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Matching Local Knowledge and Environmental Change with Policy Changes in Rangeland Tenure

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Abstract
Hardin's Tragedy of the Commons has often been cited as the rationale for the privatization of pastures throughout the world, yet rangeland degradation is still widespread. A significant body of ecological research has demonstrated negative impacts from limiting herd movement through fencing. The privatization of pastures has often followed heterogeneous patterns. We use a natural experiment in common grazing areas on the eastern Qinghai-Tibetan Plateau where land use was privatized beginning in 1999 following different land use division patterns. We measure the relationship between land use privatization paths and grassland quality using satellite data from 1989 to 2011 in five different villages, and compare how well herder environmental perceptions match satellite data. We find that rangeland degradation has significantly increased following privatization of land use, and that grassland in small individually managed fenced plots is deteriorating more significantly than in larger fenced areas with group herding. We further find that herders' had accurate perceptions of the state of their pastures that closely match remotely sensed data.

Keywords Tragedy of the commons · Normalized difference vegetation index (NDVI) · Land privatization · Rangeland degradation · Qinghai-Tibet plateau

Introduction and Background to Pastureland Management

Collective irrationality as a result of individual rational choices in the unregulated management of open access or communal pastures has been the subject of extensive scientific debate over the last five decades following the publication of the Tragedy of the Commons by Garrett Hardin (1968). Based largely on Hardin's rationale, land use privatization has been widely believed to be a way to improve the overall efficiency of economic systems, leading to improved productivity and living conditions in rural areas (Binswanger and Deininger 1999; De Soto 2000; Li *et al.* 2019; North 1981). However, it is unclear whether communal grazing is always as destructive as sometimes assumed (Mace 1991), and local management systems may be in place that successfully manage open access resources (Ostrom 1990). Hardin's theoretical predictions have been widely challenged empirically and theoretically (Feeny *et al.* 1990; Ostrom *et al.* 1999), and there is growing evidence that land use privatization has in fact resulted in increased degradation of pastures in many parts of the world, e.g., China (Gao *et al.* 2006; Harris 2010; Yu *et al.* 2010; Zhang *et al.* 2007; Zhang *et al.* 2006), Mongolia (Ojima and Chuluun 2008; Sneath 2003; Sternberg 2008; Vernooy 2011), Tajikistan (Robinson *et al.* 2010), Kyrgyzstan (Borchardt *et al.* 2011), and in many areas of Africa (Dougill *et al.* 2016; Mwangi 2007; Mwangi and Ostrom 2009; Reid *et al.* 2014). Despite the large volume of literature that does not support Hardin's views, his narrative persists and his arguments have underpinned many, often unsuccessful, rangeland development programs around the world.

While a form of quasi privatization, where long-term leaseholds provide for the exclusive use of rangelands, has been widely adopted and implemented in large areas of

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Central Asia, Mongolia, and China, the process leading to policy changes and local adaptation to top-down institutional arrangements has varied among local communities and herders. In the Qinghai-Tibet Plateau, Tibetans have been engaged in nomadic pastoralism for thousands of years. However, in the past few decades the grassland management systems in the Qinghai-Tibet Plateau have undergone frequent changes (Fig. 1; see also Supplementary Information for details). The privatization system in the pastoral areas of the Qinghai-Tibet Plateau in the 1990s can be regarded as the most important change and our focus in this paper.

The quasi-privatization process in pastoralist areas of China went through a series of phases starting from the institution of the "Household Responsibility System" (HRS) in the 1980s, which aimed at increasing pastoral output and productivity through the initial privatization of communal livestock, whilst leaving the land as open access. Dominated by modernization ideology, Chinese authorities considered mobile pastoralism to be backward, inefficient, and irrational as an economic strategy. Such perceptions are based on the assumptions that pastoralism is unstable because it is highly susceptible to fluctuations of climate conditions and that it has led to rangeland degradation due to overgrazing. As a response, a series of rangeland management policies were implemented (Gongbuzeren and Li 2015a, b). The "Integrated Socioeconomic Development in the Pastoral Regions" program (1990s) created long-term grassland leaseholds for households and included sedentarization, fencing, limiting livestock numbers, and increasing the level of technological capacities (Du and Mace 2018; Goldstein and Beall 1990; Gruschke 2012; Ho 2000; Huber 2012; Levine 2015; Miller 2000; Ning and Richard 1999; Pirie 2005). This marks the implementation of the key reform of " Separating Three Property Rights " (STPR) and the establishment of a grassland privatization system that entailed sedentarization of herding households and the fencing of pastures. It should be noted that contracted land is on a long-term lease that can establish family-based privatization of grazing use rights; these rights or pastures may not be sold by the contracted family, but they can be leased to other households. Policymakers assumed privatized land-use rights would provide incentives for herding households to manage their livestock to avoid causing rangeland degradation by making them responsible for matching herd sizes to rangeland resources and for investing in sustainable management practices (Gongbuzeren and Li 2015b; Harris 2010; Ho 2000; Yan *et al.* 2005a, b). However, empirical data suggest that in a wide range of cases, due to a general local reluctance to switch to the newly implemented land tenure system, the herders retained their traditional group-based or community-based grassland management practices to some degree (Banks *et al.* 2003; Lin 2010; Richard 2005; Richard *et al.* 2006; Yan *et al.* 2005b). Some scientists believe that this institutional change has neither improved the stability of the grassland ecosystems nor the quality of life of herder households (Hua *et al.* 2013; Tony and Banks 2001). From the outset there were problems in the process of policy interpretation, supervision, and implementation and the degree it was adopted by the herders (Jing and Zhe 2013). The dynamic and heterogeneous responses to top-down policy changes in the land contracting systems are rooted in and driven by locally specific indigenous knowledge and expertise (Hopping *et al.* 2018; Klein *et al.* 2014; Yeh *et al.* 2014; Yeh *et al.* 2017); in this context, they can be seen as a way to maintain mobility and the flexible use of limited resources, together with the necessity for secure resource tenure (Fernández-Giménez 2002; Reid *et al.* 2014). It has been argued that allowing herders to continue to have autonomy of resource management (Yan *et al.* 2005a, b) is a prerequisite for achieving sustainability in grassland social-ecological systems. The adaptation to land tenure reform is particularly relevant in light of the environmental and economic challenges that pastoralism is facing: the changes in the environment driven by anthropogenic global warming and the need to balance socioeconomic security of rural populations with the demands of industrial agriculture require an in-depth understanding of how humans and the environment interact, adapt, and shape each other.

Yak Herding in Gansu Province

Many scholars have argued that the fragmentation and sedentarization of rangelands in China has produced negative environmental (and social) consequences. Here we present an integrated analysis of herder perceptions, NDVI data from before and after quasi-privatization, and herders' responses to institutional changes. We focus on the yak

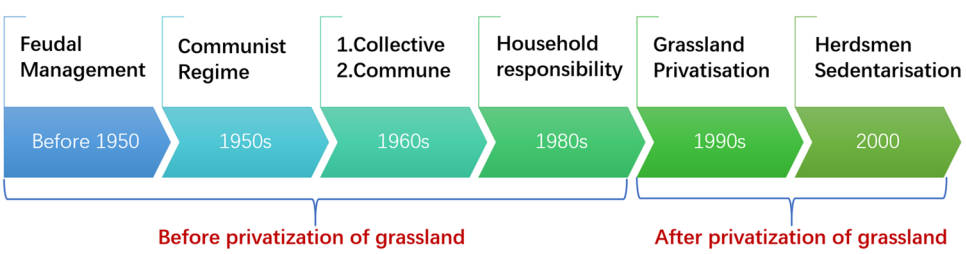

Fig. 1 Timeline of the Grassland Management Policy Changes in Qinghai-Tibet Plateau Regions from 1950 to 2000 (see SI for details)

herding systems of Maqu County (Gansu Province) in the east of the Qinghai Tibetan Plateau in China, where quasi-privatization was implemented in the late 1990s and subsequently produced a number of different response patterns from communities of herders in close proximity to each other. Our study offers a 'quasi-natural experiment' since herding regimes involving different sizes of herding groups and differently sized fenced plots were introduced in some pastures and not in others.

Prior to land division and fencing, traditional management of yaks, commonly found throughout Asia, was based on flexible seasonal movements dictated by season, climate, and landscape characteristics (Coughenour *et al.* 2008); semi-nomadic herders practiced transhumance, moving between higher-altitude summer and autumn pastures, and lower-altitude winter and spring pastures in closer proximity to permanent settlements. Management in summer consisted of pooling resources among herders from several families or villages; herders lived in campsites and moved frequently to distribute grazing pressure of the herds based on grass availability. Winter grazing was characterized by limited herd movement and, due to low forage availability, it was common for yaks to have up to 30% losses in body weight (Lv 1980). Historically, herders of Maqu engaged in transhumant pastoralism of yak and Tibetan sheep based on collective rangeland rights up to the implementation of the "Integrated Socioeconomic Development in the Pastoral Regions" programme.

From an economic perspective, the privatization of the use of rangelands in the Qinghai-Tibet Plateau has been shown to have favoured increased market access and integration (Gongbuzeren and Li 2018), pastoral sedentarization, and diversification of economic activities (Gongbuzeren and Li 2015b). In terms of ecological dynamics, large-scale patterns of greening (Piao *et al.* 2011; Xu and Liu 2007; Zhu *et al.* 2016) and changes in seasonality (Klein *et al.* 2014) due to human-driven global warming have been locally offset by local degradation of rangelands, often attributed to reduced livestock mobility following the implementation of fencing (Cao *et al.* 2011). The policy of fencing land was first implemented in Maqu in 1996; the area of land allocated to each household depended on the number of household members, with about 150,000 m^2 of land for each adult, and half that for each child. Winter pasture use rights were contracted out to individual households, and summer pasture use rights contracted to units of up to three households (Cao *et al.* 2013). However, a 2008 survey for the entire area of Maqu County identified multi-household management for winter pastures in 82% of cases, with 20% of respondents managing winter pastures in units larger than 10 households, and 86% in units larger than 15 households in summer pastures (Cao 2010). In the area we surveyed in 2015 (five administrative villages in three townships), 79% of households grazed their herds in multiple-household in winter pastures, and 92% of households were grazing their livestock together with more than 15 households in summer pastures. The largest grazing group in summer pastures exceeded 200 households, essentially retaining a similar grazing system to before privatization in some areas. Our field observation in the study area revealed that three general patterns of grassland management and zoning have emerged after the privatization of the rights to use grasslands: 1) village-scale large groups (LG) composed of 100–250 herders who have retained a strong communal approach to herding, fencing large areas that are managed collectively; 2) medium sized groups (MG) of 10–50 herders who share and manage their allocated land within their kinship group; and 3) small grazing groups (SG) of fewer than 10 households, generally five or fewer, including herders who manage land contracted to them alone.

The aim of our research was to investigate, using a 30-year time series of high-resolution satellite images, the relationship between privatization patterns and environmental changes in rangeland in three townships characterized by different local responses to privatization in Maqu County. We further investigate how herder perceptions of the state of the environment is reflected in the observed state of the grassland measured using remote sensing data, and changes following the implementation of the privatization policies.

Results

Satellite data revealed significant changes in the NDVI and our analysis shows this is associated with the scale of fencing (and hence group herding). Table 1 shows the results of the Generalised Linear Mixed Models (GLMM) associating NDVI and herding group types. NDVI values can range from −1 to 1 (with values near 0 indicating areas without vegetation and negative values indicating water). Moderate values (0.2 to 0.4) represent shrub and grassland (Wegmann *et al.* 2016).

Our results show that the baseline average normalized difference vegetation index (NDVI) value for the area covered by the five villages in the study area is 0.426. Due to their usually higher elevation and shorter vegetative season, summer pastures show lower average NDVI values in relations to the baseline (−0.044 or − 10.3%) (Fig. 2). Overall, we observed increasingly lower NDVI values from large grassland plots managed by large groups to small plots managed individually (Fig. 2): grassland managed by medium sized herding groups shows average NDVI values that are about 6.3% lower than those observed for the areas managed by large herding groups; for small herding groups/individual herders the drop in NDVI is about 14.8% (Fig. S1). Increasing precipitation and temperatures result in higher NDVI values.

Table 1 GLMM of the estimated effect of different grazing type on NDVI: large herding group (LG, $N=310$), medium herding group (MG, $N=520$), and small herding group (SG, $N=210$). LG is the reference group for herding system. Winter pastures is the reference for pastures. Winter is the reference for season. Random effects: Sites ($N=10$, 5 winter and 5 summer pasture areas for the 5 study villages); NDVI response variable derived from 104 satellite images from Jan. 1989 to Dec. 2011; The unit of precipitation is millilitres, and the unit of temperature is Celsius. ***, **, * indicate $P<0.001$, 0.01, 0.05 respectively

Effect	Estimated effect on NDVI	Std. Error	Df	t-value	Pr (>|t|)
Fixed effects					
Intercept	0.426	1.06E-02	5.299E+01	40.41	<0.001***
Herding Group: MG	−0.027	6.58E-03	1.870E+02	−4.11	<0.001***
Herding Group: SG	−0.063	9.37E-03	1.826E+02	−6.69	<0.001***
Precipitation	0.001	7.84E-05	1.023E+03	12.92	<0.001***
Temperature	0.019	7.50E-04	1.023E+03	24.86	<0.001***
Pasture: summer pasture	−0.044	8.92E-03	9.963E+00	−4.99	<0.001***
Season: spring	−0.141	8.12E-03	1.022E+03	−17.36	<0.001***
Season: summer	0.033	1.27E-02	1.022E+03	2.59	<0.01**
Season: autumn	0.032	8.30E-03	1.021E+03	3.91	<0.001***
Random effects	Name	Variance	Std.Dev.		
Sites	(Intercept)	1.082E-04	1.040E-02		

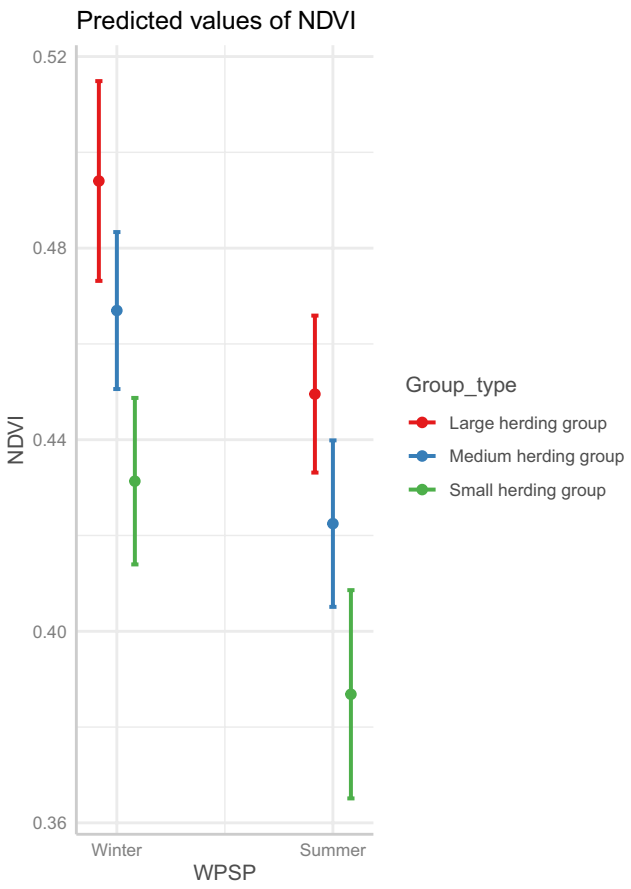

Fig. 2 The GLMM model predicts the NDVI values of different grazing group types on winter pastures and summer pastures ("Winter" means winter pasture, and "Summer" means summer pasture)

It is worth noting that while the direct use of NDVI as a proxy for grassland health or degradation is not necessarily straightforward (Hopping *et al.* 2018), changes in NDVI reflect changes in the environment which, in combination with other data sources such as herders' perceptions of the state of the environment, can provide useful insights into the condition of the pastures.

The data we collected on herders' perceptions of the environmental state of the grasslands illustrate their strong belief that the privatization of the use of the grasslands has led to increased environmental degradation of pastures, with increased perceived land degradation for privatization patterns associated with smaller fenced plots (Fig. 3). While the perceived quality of grassland scored high before the privatization (around six on a qualitative scale with seven as maximum value), herders reported significantly lower scores following the change in land tenure. We observed significantly lower values for the grass quality index reported by herders belonging to small herding groups (−3.4 index points compared to communal grazing) compared to those belonging to medium herding groups (−2.3 index points compared to communal grazing). When differentiating between winter and summer pastures (Fig. 4), the highest perceived difference in grassland quality before and after the privatization was reported for summer pastures (−2.3 index points), whereas the lowest drop (−1.9 points) in perceived grassland quality was reported for winter pastures, likely due to the fact that seasonal climate more than land tenure is the main limiting factor in the cold season. It is worth noting that the quality indices for 1999 are an estimate that herders provided from memory, as they were not surveyed before privatization.

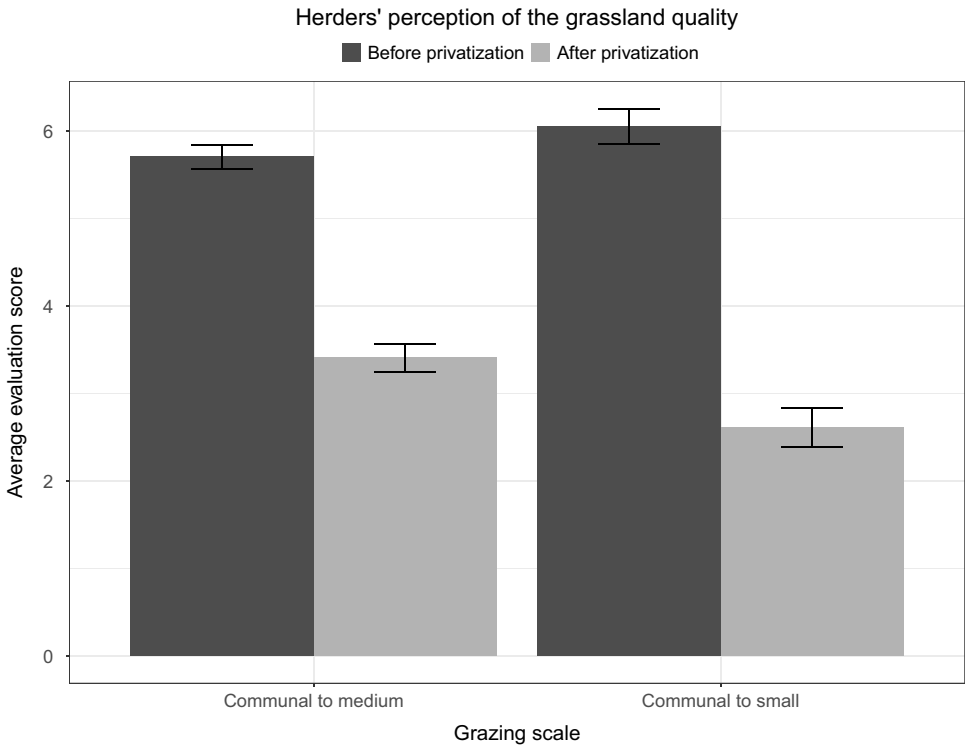

Fig. 3 Change in herders' perception of the quality of grassland based on different patterns of privatization that they experienced. Grassland quality index: 1 = Very bad, 2 = Bad, 3 = Relatively poor, 4 = Medium, 5 = Relatively good, 6 = Good, 7 = Very good. Bars represent standard errors. Number of observations communal (LG) to medium (MG): 225 households; Number of observations communal (LG) to small (SG): 83 households

Discussion

We find no evidence that land use privatization is improving the grassland in the study area of the eastern Tibetan Plateau, and some evidence to the contrary. Through linking NDVI, the herders' perception of the quality of the pastures and privatization patterns, we found that an increased fragmentation of herding in terms of spatial scales and size of the herding groups is linked with both

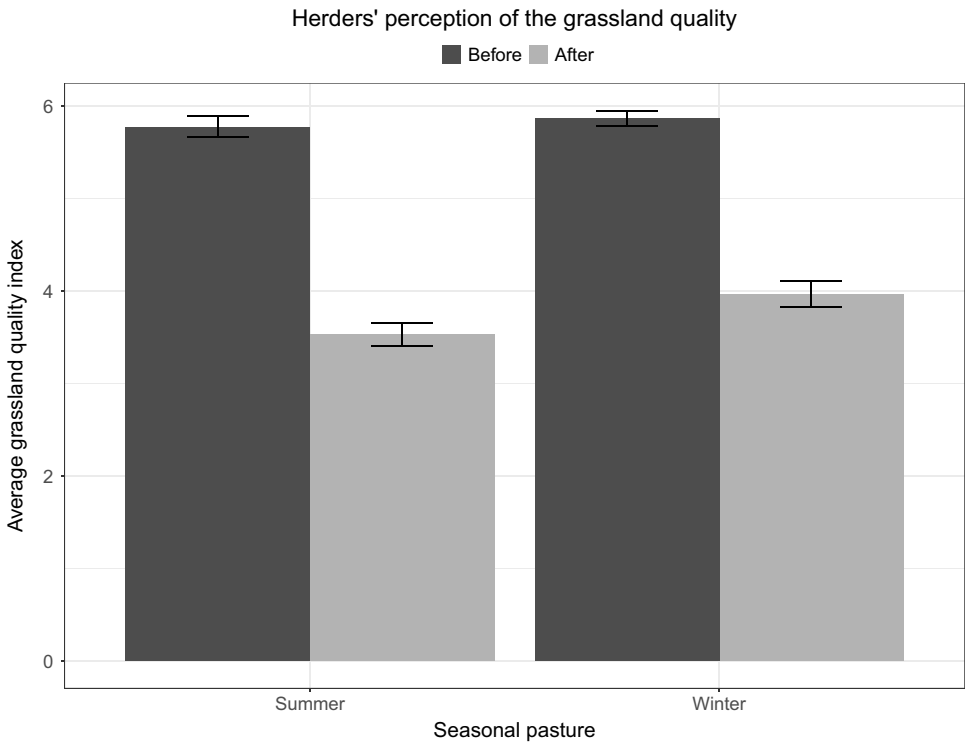

Fig. 4 Change in herder's perception on the quality of grassland based on the seasonal type of pasture before and after land privatization. Grassland quality index: 1 = Very bad, 2 = Bad, 3 = Relatively poor, 4 = Medium, 5 = Relatively good, 6 = Good, 7 = Very good. Bars represent standard errors. Number of observations Summer: 175 households and Winter: 175 households

an increased perception of grassland degradation and a decline in grassland NDVI values. Our findings support the ecological reasoning that reduced livestock mobility might disrupt, through an increase in the frequency of grassland defoliation, the recovery of grassland resulting in a reinforcing process of rangeland degradation (Cao *et al.* 2011). This appears to be in contrast with the overall greening trends that have been observed at wider spatial scales throughout the Qinghai-Tibetan Plateau and that are widely attributed to human driven global warming process (Piao *et al.* 2011; Xu and Liu 2007; Zhu *et al.* 2016). In this context, it appears that dividing the rangelands can locally lead to degradation to an extent capable of offsetting the greening effects of rising temperatures.

Historically, pastoralists have practiced collective rangeland use to manage the heterogeneous distribution of rangeland resources and climate variability that can reduce livestock management costs and facilitate better risk-coping strategies. However, the implementation of the current "Separating Three Property Rights" (STPR) policy disrupted traditional mobile grazing systems and promoted more concentrated grazing (Gongbuzeren and Li 2015a; Joyce and Marshall 2017). It decoupled pastoral production systems from the ecosystem on a large spatial scale (Li and Huntsinger 2011). As a result, livestock trampling of pasturelands increases as grazing is concentrated within smaller grazing parcels (Zhang and Li 2008). Grazing areas have no opportunity to recover due to constant grazing pressure with less herd movement. Livestock production costs increase and increased livestock numbers under STPR also threaten further rangeland degradation. In terms of perception of the condition of the environment, matching the perceived and measured state of the grassland reflects the widely shared ecological knowledge that informs decision making and management by herders (Fernandez-Gimenez 2000). The herders personal knowledge of the links between practices and environmental responses is used by herders to evaluate institutions and their rules (Zhao and Rokpelnis 2016), but it also underlies how herders adapt to policy changes shaping the credibility of the institutional arrangements themselves (Ostrom 2009; Zhao and Rokpelnis 2016). In this light, it appears that resistance to adopting a herding system based on single household management can be interpreted as the result of a lack of endogeneity (i.e., disregarding local ecological knowledge) in the formulation of top-down institutional arrangements. Adaptive responses to changes in tenure systems are particularly relevant in the context of the STPR reform. There is now a need to find a balance between the well-documented overuse of land incentivized by market-oriented tradable rights and the land consolidation achievable with more sustainable cooperative-based grassland management (Li *et al.* 2018). Privatization might disrupt other significant adaptation mechanisms such as resource pooling in times of need (Clark and Crabtree 2015) and sharing of expenses, labor, and infrastructure (Cao *et al.* 2018; Chen and Zhu 2015; Vij and Narain 2016), reducing the capacity of formal and informal mechanisms to adapt and respond sustainably to a changing environment.

Our study highlights the importance of including local ecological knowledge in policy analysis and formulation, in particular when policies are implemented in a top-down manner. A number of issues remain to be addressed in future research. Our study relies on NDVI as a proxy for monitoring the state of the environment, but its definition is too coarse to capture the level of detail that might be required for a better investigation of the environmental dynamics that follow land privatization. However, fine-grained sampled data such as soil characteristics and species composition cannot be easily scaled at the regional level. Longitudinal data on change in number of herders, household composition, rate of dispersal, stocking rates, and socioeconomic changes would provide a finer understanding of the mechanisms leading to changes in the environment following the land tenure policy changes. Further research could investigate: 1) the effect of land use privatization on the specific adaptation mechanisms and formal and informal institutions that local herders have developed in response to a changing environment; 2) the linkage between individual actions at the local scale and larger environmental trends, as highlighted by the dichotomy between local degradation and large scale greening; 3) who wins and who loses following the land tenure changes in terms of distribution of wealth based on the land allocation rules.

Methods

Maqu County and its Herding System

Maqu County (100°45′45″–102°29′00″ E, 33°06′30″– 34°30′15" N) is part of the Eastern Qinghai-Tibet Plateau in China and is located at the junction of the three provinces of Qinghai, Sichuan, and Gansu (Fig. 5). It belongs to the Amdo Tibetan area and covers an area of 10,190km^2. It has eight townships and 41 administrative villages with a total population of 56,400 in 2011, of which more than 89% is Tibetan. Maqu County has an average altitude of about 3500–3800 m.a.s.l. The mean annual air temperature is 1.2 °C and average annual precipitation is 611.9 mm. In Maqu County grassland accounts for 85.7% of the total land area, and the main economic activity is livestock husbandry, predominantly yaks, Tibetan sheep, and horses (Guo *et al.* 2012). The Yellow River crosses Maqu between Xiqin Mountain and Animaqing Mountain, providing a complete water source with an important role in

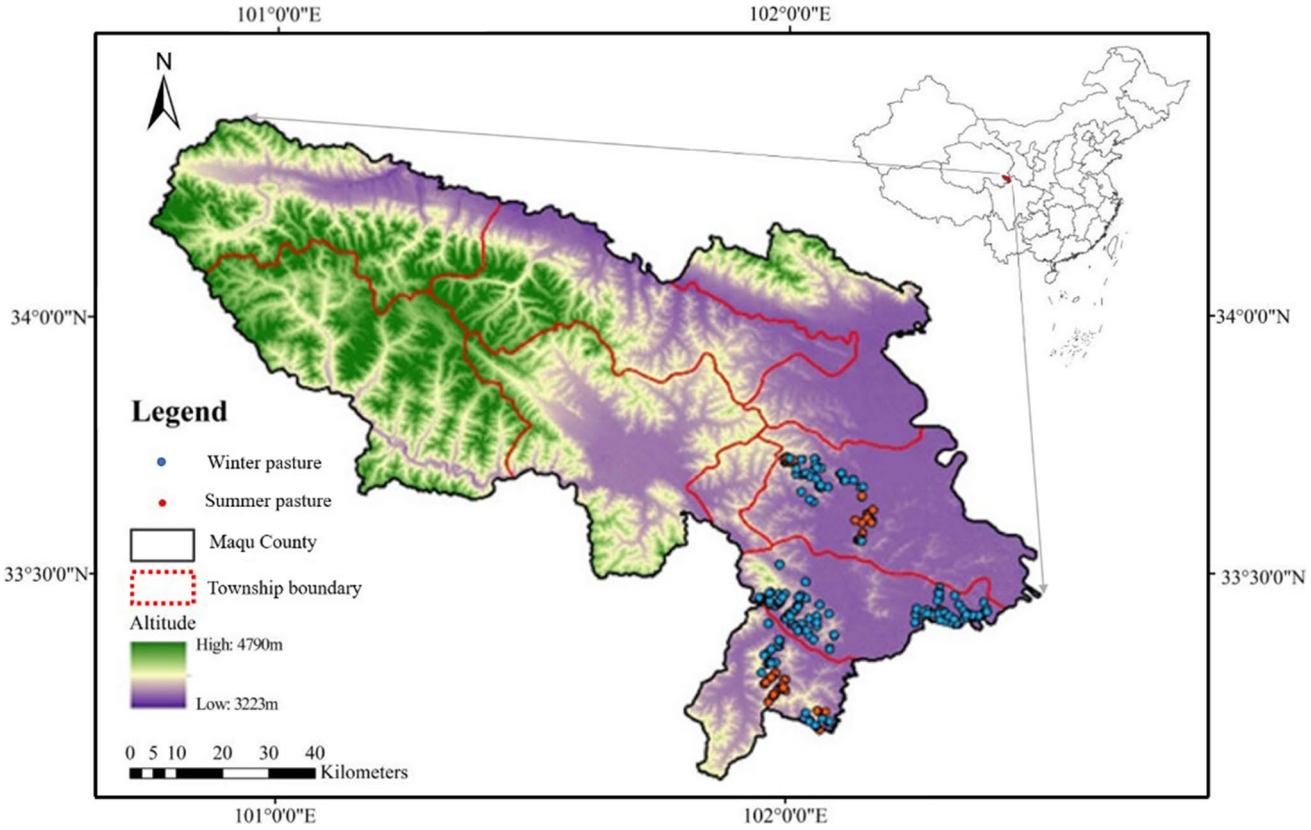

Fig. 5 Location of the research area in Maqu, Gansu Province, China. Red and blue dots represent respectively the location of the winter and summer pastures(280/483 winter and summer pasture households coordinates successfully obtained through GPS)

soil and water conservation. Our research area included five administrative villages in three townships in the south-easter of Maqu County. All five study villages implemented the privatization of grassland use rights in 1999.

Data Collection

We collected quantitative and qualitative data on herding through household questionnaires and interviews that we conducted with 483 households in the five villages from April to November 2015. The questionnaire respondents were adults of each household who are familiar with the grazing system, usually the head of household, for a total of 483 herders. We employed two Tibetan interpreters to help with language barriers. The interviews lasted. The questionnaires included basic demographic information for each of the 483 herdsmen interviewed, consisting of age, sex, education level, family labour capability, family social relations, family income and family composition (2015). We additionally interviewed each herder for between one and two hours for information on grazing systems, including the number of livestock at the time of fencing (1999) and at the time of the interview (2015), a livestock quality indicator, the amount of land owned/used (2015), a qualitative categorical assessment of the status of the grassland (1999 and 2015), the type and scale of grassland management in use (herding in groups or alone) for winter and summer pastures, including the changes between 1999 and 2015. All the participants gave informed consent and the local government gave permission for the study, which was approved by Lanzhou University and the UCL Research Ethics committee.

Of the 483 households interviewed, we used a sample of 329 households that were present both before 1999 and in 2015 to identify possible trends in population and livestock numbers (Fig. 6, Table 2). In general, the total population of the sample households increased by 14.2% from 1999 to 2015, and the total number of yaks, Tibetan sheep, and horses decreased by 18.2%, 41.3%, 7.0%, respectively. It is important to note that, due to the fact that the herding data is only from two points in time, these numbers do not represent changes due to demographic events (such as those households that moved away or were no longer present for other reasons), but they allow us to describe the characteristics and size of a large sample of the herding families in the study area and make an estimate of long term changes.

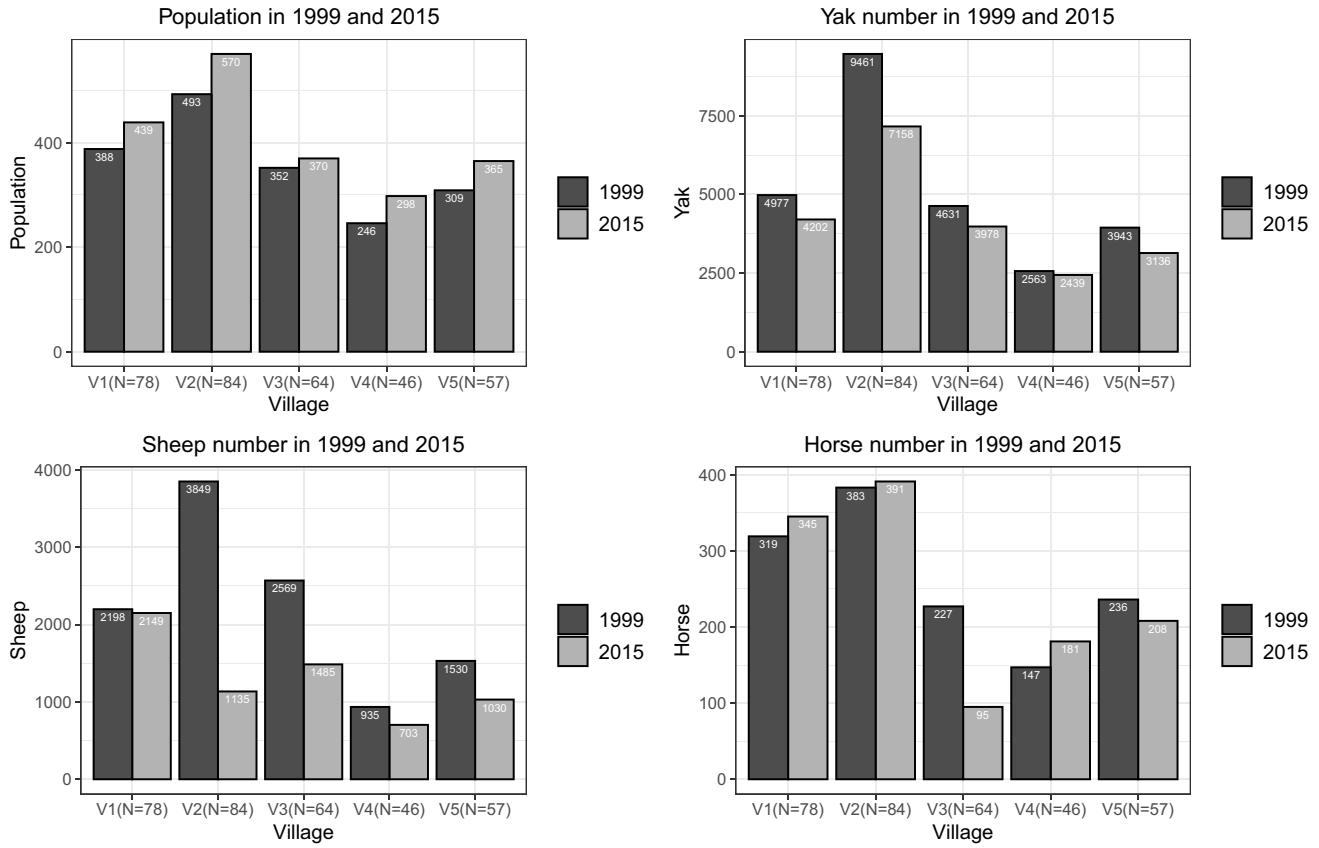

Fig. 6 Population of livestock reported retrospectively by interviewees for 1999 and for 2015. ($N = 329$ herders)

Satellite Image Processing and Spatial Analysis

We obtained a series of 491 raw images collected by the NASA Landsat 5 satellite for the area identified by path 131 and row 37 covering the South-Eastern half of the area of Maqu County from the USGS Earth Explorer portal. We used the Landsat 5 images due to the high spatial resolution (30 m), the long temporal range of data, and the sensor consistency. We used a 23-year temporal interval from 1989 to 2011, in order to place the privatization event in the middle of the time series. We performed image preprocessing in R version 3.3.1 with the packages Raster (Hijmans and van Etten 2014) and RStoolbox (Leutner and Horning 2017) and the Fmask 4.0 software (Zhu and Woodcock 2012); it included: 1) data conversion from 8-bit to top-of-atmosphere radiance values according to the Landsat 4–5 TM documentation (Schott *et al.* 2012); 2) Atmospheric correction using the Dark Object Subtraction (DOS) approach (Chavez Jr 1989; Goslee 2011); 3) a topographic illumination correction using the 'C' method (Riaño *et al.* 2003) and the SRTM Digital Elevation Model for the study area, also retrieved from the USGS EarthExplorer portal; 4) cloud and snow masking using the '*fmask*' algorithm (Zhu and Woodcock 2012). Of all the preprocessed images, we kept only those

Table 2 Summary of the data sample. SG indicates small herding groups, MG indicates the medium herding groups, LG indicates large herding groups. Percentages indicate the % of households under each management system in the summer and winter pastures of each village

Village		V1	V2	V3	V4	V5	All
Households surveyed		97	115	96	90	85	483
Summer pasture	SG	0(0%)	0(0%)	0(0%)	0(0%)	0(0%)	0(0%)
	MG	97(100%)	115(100%)	96(100%)	0(0%)	0(0%)	308(64%)
	LG	0(0%)	0(0%)	0(0%)	90(100%)	85(100%)	175(36%)
Winter pasture	SG	95(98%)	104(90%)	94(98%)	0(0%)	2(2%)	295(61%)
	MG	2(2%)	11(10%)	2(2%)	90(100%)	83(98%)	188(39%)
	LG	0(0%)	0(0%)	0(0%)	0(0%)	0(0%)	0(0%)

with less than 20% cloud and/or snow cover, which resulted in 104 usable images. We used the dataset of processed images to compute a time series of the Normalized Difference Vegetation Index (NDVI). The NDVI has shown to be well correlated to vegetation biomass and cover, giving an accurate indication of net primary productivity. It has been widely used in ecology as a correlate of biodiversity, vegetation productivity and land degradation (Gillespie 2005; Pettorelli 2013). The NDVI was calculated from the red and near-infrared bands (band 3 and band 4 respectively of the Landsat images) of each scene for each 30 m × 30 m pixel according to the formula (1: Wegmann *et al.* 2016)

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (1)$$

We used local NDVI values based on the outlines of the summer and winter pastures for the five study villages, for a total of 10 areas each with a series of 104 NDVI images that we used as the response variable to build a regression model linking fencing scales on the state of the rangeland.

Different Grazing and Fencing Scales and Grassland NDVI

To analyse the effect of different fencing scales on the quality of grassland we fit a generalized linear mixed effect model in which the random effects are 10 sites (five villages each with two seasonal pastures (winter and summer)). The fixed effect predictors are annual precipitation, annual temperature (from the Gansu Provincial Meteorological Agency - Jan-1989 to Dec-2011), a binary variable to identify winter or summer pastures, and a categorical variable describing the patterns of fencing (i.e., group herding) adopted after land privatization (three levels define the change after privatization: from communal herding to large herding groups/fences, medium herding/fences, and small herding groups/fences). The three-scale grouping is based on three distinct differences in the fencing patterns in our study area. The boundary information of the winter pasture and summer pasture used in the process of matching the NDVI image with the management type (winter and summer pasture boundaries are the factual basis for the classification of large, medium, and small groups in articles and models, that is, the winter and summer pastures of a village can be divided into two types according to the overall size of the grazing group) was provided by the local grassland management department, and did not change after the privatization of the grassland; we also verified the coordinates (Table 2). The model was fitted in R 4.0.3 with the package lme4 and lmerTest (Pinheiro *et al.* 2016).

Analysis of Herder Perceptions of Grassland Quality

In order to investigate the perceptions of herdsmen on the status and changes of grassland after privatization, we conducted a series of paired t-tests on the grassland quality classifications reported by herdsmen, from level 1 (very poor) to level 7 (very good). The time nodes used were 1999 (the year when the land use rights were privatized) and 2015 (the year of our survey). We asked our informants: based on your long-term grazing experience and direct judgment, please rate the grassland status at present and in the year when the grassland was privatized, 1 is very poor, rising in turn, 7 is very good, the middle level is 4. The supplementary explanation is the grassland condition, that is, the grassland productivity status/availability of grass biomass, which is herders' most intuitive and direct understanding of the status of pastures. Each pairwise comparison was performed on subsets of herders defined by the size of their herding group after the privatization. Our first is based on the different privatization models they have experienced, their changing perceptions of the quality of grassland (Fig. 3), involving 308 herders in the five villages, who all experienced privatization of grassland use rights, and are all adults with senior grazing management experience in their households. The number of households experiencing a change from communal to medium herding group was 225, and the number of households from communal to small group was 83. Our second comparison is change in perceptions of herders on the quality of grassland based on the seasonal type of pasture before and after land privatization (Fig. 4), for only two of the villages (175 households/herders). We asked them to compare their perceptions of the quality of grassland differentiating between winter and summer pastures.

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Author contributions RM conceived the study. All authors developed the hypotheses. BPP and JD collected the field data. BPP and MM collected and analysed the satellite data. BPP, MM and RM wrote the paper. All authors reviewed the draft.

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Data Availability Most of our data is in the SI. The data on herders that supports our findings in this study are available from the first author on request. These data are not publicly available to protect the privacy of research participants. Remotely sensed data is publicly available from the U.S. Geological Survey portal EarthExplorer (https://earthexplorer.usgs.gov/). (Kraudzun 2012).

Declarations

Conflict of Interest The authors declare no competing interests.

References

Banks, T., Richard, C., Ping, L.,Zhaoli, Y. (2003). Community-based grassland management in western China rationale, pilot project experience, and policy implications. Mountain Research and Development 23: 132-41.

Binswanger, H.P., Deininger, K. (1999). Explaining agricultural and agrarian policies in developing countries, The World Bank.

Borchardt, P., Schickhoff, U., Scheitweiler, S., Kulikov, M. (2011). Mountain pastures and grasslands in the SW Tien Shan, Kyrgyzstan—floristic patterns, environmental gradients, phytogeography, and grazing impact. Journal of Mountain Science 8: 363-73.

Cao, J. (2010). Research on Grassland Management on Qinghai Tibetan Plateau. Lanzhou University Press: Lanzhou.

Cao, J.-J., Xiong, Y.-C., Sun, J., Xiong, W.-F., Du, G.-Z. (2011). Differential benefits of multi-and single-household grassland management patterns in the Qinghai-Tibetan Plateau of China. Human Ecology 39: 217-27.

Cao, J., Yeh, E.T., Holden, N.M., Yang, Y., Du, G. (2013). The effects of enclosures and land-use contracts on rangeland degradation on the Qinghai–Tibetan plateau. Journal of Arid Environments 97: 3-8.

Cao, J., Li, M., Deo, R.C., Adamowski, J.F., Cerdà, A., Feng, Q., Liu, M., Zhang, J., Zhu, G., Zhang, X. (2018). Comparison of social-ecological resilience between two grassland management patterns driven by grassland land contract policy in the Maqu, Qinghai-Tibetan Plateau. Land use Policy 74: 88-96.

Chavez, P.S. Jr (1989). Radiometric calibration of Landsat Thematic Mapper multispectral images. Photogrammetric engineering and remote sensing 55: 1285-94.

Chen, Haiyun, and Zhu, T. (2015). The dilemma of property rights and indigenous institutional arrangements for common resources governance in China. Land use Policy 42: 800-05.

Clark, J., Crabtree, S. (2015). Examining social adaptations in a volatile landscape in Northern Mongolia via the agent-based model Ger grouper. Land 4: 157-81.

Coughenour, M., Behnke, R., Lomas, J., Price, K. (2008). Forage distributions, range condition, and the importance of pastoral movement in Central Asia-a remote sensing study. in, *The Socio-Economic Causes and Consequences of Desertification in Central Asia*, Springer.

De Soto, H. (2000). The mystery of capital: Why capitalism triumphs in the West and fails everywhere else, Basic Civitas Books.

Dougill, A.J., Akanyang, L., Perkins, J.S., Eckardt, F.D., Stringer, L.C., Favretto, N., Atlhopheng, J., Mulale, K. (2016). Land use, rangeland degradation and ecological changes in the southern Kalahari, Botswana. African Journal of Ecology 54: 59-67.

Du, J., Mace, R. (2018). Parental investment in Tibetan populations does not reflect stated cultural norms. Behav Ecol, 29: 106-16.

Feeny, D., Berkes, F., McCay, B.J., Acheson, J.M. (1990). The tragedy of the commons: twenty-two years later. Human Ecology 18: 1-19.

Fernandez-Gimenez, M.E. (2000). The role of Mongolia nomadic pastoralist's ecological knowledge in rangeland management. Ecological Applications 10: 1318-26.

Fernández-Giménez, M.E. (2002). Spatial and Social Boundaries and the Paradox of Pastoral Land Tenure: A Case Study from Postsocialist Mongolia. 30: 49-78.

Gao, Q., Li, Y., Wan, Y., Lin, E., Xiong, W., Jiangcun, W., Wang, B., Li, W. (2006). Grassland degradation in Northern Tibet based on remote sensing data. Journal of Geographical Sciences 16: 165-73.

Gillespie, T.W. (2005). Predicting woody-plant species richness in tropical dry forests: a case study from south Florida, USA. Ecological Applications 15: 27-37.

Goldstein, M.C., Beall, C.M. (1990). Nomads of western Tibet: the survival of a way of life. Univ of California Press.

Gongbuzeren, Y.L., Li, W. (2015a). China's Rangeland Management Policy Debates: What Have We learned? Rangeland Ecology & Management 68: 305-14.

Gongbuzeren, Y.L., Li, W. (2015b). China's Rangeland Management Policy Debates: What Have We learned? Rangeland Ecology & Management 68: 305-14.

Gongbuzeren, L.H., Li, W.J. (2018). Rebuilding pastoral social-ecological resilience on the Qinghai-Tibetan Plateau in response to changes in policy, economics, and climate. Ecology and Society 23.

Goslee, S. C. (2011). Analyzing remote sensing data in R: the landsat package. Journal of Statistical Software 43: 1-25.

Gruschke, A. (2012). Tibetan pastoralists in transition. Political change and state interventions in nomad societies. In, Pastoral practices in High Asia, Springer.

Guo, N., Li, Y., Han, L., Wang, S. (2012). The effects of climate change on different types of grassland in Maqu County in Northeast Tibetan Plateau. In 2012 IEEE International Geoscience and Remote Sensing Symposium, 1139-42. IEEE.

Hardin, G. (1968). 'The tragedy of the commons. Science 162: 1243-48.

Harris, R.B. (2010). Rangeland degradation on the Qinghai-Tibetan plateau: a review of the evidence of its magnitude and causes. Journal of Arid Environments 74: 1-12.

Hijmans, R.J., van Etten, J. (2014). raster: Geographic data analysis and modeling. R package version 2.

Ho, P. (2000). China's rangelands under stress: A comparative study of pasture commons in the Ningxia Hui Autonomous Region. Development and Change 31: 385-412.

Hopping, K.A, Yeh, E.T., Harris, R.B. (2018). Linking people, pixels, and pastures: A multi-method, interdisciplinary investigation of how rangeland management affects vegetation on the Tibetan Plateau. Applied Geography 94: 147-62.

Hua, Xiaobo, Yan, Jianzhong, Liu, X. (2013). Settled Herdsmen's Adaptation Strategies to Pasture Degradation——Case Study of Naqu County in Tibet Plateau. Journal of Mountain Science 31: 140-49.

Huber, T. (2012). The changing role of hunting and wildlife in pastoral communities of Northern Tibet. In, Pastoral practices in High Asia, Springer.

Jing, L., Zhe, Y. (2013). The Research 0f Grassland Contract Policy and its implementation in Tibetan areas——Taking Maqu County in Gansu Province and Damshong County in Tibet as examples, Journal of Tibet University 28: 29-33.

Joyce, L.A., Marshall, N.A. (2017). Managing Climate Change Risks in Rangeland Systems, Springer International Publishing.

Klein, J.A, Hopping, K.A., Yeh, E.T., Nyima, Y., Boone, R.B., K.A. Galvin. 2014. Unexpected climate impacts on the Tibetan Plateau: Local and scientific knowledge in findings of delayed summer. Global Environmental Change. 28: 141-52.

Kraudzun, T. (2012). Pastoral practices in High Asia. Advances in Asian Human-Environmental Research.

Leutner, B., Horning, N. (2017). Stoolbox: tools for remote sensing data analysis. R package version 0.1, 7.

Levine, N.E. (2015). Transforming inequality: Eastern Tibetan pastoralists from 1955 to the present. Nomadic Peoples: 164-88.

Li, W., Huntsinger, L. (2011). China's Grassland Contract Policy and its Impacts on Herder Ability to Benefit in Inner Mongolia: Tragic Feedbacks. Ecology & Society 16: 1.

Li, A., Wu, J., Zhang, X., Xue, J., Liu, Z., Han, X.,Huang, J. (2018). China's new rural "separating three property rights" land reform results in grassland degradation: Evidence from Inner Mongolia. Land Use Policy 71: 170-82.

Li, D., Hruska, T., Talinbayi, S., Li, W. (2019). Changing Agro-Pastoral Livelihoods under Collective and Private Land Use in Xinjiang, China. Sustainability 11: 166.

Lin, L. (2010). A very different choice from individual household contracts. Man and the Biosphere 2: 68-73.

Lv, G.H. (1980). The regulation of change of yak's body weight and relationship between its slaughtered age and different seasons under the condition of natural grazing. Abstract Collection of Theses of Animal Husbandry and Veterinary Medicine of China 26: 1-20.

Mace, R. (1991). Overgrazing overstated. Nature 349: 280-81.

Miller, D.J. (2000). Tough times for Tibetan nomads in western China: snowstorms, settling down, fences and the demise of traditional nomadic pastoralism. Nomadic Peoples: 83-109.

Mwangi, E. (2007). The puzzle of group ranch subdivision in Kenya's Maasailand. Development and Change, 38: 889-910.

Mwangi, E., Ostrom, E. (2009). Top-down solutions: looking up from East Africa's rangelands. Environment: Science and Policy for Sustainable Development, 51: 34-45.

Ning, W., Richard, C.E. (1999). The privatisation process of rangeland and its impacts on the pastoral dynamics in the Hindu Kush Himalaya: The case of Western Sichuan, China. In People and Rangelands. Proceedings of VI International Rangelands Congress, Townsville, Australia, 14-21. Citeseer.

North, D.C. (1981). Structure and change in economic history, Norton.

Ojima, D., Chuluun, T. (2008). Policy changes in Mongolia: implications for land use and landscapes. In, Fragmentation in semi-arid and arid landscapes, Springer.

Ostrom, E. (1990). Governing the commons: The evolution of institutions for collective action, Cambridge university press.

Ostrom, E. (2009). Understanding Institutional Diversity. Princeton: Princeton University Press.

Ostrom, E., Burger, J., Field, C.B., Norgaard, R.B., Policansky, D. (1999). Revisiting the commons: local lessons, global challenges. Science 284: 278-82.

Pettorelli, N. (2013). The normalized difference vegetation index, Oxford University Press.

Piao, S., Cui, M., Chen, A., Wang, X., Ciais, P., Liu, J., Tang, Y. (2011). Altitude and temperature dependence of change in the spring vegetation green-up date from 1982 to 2006 in the Qinghai-Xizang Plateau. Agricultural and Forest Meteorology 151: 1599-608.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., R Core Team. (2016). nlme: Linear and Nonlinear Mixed Effects Models, 2015. R package version 3: 103.

Pirie, F. (2005). Segmentation within the state: the reconfiguration of Tibetan tribes in China's reform period. Nomadic peoples 9: 83-102.

Reid, R.S., Fernández-Giménez, M.E., Galvin, K.A. (2014). Dynamics and resilience of rangelands and pastoral peoples around the globe, Annual Review of Environment and Resources 39: 217-42.

Riaño, D., Chuvieco, E., Salas, J., Aguado, I (2003). Assessment of different topographic corrections in Landsat-TM data for mapping vegetation types (2003), IEEE Transactions on geoscience and remote sensing 41: 1056-61.

Richard, C. (2005). Developing alternatives to resettlement for pastoralists on the Tibetan Plateau. Nomadic Peoples 9: 103-06.

Richard, C., Zhaoli, Y., Guozhen, D. (2006). The paradox of the individual household responsibility system in the grasslands of the Tibetan Plateau, China. In: Bedunah, Donald J., McArthur, E. Durant, and Fernandez-Gimenez, Maria, comps. 2006. Rangelands of Central Asia: Proceedings of the Conference on Transformations, Issues, and Future Challenges. 2004 January 27; Salt Lake City, UT. Proceeding RMRS-P-39. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 83-91.

Robinson, S., Whitton, M., Biber-Klemm, S., Muzofirshoev, N.. (2010). The impact of land-reform legislation on pasture tenure in Gorno-Badakhshan: From common resource to private property? Mountain Research and Development 30: 4-14.

Schott, J.R., Hook, S.J., Barsi, J.A., Markham, B.L., Miller, J., Padula, F.P., Raqueno, N.G. (2012). Thermal infrared radiometric calibration of the entire Landsat 4, 5, and 7 archive (1982–2010). Remote sensing of environment 122: 41-49.

Sneath, D. (2003). Land use, the environment and development in post-socialist Mongolia. Oxford Development Studies 31: 441-59.

Sternberg, T. (2008). Environmental challenges in Mongolia's dryland pastoral landscape. Journal of Arid Environments 72: 1294-304.

Tony, Banks. (2001). Property Rights and the Environment in Pastoral China: Evidence from the Field. Development & Change.

Vernooy, R. (2011). How Mongolian herders are transforming nomadic pastoralism. Solutions 2: 82-87.

Vij, S., Narain, V. (2016). Land, water & power: The demise of common property resources in periurban Gurgaon, India. Land use Policy 50: 59-66.

Wegmann, M., Leutner, B., Dech, S. (2016). Remote sensing and GIS for ecologists: using open source software, Pelagic Publishing Ltd.

Xu, W., Liu, X. (2007). Response of vegetation in the Qinghai-Tibet Plateau to global warming. Chinese Geographical Science 17: 151-59.

Yan, Z., Wu, N., Yeshi, D., Ru, J. (2005a). A review of rangeland privatization and its implications in the Tibetan Plateau, China. Nomadic Peoples, 9: 31-51.

Yan, Z., Wu, N., Dorji, Y., Ru, Jia. (2005b). A Review of Rangeland Privatisation and its Implications in the Tibetan Plateau, China, Nomadic Peoples 9: -.

Yeh, E.T., Nyima, Y., Hopping, K.A., Klein, J.A. (2014). Tibetan pastoralists' vulnerability to climate change: a political ecology analysis of snowstorm coping capacity. Human Ecology 42: 61-74.

Yeh, E.T., Samberg, L.H., Volkmar, E., Harris, R.B. (2017). Pastoralist decision-making on the Tibetan Plateau. Human Ecology 45: 333-43.

Yu, H., Luedeling, E., Jianchu X. (2010). Winter and spring warming result in delayed spring phenology on the Tibetan Plateau. Proceedings of the National Academy of Sciences 107: 22151-56.

Zhang, Q., Li, W.J. (2008). Distributed overgrazing: a neglected cause of grassland degradation in Inner Mongolia. Journal of Arid Land Resources and Environment 22: 8-16.

Zhang, Y., Liu, L., Bai, W., Shen, Z.X., Yan, J.Z., Ding, M.J., Li, S.C., Zheng, D. (2006). Grassland degradation in the source region of the Yellow River. Acta Geographica Sinica-Chinese Edition 61: 1.

Zhang, J., Yao, F., Zheng, L., Yang, L. (2007). Evaluation of grassland dynamics in the Northern-Tibet Plateau of China using remote sensing and climate data. Sensors 7: 3312-28.

Zhao, H., Rokpelnis, K. (2016). Local perceptions of grassland degradation in China: a socio-anthropological reading of endogenous knowledge and institutional credibility. The Journal of Peasant Studies 43: 1206-23.

Zhu, Z., Woodcock, C.E. (2012). Object-based cloud and cloud shadow detection in Landsat imagery. Remote sensing of environment 118: 83-94.

Zhu, Z., Piao, S., Myneni, R.B., Huang, M., Zeng, Z., Canadell, J.G., Ciais, P., Sitch S., Friedlingstein, P., Arneth, A. (2016). Greening of the Earth and its drivers. Nature Climate Change 6: 791.