provide further support to Egeru et al. (2015), Fernandez-Gimenez et al. (2015), and Klein et al. (2014) regarding the consistency and complementarity of TEK of local herders on pasture and rangeland conditions with satellite-derived vegetation indexes and advocate for integration of local TEK in regional rangeland monitoring and management programes along with remote sensing techniques for a more efficient, applicable and acceptable approach to rangeland monitoring.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

References

Addison J, Friedel M, Brown C, Davies J, Waldron S (2012) A critical review of degradation assumptions applied to Mongolia's Gobi Desert. Rangel J 34:125–137

Akiyama T, Kawamura K (2007) Grassland degradation in China: Methods of monitoring, management and restoration. Grassl Sci 53:1–17. https://doi.org/10.1111/j.1744-697X.2007.00073.x

Bailagasov LV (2011) The use of pastures in light of the establishment of the national park on the ridge Sailugem (Altai Republic). Steppe Bull 31:11–18

Boone RB, Lackett JM, Galvin KA, Ojima DS, Tucker CJ (2007) Links and broken chains: evidence of human-caused changes in land cover in remotely sensed images. Environ Sci Policy 10:135–149

Booth DT, Tueller PT (2003) Rangeland monitoring using remote sensing. Arid Land Res Manag 17:455–467

Brown LH (1971) The biology of pastoral man as a factor in conservation. Biol Conserv 3:93–100. https://doi.org/10.1016/0006-3207(71)90007-3

Colombo R, Busetto L, Fava F, Di Mauro B, Migliavacca M, Cremonese E, Galvagno M, Rossini M, Meroni M, Cogliati S, Panigada C, Siniscalco C, Morra di Cella U (2011) Phenological monitoring of grassland and larch in the Alps from Terra and Aqua MODIS images. Ital J Remote Sens 43:83–96

Cui X, Guo ZG, Liang TG, Shen YY, Liu XY, Liu Y (2012) Classification management for grassland using MODIS data: a case study in the Gannan region, China. Int J Remote Sens 33 (10):3156–3175

De Haan C, Steinfeld H, Blackburn H (1997) Livestock and the Environment: Finding a Balance. Commission on of the European Communities, Food and Agricultural Organization of the United Nations, and the World Bank, Brussels

Egeru A, Wasonga O, Yazan J, Mburu E, Majaliwa MGJ, MacOpiyo L, Bamutaze Y (2015) Drivers of forage availability: an integration of remote sensing and traditional ecological knowledge in Karamoja sub-region, Uganda. Pastor: Res, Policy Pract 5:1–18

Erdenesan E (2016) Livestock Statitics in Mongolia. FAO Asia and Pacific Commission on Agricultural Statistics Twenty-Sixth Session, 15–19 February 2016. Thimphu, Bhutan. http://www.fao.org/fileadmin/templates/ess/documents/apcas26/presentations/APCAS-16-6.3.5_-_Mongolia_-_Livestock_Statistics_in_Mongolia.pdf

ESRI (2014) ArcGIS Desktop: Release 10.2.2. Environmental Systems Research Institute, Redlands, California

Fernandez-Gimenez M (2000) The role of Mongolian nomadic pastoralists' ecological knowledge in rangeland management. J Ecol Appl 10:1318–1326. https://doi.org/10.1890/1051-0761(2000)010[1318:TROMNP]2.0.CO;2

Fernandez-Gimenez ME (1997) Landscapes, livestock, and livelihoods: social, ecological, and land-use change among the nomadic pastoralists of Mongolia. PhD Dissertation, University of California, Berkeley, CA

Fernandez-Gimenez ME, Angerer JP, Allegretti AM, Fassnacht SR, Byamba A, Chantsallkham J, Reid R, Venable NBH (2015) Integrating herder observations, meteorological data and remote sensing to understand climate change patterns and impacts across an eco-climatic gradient in Mongolia. Proceedings of the transdisciplinary research conference: building resilience of Mongolian Rangelands, Ulaanbaatar, Mongolia, pp 228–234

Ferreira LG, Yoshioka H, Huete A, Sano EE (2004) Optical characterization of the Brazilian Savanna physiognomies for improved land cover monitoring of the cerrado biome: preliminary assessments from an airborne campaign over an LBA core site. J Arid Environ 56:425–447

Ghorbani M, Azarnivand H, Mehrabi AA, Jafari M, Nayebi H, Seeland K (2013) The role of indigenous ecological knowledge in managing rangelands sustainably in Northern Iran. Ecol Soc 18 (2):15. https://doi.org/10.5751/ES-05414-180215

Guo N, Lanzhou CMA, Wang X, Cai D, Yang J (2007) Comparison and evaluation between MODIS vegetation indices in Northwest China. Geoscience and Remote Sensing Symposium, 2007. IGARSS 2007. IEEE International. IEEE, Barcelona, pp 3366–3369

He S, Richards K (2015) Impact of meadow degradation on soil water status and pasture management—a case study in Tibet. Land Degrad Dev 26:468–479

Hellier A, Newton AC, Gaona SO (1999) Use of indigenous knowledge for rapidly assessing trends in biodiversity: a case study from Chiapas, Mexico. Biodivers Conserv 8:869–889

Hilker T, Natsagdorj E, Waring RH, Lyapustin A, Wang Y (2014) Satellite observed widespread decline in Mongolian grasslands largely due to overgrazing. Glob Chang Biol 20:418–428. https://doi.org/10.1111/gcb.12365

Huete AR, Justice C (1999) MODIS vegetation index (MOD13) algorithm theoretical basis document. Version 3. https://modis.gsfc.nasa.gov/data/atbd/atbd_mod13.pdf
Huete A, Didan K, Miura T, Rodriguez EP, Gao X, Ferreira LG (2002) Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens Environ 83:195–213
Homewood K, Rodgers WA (1989) Pastoralism, conservation and the overgrazing controversy. In: Anderson D and Grove R (eds) *Conservation in Africa: people, policies, and practice*. Cambridge University Press, Cambridge, UK, pp 111–128
Huntington H, Callaghan T, Fox S, Krupnik I (2004) Matching traditional and scientific observations to detect environmental change: a discussion on arctic terrestrial ecosystems. JSTOR 18–23. http://www.jstor.org/stable/25094583
Jost L (2006) Entropy and diversity. Oikos 113:363–375
Klein JA, Hopping KA, Yeh ET, Nyima Y, Boone RB, Galvin KA (2014) Unexpected climate impacts on the Tibetan Plateau: local and scientific findings of delayed summer. Glob Environ Change 28:141–152
Kong TM, Marsh SE, van Rooyen AF, Kellner K, Orr BJ (2015) Assessing rangeland condition in the Kalahari Duneveld through local ecological knowledge of livestock farmers and remotely sensed data. J Arid Environ 113:77–86. http://hdl.handle.net/10150/268615
Lauera M, Aswani S (2008) Integrating indigenous ecological knowledge and multi-spectral image classification for marine habitat mapping in Oceania. Ocean Coast Manag 51(6):495–504
Liu YS, Hu YC, Peng LY (2005) Accurate quantification of grassland cover density in an alpine meadow soil based on remote sensing and GPS. Pedosphere 15(6):778–783
Maroney RL (2005) Conservation of argali Ovis ammon in western Mongolia and the Altai-Sayan. Biol Conserv 121:231–241
Matsushita B, Yang W, Chen J, Onda Y, Qiu G (2007) Sensitivity of the Enhanced Vegetation Index (EVI) and Normalized Difference Vegetation Index (NDVI) to Topographic Effects: A Case Study in High-Density Cypress Forest. Sensors 7:2636–2651
Maynard NG, Burgess P, Oskal A, Turi JM, Mathiesen SD, Gaup IGE, Yurchak B, Etylin V, Gebelein J 2016 n.d. Eurasian Reindeer Pastoralism in a Changing Climate: Indigenous Knowledge & NASA Remote Sensing. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080041555.pdf. Accessed 15 Jan
Mills D, Blech R, Gillam B, Martin M, Fithardinge G, Davies J, Campbell S, Woodhams L (2002) Rangelands: people, perceptions and perspectives. In: Grice AC, Hodgkinson KC (eds) *Global rangelands: progress and prospects*. CAB International, Wallingford, Oxfordshire, UK, pp 43–54
Naidansuren E, Bayasgalan O (2012) An Economic Analysis of the Environmental Impacts of Livestock Grazing in Mongolia. Research Report, Singapore: Economy and Environment Program for Southeast Asia
Naidoo R, Hill K (2006) Emergence of indigenous vegetation classifications through integration of traditional ecological knowledge and remote sensing analyses. Environ Manag 38(3):377–387
NASA LP DAAC (2016) NASA Distributed Active Archive Center (DAAC) at NSDIC. MODIS Data. https://nsidc.org/data/modis/terra_aqua_differences. Accessed 5 Jul 2016
Niamir-Fuller M (1995) Indigenous systems of natural resource management among pastoralists of arid and semi-arid Africa. In: Warren DM, Slikkerveer LJ (eds) *The cultural dimension of development.* Intermediate Technology Publications, London, UK, pp 245–257
Oba G (2012) Harnessing pastoralists' indigenous knowledge for rangeland management: three African case studies. *Pastoralism, Research, Policy and Practice* 2 (1). https://doi.org/10.1186/2041-7136-2-1
Oba G, Kotile DG (2001) Assessment of landscape level degradation in southern Ethiopia: pastoralists versus ecologists. Land Degrad Dev 12:461–475
Olson JS, Watts JA, Allison LJ (1983) Carbon in Live Vegetation of Major World Ecosystems. Oak Ridge National Laboratory, Tennessee, Report ORNL-5862
Paltsyn MY, Spitsyn SV, Kuksin AN, Istomov SV (2012) Conservation of snow leopard in Russia. WWF Russia, Krasnoyarsk, Russia. http://wwf.ru/resources/publ/book/eng/599
Paltsyn MYu, Gibbs JP, Iegorova LV, Mountrakis G (2017) Estimation and prediction of grassland cover in western mongolia using MODIS-derived vegetation indices. Rangel Ecol Manag Rangel Ecol Manag 70(6):723–729
Pitt AL, Baldwin RF, Lipscomb DJ, Brown BL, Hawley JE, Allard-Keese CM, Leonard PB (2012) The missing wetlands: using local ecological knowledge to find cryptic ecosystems. Biodivers Conserv 21(1):51–63
Polfus JL, Heinemeyer K, Hebblemewhite M (2014) Comparing traditional ecological knowledge and western science woodland caribou habitat models. J Wildl Manag 78(1):112–121
Purevdorj TS, Tateishi R, Ishiyama T, Honda Y (1998) Relationships between percent vegetation cover and vegetation indices. Int J Remote Sens 19(18):3519–3535. https://doi.org/10.1080/014311698213795
Roba HG, Gufu O (2009) Efficacy of integrating herder knowledge and ecological methods for monitoring rangelands degradation in Northern Kenya. Hum Ecol 37:589–612
Robbins P (2003) Beyond ground truth: GIS and the environmental knowledge of herders, professional foresters, and other traditional communities. Hum Ecol 31(2):233–253
Seaniger C-A (2016) Dzud may affect up to 150,000 herders. UB Post. December 23 2016. http://theubpost.mn/2016/12/23/dzud-may-affect-up-to-150000-herders/
Selemani IS, Eik LO, Holand O, Ådnøy T, Mtengeti E, Mushi D (2012) The role of indigenous knowledge and perceptions of pastoral communities on traditional grazing management in north-western Tanzania. Afr J Agric Res 7(40):5537–5547
Shang ZH, Gibb MJ, Long RJ (2012) Effect of snow disasters on livestock farming in some rangeland regions of China and mitigation strategies – a review. Rangel J 34:89–100
Spooner B (1973) The cultural ecology of pastoral nomads. Addison-Wesley Module in Anthropology No. 45. Addison-Wesley Publishing Company, Reading, Massachusetts, USA
Stumpp M, Wesche K, Retzer V, Miehe G (2005) Impact of grazing livestock and distance from water source on soil fertility in southern Mongolia. Mountain Research and Development 25:244–251
Sulieman HM, Ahmed AGM (2013) Monitoring changes in pastoral resources in eastern Sudan: a synthesis of remote sensing and local knowledge. *Pastoralism: Research, Policy and Practice* 3 (22). https://doi.org/10.1186/2041-7136-3-22
UNESCO (1992–2016) UNESCO World Heritage Convention: World Heritage List. http://whc.unesco.org/en/list. Accessed 16 June 2016
White RP, Murray S, Rohweder M (2000) Pilot Analysis of Global Ecosystems: Grassland Ecosystems. World Resources Institute, Washington DC, Technical Report
WWF (2012) Altai-Sayan Ecoregional Conservation Strategy. WWF