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Contrasting policy shifts influence the pattern of vegetation production and C sequestration over pasture systems: A regional-scale comparison in Temperate Eurasian Steppe

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ABSTRACT

Socio-economical conditions profoundly influence terrestrial ecosystems, especially the agroecosystems. However, the effects of large-scale “top-down” socio-economical changes on patterns of vegetation production and C sequestration in pastures remain largely unclear. The contrasting institutional and policy shifts in 1990s over the two sub-region of Temperate Eurasian Steppe (TES), *i.e.*, the Kazakh Steppe (KS) and the Mongol Steppe (MS), provide a unique opportunity to illustrate the human and natural interactions. Combining multiple information from remote sensing, land model, climate and inventory data, this study investigated how the regional trend and inter-annual variability (IAV) of leaf area index (LAI), net primary productivity (NPP), net ecosystem productivity (NEP) were associated with different institutional and policy shifts. From 1997 to 2016, climate is the primary control factor to the IAV of the ecosystem indexes (EIs, *i.e.*, LAI, NPP, NEP) at a regional view. Highly contrasting impacts of human appropriation indexes (HAIs, *i.e.*, livestock number and agricultural GDP) to the EIs were found for the two sub-region. The effect of HAIs on EIs was weak in the MS, but significant negative correlations between HAIs and EIs were found in the KS. Further decomposition into administrative divisions showed that the swift rise of human appropriation in China was accompanied with increases in grassland NPP and NEP, owing to the policy shift to sustainable management. But the institutional shift to market-driven economy and increasing human appropriation generally acted as a negative factor to EIs in various countries over the KS, especially in Uzbekistan and Turkmenistan. Regional evidences revealed the importance of large-scale socio-economic shifts in shaping the pattern of important ecosystem properties of grasslands and emphasized the importance of sustainability development in managing pasture systems.

1. Introduction

Grasslands are the dominant land cover type in the world, providing a range of important ecosystem services (White et al., 2000). Grassland ecosystems have absorbed and accumulated large amounts of carbon over time and thus represent a significant carbon pool of about 20% of the world's soil carbon stocks (Wang et al., 2008). Grasslands also provide essential products for human beings and are closely related to global food security. According to an FAO Report (Conant, 2010), grasslands account for 27% and 23% of global production of milk and beef, respectively. Therefore, quantitative assessment of the spatio-temporal patterns of ecosystem services in grasslands is important to land resource conservation, global C sequestration, food security, and socio-economic stability.

Long-term trends and interannual variability (IAV) are two important properties in shaping the spatio-temporal pattern of various ecosystems in the context of climate change and socio-economic shifts (van der Werf et al., 2006; Wu et al., 2012; Piao et al., 2015; Yao et al.,

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2018). The recognition of human interference in vegetation areas has gradually modified our understanding of the main driving forces controlling trends and IAV of important ecosystem indicators, *e.g.*, leaf area index, vegetation production and C sequestration. The impact of land use and management on terrestrial C stocks have been observed and evaluated over the long-term (Post and Kwon, 2000; Jangid et al., 2008; Zhang et al., 2013). Many studies have indicated that anthropogenic activities contributed to the increasing trend of grassland NPP during the last three decades over different types of grasslands, such as alpine meadows (Chen et al., 2014), desert steppe (Xu et al., 2011) and temperate steppes (Mu et al., 2013). It is estimated that grazing contributes one-third to the management-induced difference of global vegetation biomass stocks (Erb et al., 2018). Globally, NPP losses from pasture systems due to degradation are about 58.84 $Tg\,C\,yr^{-1}$ (Gang et al., 2014). Although uncertainty still exists (Pongratz et al., 2014; Fetzel et al., 2017), the increasing magnitude of human appropriation is important in controlling long-term trends and IAV of C budgets over large scales. As a consequence, anthropogenic factors (*i.e.*, Shared Socio-economic Pathways) were considered in the next round of the Coupled Model Inter-comparison Project (CMIP) simulations and the Intergovernmental Panel on Climate Change (IPCC) assessments in concert with the climatic scenarios (O'Neill et al., 2014; Fujimori et al., 2017; Riahi et al., 2017). Recent studies emphasize the large effect of top-down ecological restoration programs on pasture systems (Xiao, 2014; Chen et al., 2015c; Liang et al., 2015b), but how different types of socio-economic shifts influence long-term trends and IAV of vegetation production and C sequestration in pasture systems has seldom been explicitly quantified and compared.

Temperate Eurasian Steppe (TES) is the world's largest continuous pasture system with various environmental, social, and economic stresses. It is a hot spot of climate change and has been extensively appropriated by humans (Groisman et al., 2017; Monier et al., 2017). Climatic conditions during the past several decades over the region have substantially changed. In the past three decades, warming in TES has spread from Hungary in the west (Mátyás et al., 2018) to Northeast China in the East (Chun-Yu et al., 2013). Quantitatively, since the 1970s, mean annual temperature over TES has increased by about 1.5 °C (Schwartz et al., 2006; Bulygina et al., 2011). Generally speaking, warming in TES should cause a greater water deficit and lead to drier conditions unless there is a simultaneous increase in atmospheric precipitation that can compensate for the increasing water demand of the terrestrial ecosystems. However, it appears that during most of the year (autumn, winter, and spring), there were no significant changes in the precipitation totals over most of TES. This has exaggerated dry weather conditions over TES (Groisman et al., 2018).

In the 1990s, the region experienced huge institutional and policy shifts. For the KS, huge agricultural abandonment occurred due to corruption of the former USSR. Since the late 1990s, grasslands in the KS have begun to be reestablished. According to a report from Agency of Statistics of the Republic of Kazakhstan (ASK), nearly 19 million ha of agricultural lands were withdrawn from cropland production from 1992 to 2000 in Kazakhstan, many of which happened in the years following the corruption (ASK, 2003). Correspondingly, the grasslands expanded rapidly during that period (Kraemer et al., 2015). Pasture systems were re-established starting in 1995 with the transition of economic strategy from state-controlled to market-driven for the former USSR countries (Dudwick et al., 2007; Meyfroidt et al., 2016; Prishchepov et al., 2017). During the same period, a series of ecological restoration programs were implemented in the MS. Rapid expansion of the husbandry industry has occurred since the 1980s but the speed and scale of this expansion may be greater than livestock carrying capacity of the grasslands in this region. During this time, the Chinese government has promoted large ecological recovery programs in major pasture systems such as Grain for Green Program: the Returning Grazing to Grassland Program, and the Program to Combat Desertification around Beijing and Tianjin (Liu et al., 2018). As the two largest continuous grasslands in China, the pasture systems in Inner Mongolia and Xinjiang were extensively involved in these ecological restoration programs. For example, in Inner Mongolia, the infrastructure, including animal sheds and corrals, increased by 20%, and fenced grassland increased nearly three-fold from 1999 to 2008. Correspondingly, NPP of grasslands in Inner Mongolia increased by 40.6 $gC/m^2\,yr^{-1}$ between 2001 and 2009 (with climatic factors excluded) (Mu et al., 2013). As a result, grassland production and rain use efficiency had systematic increases since 2000 in Chinese grasslands (Huang et al., 2013). The contrasting difference of "top-down" institutional or policy shifts over this continuous pasture system in the same period provide a unique opportunity to study how human appropriation.

In this study, we gathered and combined information and statistics from climate, remote sensing, process-based models, and socio-economy inventories to study the spatio-temporal trends and IAV of important ecosystem indexes (EIs, *i.e.*, LAI, NPP and NEP) and the potential drivers in TES from 1997 to 2016. The objects of this study were to analyze (1) how different policy or institutional shifts affect the trends and IAV of EIs and (2) their relative importance against climate in different sub-regions of TES.

2. Materials and methods

2.1. Study region

The study includes the main areas of the Eurasian steppe zone, extending to Russia's Volgograd to the west, and to Mongolia and Inner Mongolia to the east. The latitude and longitude range is 39.5°E–124.5°E and 35.7°N–54.5°N, respectively. Due to the wide latitude and longitude span of the region, the topography, soil, and climatic conditions in the region are highly variable. The climate of the Eurasian steppe zone is the typical temperate continental climate but different regions vary in terms of drought conditions. Due to the variation in environmental conditions, the grassland vegetation also has regional differences. Climate variation along the latitudinal gradient gradually weakens the degree of drought and gradually prolongs the non-glacial period, producing different grassland vegetation types. The distribution of the zonal grassland from north to south includes the meadow steppe in the moist area (forest grassland), typical steppe in the semi-arid area, semi-desert grassland in the arid area, and desert steppe in the extremely arid area. Climate variation along the longitude determines the degree of continental climate in sub-regions. The Eurasian steppe zone, based on the longitudinal distribution of climatic conditions, is divided into two regions: the Kazakh Steppe (KS) and the Mongolian Steppe (MS). The KS includes the grassland in Kazakhstan and the surrounding Soviet countries (Russia, Uzbekistan, Tajikistan, Kyrgyzstan, and Uzbekistan); the MS contains the grassland in Mongolia, China's Inner Mongolia, and some parts in Xinjiang (Fig. 1).

2.2. Model description

2.2.1. The boreal ecosystem productivity simulator (BEPS)

In this study, we used a grassland version of BEPS (Chen et al., 2017). The model has been widely used to estimate regional or global terrestrial carbon and water fluxes (Liu et al., 1997; Ju et al., 2007; Zhou et al., 2007; Schwalm et al., 2010; Liu et al., 2013; Liu et al., 2017). Detailed model descriptions are in previous studies (Liu et al., 1997; Chen et al., 1999; Liu et al., 2003; Ju et al., 2006; Chen et al., 2007). Here we only introduce the NPP and NEP simulations:

$$NEP = NPP - R_h \tag{1}$$

$$NPP = GPP - R_a \tag{2}$$

where NEP is net ecosystem productivity ($gC/m^2\,yr^{-1}$), NPP is net primary productivity ($gC/m^2\,yr^{-1}$), GPP is total primary productivity ($gC/m^2\,yr^{-1}$), and R_a and R_h are autotrophic respiration ($gC/m^2\,yr$) and heterotrophic respiration ($gC/m^2\,yr$), respectively.

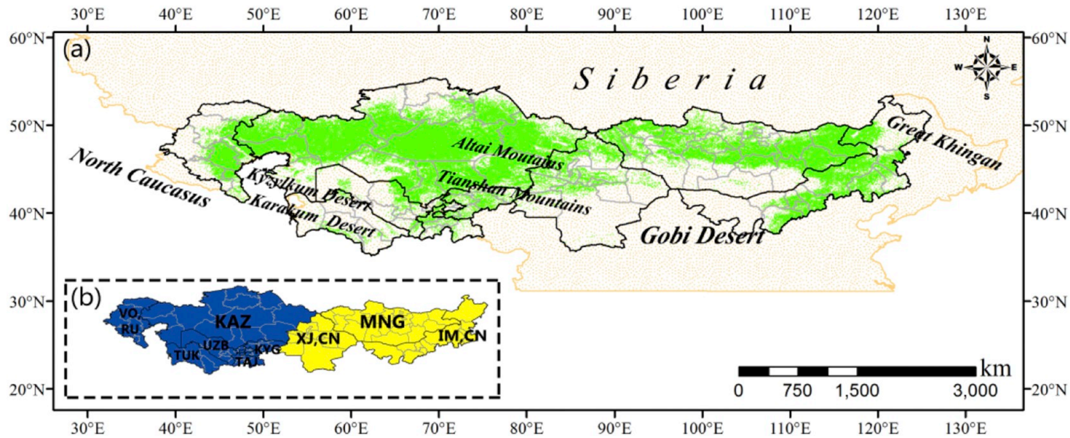

Fig. 1. Map of the study region. (a) The spatial distribution of Temperate Eurasian Steppe. (b) The region divided into two sub-regions. The blue area represents the Kazakh Steppe, including: Kazakhstan (KAZ), Uzbekistan (UZB), Kyrgyzstan (KYG), Turkmenistan (TUK), Tajikistan (TAJ) and Volgograd, Russia (VO, RU). The yellow area represents the Mongol Steppe, including Mongolia (MNG), Inner Mongolia, China (IM, CN), and Xinjiang, China (XJ, CN). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In BEPS, the total instantaneous photosynthesis rate of a canopy (μmol $m^{-2} s^{-1}$) is calculated as follows:

$$A_{canopy} = A_{sunlit} \times LAI_{sunlit} + A_{shade} \times LAI_{shade} \quad (3)$$

where A_{sunlit} and A_{shade} are the instantaneous photosynthesis rates for sunlit and shaded leaves (μmol $m^{-2} s^{-1}$), respectively, which are simulated from the Farquhar biochemical model (Farquhar et al., 1980). LAI_{sunlit} and LAI_{shade} are the leaf area index (LAI) of sunlit and shaded leaves (m^2/m^2), which are calculated from the LAI data input and the double-leaf scheme from Norman (1982) and Chen et al. (1999). GPP is then calculated by integrating A_{canopy} over the year using a scheme from Chen et al. (1999).

Vegetation with autotrophic respiration consists of growth respiration and maintenance respiration. In the original BEPS model, growth respiration is considered to be 25% of GPP and maintenance respiration uses the method of Bonan (1995). This study preserves the algorithm for the original model on growth respiration, while improving the algorithm on maintenance respiration by quantifying it from different parts of the vegetation:

$$R_{m,.k} = T_k \times r_{m,k} \times Q_{10,r}^{\frac{(T-T_r)}{10}} \quad (4)$$

where T_k is the productivity allocated in component k, $r_{m,k}$ is the carbon partition coefficient in plant component k, and $Q_{10,r}$ is the temperature sensitivity parameter of maintenance respiration. In this study, $Q_{10,r}$ is calculated by air temperature (T) following Arora (2003):

$$Q_{10,r} = 3.22 - 0.046T \quad (5)$$

The soil respiration R_h is calculated from the product between the carbon stock size (C_k) and the carbon release rate (p_k) (Ju et al., 2010):

$$R_h = \sum_{k=1}^{8} p_k C_k \quad (6)$$

where C_k is obtained by initializing the model. p_k is affected by factors such as soil temperature and humidity, soil texture and soil N availability:

$$p_k = P_m F_{SN} F_{ST} F_{SM} F_{Tex} F_{Lg} \quad (7)$$

where P_m is the maximum decomposition rate in the k pool; F_{SN} is the impact factor of soil N availability on C degradation, which affects the C decomposition rate of the structural carbon pool, metabolic carbon pool, chronic carbon pool, and inert carbon pool; F_{ST} and F_{SM} are the abiotic factors of soil temperature and soil moisture, respectively, that act on all soil C pools; F_{Tex} is the impact factor of soil texture on soil microbiome decomposition; and F_{Lg} is the impact factor of lignin on the structural pool.

The model has been well validated over the region and we further verified the model ability and performance using both flux and field observations. Detail model validations were presented in the Supplementary Material.

2.3. Data used

2.3.1. Remote sensing LAI dataset

The long-term remote-sensing derived LAI dataset, GlobalLAI, was used in this study (http://www.globalmapping.org/globalLAI/). The dataset is derived from MODIS and AVHRR based on the MODIS LAI products (MOD09A1) by the relationship between AVHRR SR and MODIS LAI established pixel by pixel during the overlapping period (2000–2006). Based on these relationships, LAI series were retrieved from AVHRR for the period prior to 2000. A detailed introduction of the dataset can be seen in Liu et al. (2012). The annual growing season LAI was calculated by averaging LAI data from April to September for each study year. The spatial resolution of the dataset is 8 km.

2.3.2. The standardized precipitation-evapotranspiration index (SPEI) dataset

The 1-month scale SPEI datasets (http://spei.csic.es/) from 1997 to 2014 were used in this study to represent the regional pattern of climate variations. This synthetic index enables to identify the drought duration and magnitude and facilitate the analysis of spatio-temporal changes in climatic drought conditions. The growing season SPEI was calculated by averaging the monthly SPEI from April to September for each study year. The spatial resolution of the dataset is 0.5°.

2.3.3. Socio-economic dataset

The national level socio-economic dataset of livestock number (LN) and agricultural GDP (agGDP) from Mongolia, Kazakhstan, Uzbekistan, Turkmenistan, Tajikistan, and Kyrgyzstan were collected from the FAOstat dataset (http://www.fao.org/faostat/) and the World Bank dataset (https://data.worldbank.org/), respectively. The provincial level dataset of Inner Mongolia and Xinjiang in China were collected from the official statistical yearbook in China (http://tongji.cnki.net/). The provincial level dataset of Volgograd, Russia were from the Federal Service of State Statistics in Russia (http://statinfo.biz/).

2.3.4. Model input data

The input data of this study included vegetation canopy information, and data of climate, land use type, soil texture, and atmospheric CO_2. The LAI data used in this study were from the GlobalLAI dataset as introduced above. The land cover data were the MODIS Land Cover

Data Set of 2001 (https://lpdaac.usgs.gov), which used the IGBP vegetation classification system. The meteorological forcing data were from the Global Meteorological Forcing Dataset for Land Surface Modeling (http://rda.ucar.edu/datasets/ds314.0/), including the minimum daily temperature, the maximum daily temperature, relative humidity, precipitation, and total solar radiation. Soil texture data came from the Global Soil Dataset for use in Earth System Models (http://globalchange.bnu.edu.cn/research/soilw). Monthly atmospheric CO_2 data were from the Mauna Loa Observatory (MLO), Hawaii (20°N, 156°W) (http://cdiac.esd.ornl.gov/ftp/trends/co2/maunaloa.co2). The spatial resolution of all the spatial explicit datasets is 8 km.

2.4. Data analysis

2.4.1. Spatio-temporal pattern analysis

First, multi-year datasets of various indexes were averaged into annual values to calculate their spatial patterns for the study period. Thereafter, the linear trends of the indexes were calculated using a simple linear correlation with time. The spatio-temporal trend distributions of LAI, NPP, NEP, and SPEI were calculated over a pixel level as a function of time and then aggregated into sub-region and national level to generate the temporal trends. For LN and agGDP, temporal trends for sub-regions were calculated by aggregating the national/provincial level dataset.

2.4.2. Trend-involved (Tr-in) and detrend (Detr) correlation analysis

Linear correlations of EIs against SPEI and HAIs were analyzed on the sub-regional scale. We undertook both trend-involved (Tr-in) and detrend (Detr) correlation analysis. In Detr analysis, we determined the linear fit between the variable and time, and then removed the linear trend from the index if it was significant (Wang and You, 2004; Xiao et al., 2015). Specifically, if the Tr-in correlation was much higher than the Detr correlation, it means that the two indexes have little similarity for IAV but with similar long-term trends. In contrast, if the Detr correlation is much higher than or equal to the Tr-in outputs, it means that the two indexes have a close relationship for IAV, while the long-term trend is different. All indexes were normalized to a range of 0–1.

2.4.3. Partial correlation analysis

In order to quantify the relative importance of climate and human appropriation in controlling the variability of EIs, the partial correlation between EIs and SPEI or human appropriation indicators (HAIs) were analyzed. The partial correlation analysis was undertaken on sub-regional and national/province scales. Because LN and agGDP shared a very similar trend, we separated the analysis into two groups (*i.e.*, EI-SPEI-LN and EI-SPEI-agGDP) and calculated the partial correlation using LN and agGDP as HAI, respectively.

3. Results

3.1. The spatial patterns of climate, ecosystem indicators, and human appropriation in TES

3.1.1. Ecosystem indexes

LAI and NPP shared similar spatial patterns (Fig. 2a and b). The high-value areas were distributed in areas with good climatic conditions and high potential for vegetation growth, including the eastern MS and the meadow steppe between the Great Khinghan and Siberian forests, the alpine meadow steppe in Tianshan and Altai mountains, and the Russian steppe region bordering the North Caucasian forest. Most of these areas bordered forest ecosystems, in which NPP usually reaches > 150 gC/m^2 yr^{-1}; The low value areas were distributed in areas close to the desert such as Kizilke, near Karakum and the Gobi Desert, where NPP were usually < 40 gC/m^2 yr^{-1} and 50 gC/m^2 yr^{-1}, respectively.

Over the two decades, the region acted as a weak C sink, with only areas close to the deserts (*i.e.*, the Karakum and Gobi Deserts) characterized as C sources. The spatial pattern of NEP also had similar characteristics with NPP (Fig. 2c). The main differences existed in the northeastern region of the Mongolian Plateau (in the Dornod province in Mongolia and Hailar in Inner Mongolia) and the northeastern region of Kazakhstan (in the Pavlodar province).

3.1.2. Climate

The regional SPEI pattern showed that the MS is drier than the KS (Fig. 2d). SPEI over most of the MS was lower than −0.2, indicating a pervasive drought condition during the past two decades. The major humid areas (SPEI > 0) are grasslands in Northeastern Inner Mongolia, which is close to the Great Khinghan forests. In contrast, SPEI over the KS was higher than 0, indicating a better water supply condition. The dry areas (SPEI < 0) were distributed over the desert areas of Karakum and Kyzylkum.

3.1.3. Human appropriation

The spatial pattern of LN is highly imbalanced over TES (Fig. 2e). LN is much higher in the MS than in the KS. The mean LN is about 50 million head for the three MS countries/provinces, while the mean LN is only about 12 million head for the 6 KS countries/provinces. This contrasting spatial pattern is due to the collapse of the previous agricultural system of the former USSR over the KS and the boom of animal husbandry in China and Mongolia since the 1990s.

agGDP is an index that relates more to national socio-economic developments. The Chinese regions showed the highest agGDP over the last two decades (Fig. 2f). The agGDPs are 12.6 and 11.1 billion US Dollars for Inner Mongolia and Xinjiang, respectively. While the economy of Mongolia is highly reliant on its agriculture, the absolute value of agGDP is much lower due to slower macro-economic development. The total agGDP over the Chinese region represents about 95% of the total agGDP in the MS. For the KS, although the region experienced a high increasing rate of economic development in recent years, the absolute agGDP amount is low in the former USSR countries. With agGDP of 5.9 and 5.2 billion US Dollars, Kazakhstan and Uzbekistan contribute > 70% of agGDP to the KS sub-region.

3.2. The trends of climate, ecosystem indicators, and human appropriation in TES

The temporal trends of climate, ecosystem indicators, and human appropriation are shown in Figs. 3 and 4. SPEI did not have significant trends over most of the region. Only some areas of North Mongolia and Northeast Kazakhstan had significant increasing trends, while part of Northwestern Kazakhstan had significant decreasing trends. Aggregated to the sub-regional scale, the climatic conditions over the KS and MS fluctuated during the two decades and no significant trends were found (Fig. 4).

For the EIs, the region showed increases of LAI and NPP over the last two decades. Statistically, over 70% of the areas in TES had increasing trends, and 25% and 31% of them were significant ($p < .05$) for LAI and NPP, respectively. Major increases were found in Northeastern Kazakhstan, Northwestern Mongolia, and Southern Inner Mongolia. Aggregated by sub-region, the KS did not show any significant trends of LAI and NPP during the study period, while both LAI and NPP had significant increasing trends in the MS (Fig. 4b).

The NEP trend exhibited a similar spatial distribution with LAI and NPP (Fig. 3c). However, most of the areas exhibited insignificant temporal trends over the two decades. This pattern was also reflected by the regional aggregated annual outputs. NEP of both sub-regions fluctuated during the two decades and no significant trend was found (Fig. 4).

The two HAIs (LN and agGDP) in both sub-regions showed significant increases during the study period, illustrating the human activity in the KS. Same as in the KS, both LN and agGDP in the MS increased significantly over the study period. Simultaneous increase were found among SPEI, LAI, NPP, and NEP for the second decade (2007–2016), while the SPEI trend was different from the EIs for the entire period. Smaller increases of the EIs were stimulated by

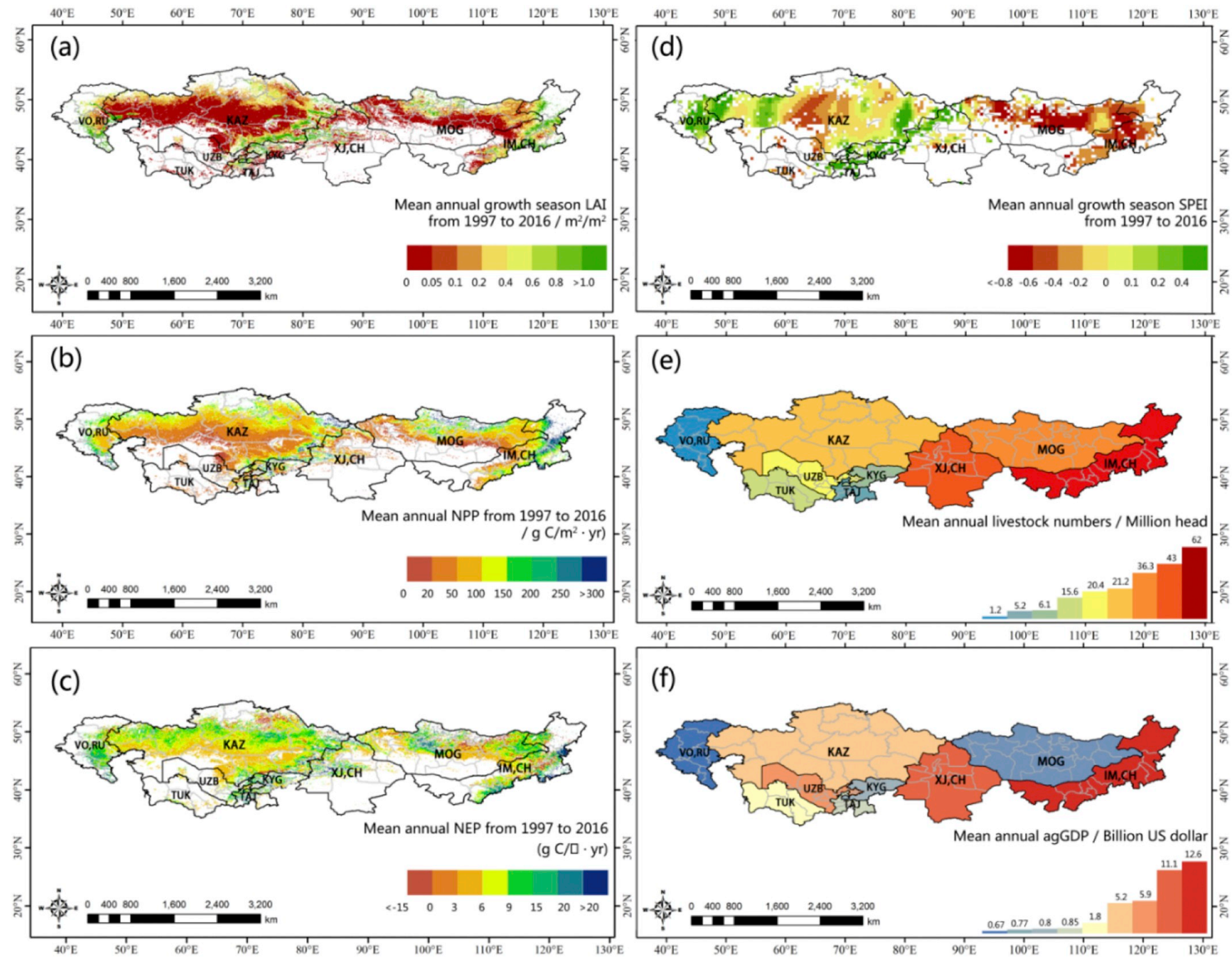

Fig. 2. Spatial patterns of mean annual (a) growing season LAI, (b) NPP, (c) NEP, (d) growing season SPEI, (e) LN and (f) agGDP over TES. The period of all dataset is from 1997 to 2016 except the growing season SPEI with a period from 1997 to 2014.

improvement of climatic conditions in 1998 and 2003. The IAV of LAI, NPP, and NEP showed high similarity with SPEI over the entire period.

3.3. The impact of climate on the trends and IAV of LAI, NPP, and NEP in TES

Since no linear trend was found for SPEI and EIs, there is only one output of linear correlation for the KS (Fig. 5a). The result indicated a significant positive relationship between SPEI and all three EIs over the KS. The R^2 values were 0.39, 0.28, and 0.61 for LAI, NPP, and NEP, respectively.

For the MS, SPEI had a weak correlation with the EIs in the Tr-in analysis (Fig. 5b). The R^2 values were 0.17 (not significant), 0.39 ($p < .05$), and 0.375 ($p < .05$). The correlations were significant for all three indexes in the Detr analysis (Fig. 5c). The R^2 values were 0.61 ($p < .001$), 0.8 ($p < .001$), and 0.61 ($p < .001$) for LAI, NPP and NEP, respectively, indicating strong influence of climate condition on IAV of EIs over the MS and less consistency of the long-term trend between climate variability and EIs.

3.4. The impact of human appropriation on the trend and IAV of LAI, NPP, and NEP in TES

Figs. 6 and 7 show the linear correlation between HAIs and EIs over the KS and MS, respectively. The results indicated that over the KS, both LN and agGDP were negatively correlated with the EIs (Fig. 6). However, the correlations are weak in the Tr-in analysis. In the Detr analysis, the negative correlations were slightly increased for both LN and agGDP. R^2 changed from non-significant to 0.15 for LN-NPP correlation, from 0.18 ($p < .1$) to 0.29 ($p < .05$) for the agGDP-LAI correlation, and from 0.13 ($p < .1$) to 0.37 ($p < .01$) for the agGDP-NPP correlation.

In contrast, both LN and agGDP were positively correlated with the EIs in the MS (Fig. 7). In Tr-in analysis, R^2 values were 0.63, 0.46, and 0.27 for LN-LAI, LN-NPP, and LN-NEP, respectively. The corresponding R^2 values for agGDP-LAI, agGDP-NPP and agGDP-NEP were 0.87, 0.79, and 0.61, respectively. However, the correlations decreased in the Detr analysis. No correlations were found in the LN-EIs Detr analysis. The R^2 values decreased to 0.23, 0.63, and 0.2 in agGDP-LAI, agGDP-NPP, and agGDP-NEP, respectively. The results suggested that the HAIs share similar long-term trends with EIs, while they have minor impacts on IAV of EIs in the MS.

3.5. The relative importance of climate and human appropriations in controlling IAV of EIs over KS and MS

The statistical summary of partial correlation analysis is shown in Table 1. The results of partial correlation analysis indicated that climate variability strongly controls the IAV of EIs in the MS. The HAIs were positively correlated with LAI and NPP and negatively correlated with

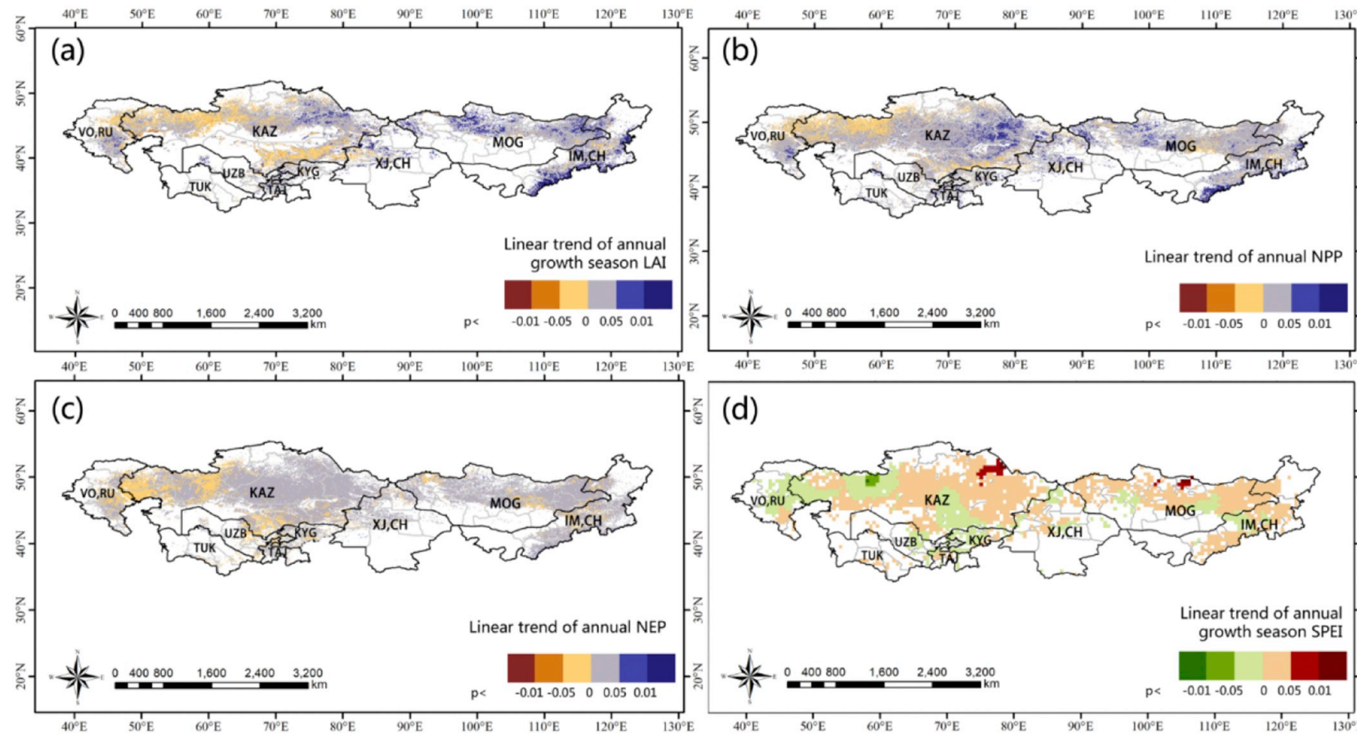

Fig. 3. Spatial distribution of linear trends of (a) LAI, (b) NPP, (c) NEP from 1997 to 2016 and (d) SPEI from 1997 to 2014 in TES.

NEP, but neither relationship was significant. For the KS, similar strong positive correlations were found between SPEI and EIs. However, both LN and agGDP acted as negative factors to the IAV of EIs, especially for agGDP-EI correlations. The negative correlations between agGDP and LAI or NPP were as important as the positive correlation of SPEI in LAI and NPP analysis. The correlation coefficient (r) of SPEI-LAI and agGDP-LAI were 0.73 and −0.67, respectively, while the r of SPEI-NPP and agGDP-NPP were 0.64 and −0.71, respectively. The results imply the strong negative effect of economic development on IAV of EIs in the KS.

We further examined the partial correlations at the national/province level over TES (Fig. 8). The results indicated that the positive correlations between EIs and HAIs in the MS were from the Chinese grasslands. All three EIs were significantly positive correlated with LN. The r values were 0.56 ($p < .05$), 0.61 ($p < .05$), and 0.72 ($p < .01$) for LAI, NPP, and NEP, respectively. The positive correlations between EIs and agGDP were less significant, only the correlation between LAI-agGDP was significant with an r of 0.74. In the KS, the contrasting correlations over EIs from SPEI and HAIs were from Uzbekistan and Turkmenistan. In Turkmenistan, all EIs were significantly positively correlated with SPEI and significantly negatively correlated with LN. The r values were 0.68 ($p < .01$), 0.59 ($p < .05$), and 0.58 ($p < .05$), for LAI-SPEI, NPP-SPEI, and NEP-SPEI, respectively, and the r values were −0.52 ($p < .05$), −0.55 ($p < .05$), and −0.58 ($p < .05$) for LAI-LN, NPP-LN, and NEP-LN, respectively. However, the correlation between EIs and agGDP was weak in SPEI-agGDP analysis. In Uzbekistan, the significant negative correlations were from SPEI-agGDP analysis, the r of NPP-agGDP and NEP-agGDP were −0.72 ($p < .01$) and −0.63 ($p < .05$), respectively.

4. Discussion

The strong influence of climate on IAV of EIs found in this study is similar to the general regional knowledge and consensus (Bai et al., 2008; Zhang et al., 2011; Chuai et al., 2013). Specifically, there was a higher influence of climate over the MS compared to the KS. This result is also consistent with previous findings (Li et al., 2017; Zhang and Ren, 2017) and is due to better climate conditions over the KS, especially for grasslands around Tienshan Mountain and Altai Mountain, where the grasslands are mainly alpine steppes with good moisture conditions (Liang et al., 2015a).

Our study also revealed the regional impact of policy shifts on the pattern of ecosystem properties in addition to climate. Based on the Human Appropriation of NPP (HANPP) or residue trend method, the amounts of grassland production consumed by human beings were reported in previous studies (Li et al., 2012; Mu et al., 2013). Our study provided quantitative information on how human appropriation modified the IAV of important ecosystem indicators of vegetation production and C sequestration using explicit HAIs. Our results reinforce the previous conclusion of the significant impact of different policy shifts to EIs over the MS, and the contrasting relationship between human appropriation and vegetation production in Inner Mongolia, China, and Mongolia (Chen et al., 2015b). However, our results suggest that climate is still the dominant factor in determining the variations of ecosystem properties, which is different from the results of Chen et al. (2015a), who suggested that human influences had exceeded the climate influences in controlling the pasture systems in the MS. One important reason leading to the difference is the different time span investigated. A much longer period prior to the policy shifts (1981–2010) were included in the study of Chen et al. (2015a), while our study focused on the period after the policy shifts (1997–2016). Another reason should be the different use of climate indicator. The aridity index (*i.e.*, SPEI) used in this study is a more comprehensive index to include both thermal and moisture conditions in consideration. The contrasting results also imply that the influence of policy or institutional shifts may gradually diminish after its implementation.

Increased human appropriations in both sub-regions suggested a continuous need for animal products from the pasture systems over the entire TES. However, the sub-regional consequences of intensifying human appropriation were opposite, which emphasizes the impact of policy shifts on the spatio-temporal patterns of EIs in pasture systems.

The strong negative impact of human appropriation on EIs in the KS indicates the potential destructive effect of unsustainable increased use of pasture systems on local ecosystems. As a major policy shift in the sub-region, the drastic transition from planned economy to market-driven economy leaves gaps such as incomplete land restoration, loss of

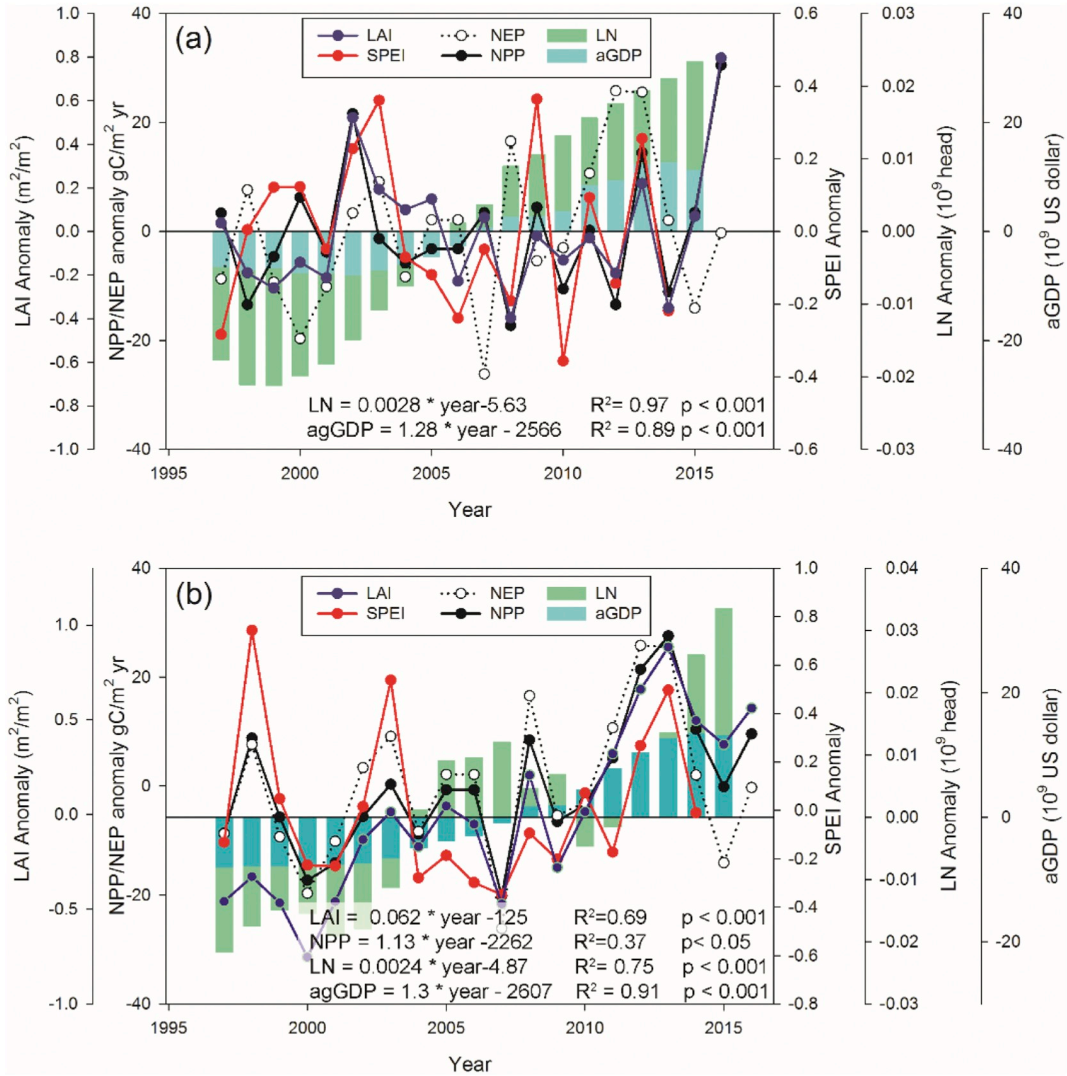

Fig. 4. Temporal trends of anomalies of LAI, NPP, NEP, SPEI, LN and agGDP in (a) the KS and (b) the MS.

guaranteed markets, and dramatic declines in subsidies and infrastructure inputs for the livestock sectors (Prishchepov et al., 2013). After the dissolution of the USSR, the countries promoted state strategies to achieve food self-sufficiency, so land where feed crops were grown were converted and used for human food supply. In return, the local forage production sharply decreased. For example, in Uzbekistan, lands for feed crops decreased by 50% from 1995 to 2005 (Lerman and Roth, 2007). At the same time, animal husbandry has recovered due to rapid development of the private livestock sector and policy support for livestock production (Baydildina et al., 2000; Pomfret, 2008). The contradictory trends of feed supply and livestock demand leads to the higher dependency on grazing. Currently, the livestock sector is mainly

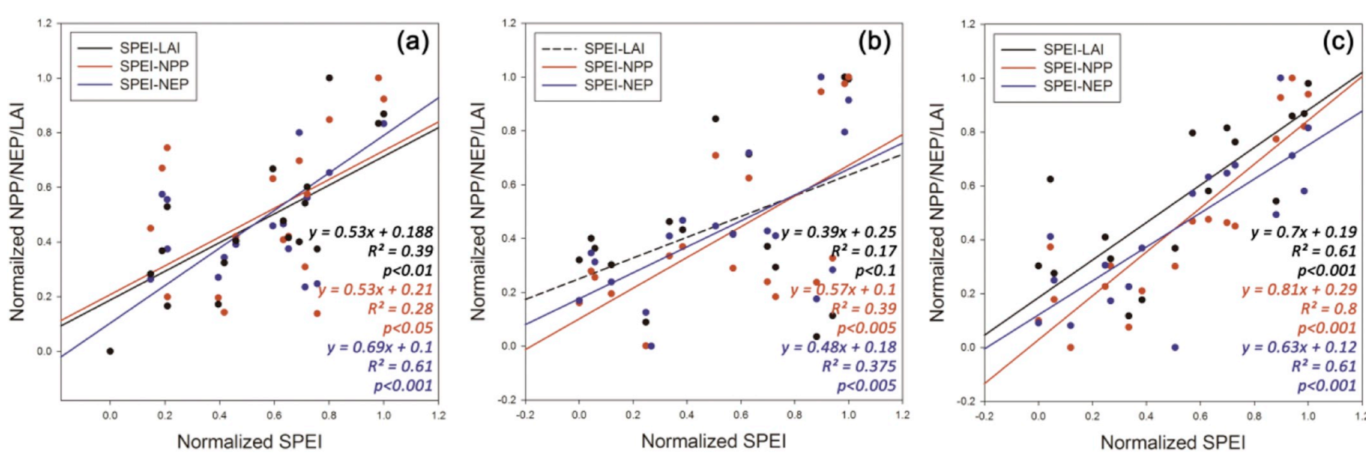

Fig. 5. Relationships between SPEI and LAI, NPP, and NEP over (a) the Kazakh Steppe (KS) and (b) the Mongol Steppe (MS).

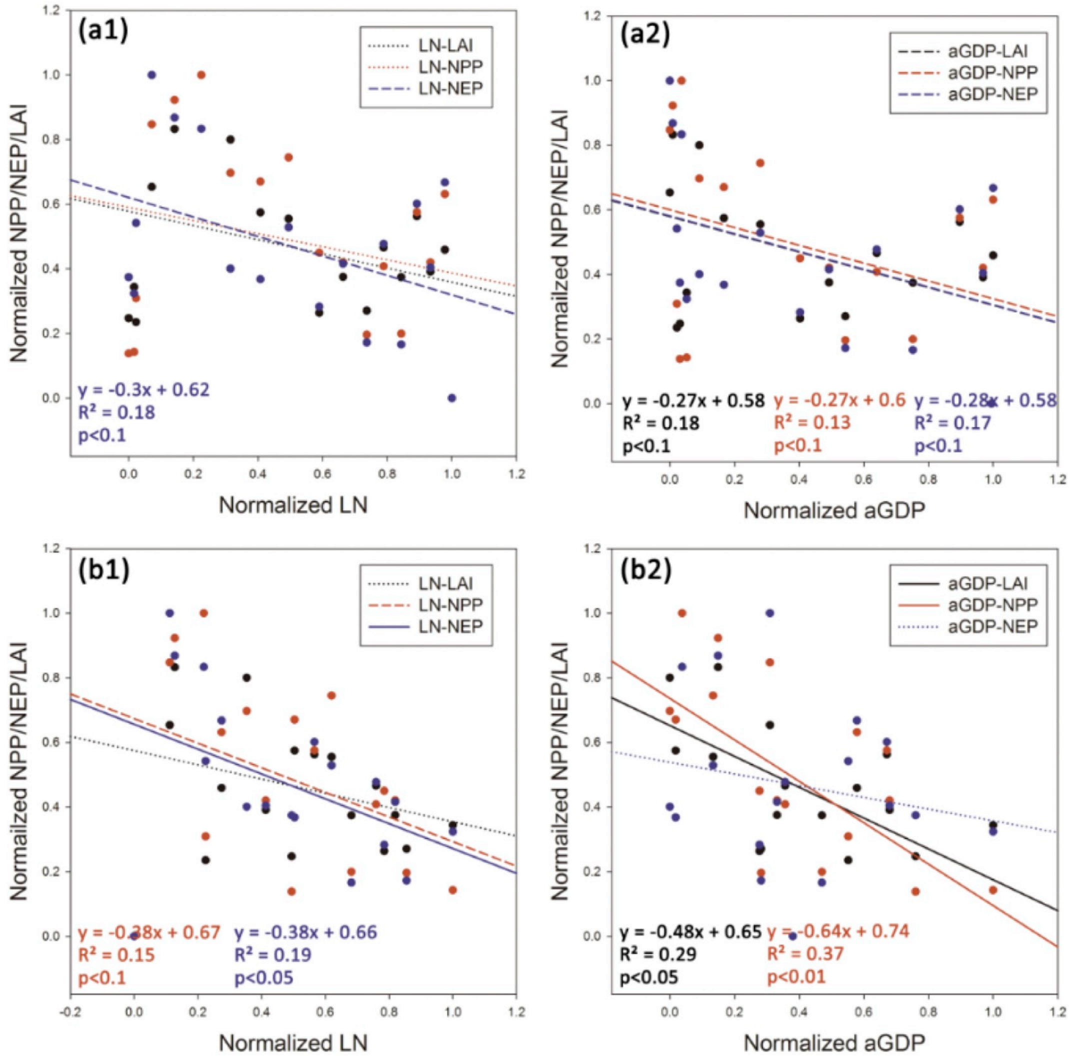

Fig. 6. Relationships between human appropriations and LAI, NPP, and NEP over the Kazakh Steppe. (a1) LN and NPP/NEP/LAI with trend included, (a2) agGDP and NPP/NEP/LAI with trend included, (b1) LN and NPP/NEP/LAI detrended and (b2) agGDP and NPP/NEP/LAI detrended.

based on grazing on grasslands in the KS, especially for Uzbekistan and Turkmenistan (Lerman et al., 2012). As a result, the livestock density is far beyond the recommended scale and the C consumption from livestock alone is much higher than the C sequestration in most grasslands of the two countries (Chen et al., 2017).

In contrast, no significant correlation was found between HAIs and EIs in the MS. This overall relationship is due to the combined effect of the negative correlation for the Mongolia region and positive correlations for the Chinese region. Two policy factors appear to be responsible for positive correlations in China. First, regional sustainability programs tend to preserve grassland resources by transforming grazing and cropping activity to a sustainable style. With increasing infrastructure like animal sheds and corrals, livestock are excluded from degraded areas. Significant recovery of grasslands has been observed (Huang et al., 2013; Zhou et al., 2017). Appropriate grazing intensity can improve grassland quality in higher productive areas by releasing the limitation from older tissue and detritus (Matches, 1992; Milchunas and Lauenroth, 1993). Overcompensation could occur once the regrowth overrides the biomass remove from livestock, which can therefore contribute to the grassland production enhancement (Leriche et al., 2001; Knapp et al., 2012; Luo et al., 2012). Second, in order to deal with the boom of demands for animal products, the regional government encouraged indoor feeding with high quality feed crop in the livestock diet. Recent statistics manifested that fodder production in the major Chinese pastures significantly increased since late 1990s (Bain, 2010; Wang et al., 2013). This transformation promoted the feeding style from high dependence of extensive grazing feeding to a more efficient style of indoor feeding (Wang et al., 2007; Zhang et al., 2014). In this way, the grazing intensities were alleviated from the direct biomass consumption.

Our simulated NPP and NEP are comparable with the major outputs from previous studies (Table 2). The NPP result is consistent with the results from remote sensing-based models like GEO-LUE, GLO-PEM, and a previous BEPS version, but is less than the result based on the original CASA model for a certain level (Table 2). However, it seems like the original CASA model tends to over-estimate grassland NPP due to the lack of localized parameterization. Our result is similar to that from an improved version of the CASA model, which used a more realistic parameterization based on field observations. Compared to the fully prognostic models, our results are lower than the terrestrial ecosystem model (TEM) and the arid ecosystem model (AEM). The prognostic models do not consider the effects of disturbances on LAI and biomass if no specific modules (grazing and fire) are set in the analyses. In addition, the underestimation of LAI in the forcing data should also be responsible for the discrepancy in the results. As reported, the GlobalLAI tended to underestimate LAI due to unstable reflectance and soil effects over those sparse vegetation areas (Liu et al., 2012).

For the comparison of NEP, our results are similar to those of recent studies. The spatial pattern in the KS was similar to Han et al. (2016)

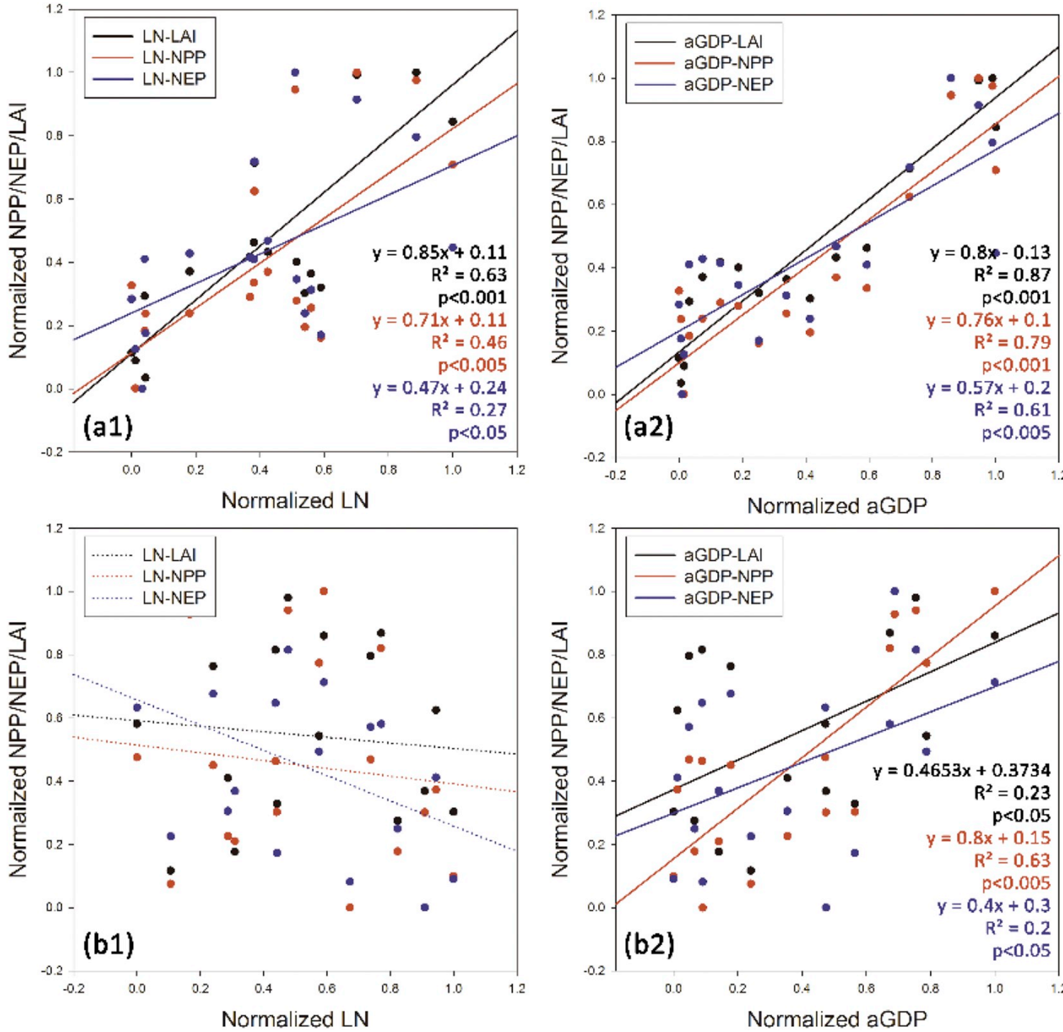

Fig. 7. Relationships between human appropriations and LAI, NPP, and NEP over the Mongol Steppe. (a1) LN and NPP/NEP/LAI with trend included, (a2) agGDP and NPP/NEP/LAI with trend included, (b1) LN and NPP/NEP/LAI detrended and (b2) agGDP and NPP/NEP/LAI detrended.

Table 1
Partial correlation analysis of ecosystem service indexes to climate and human appropriation indexes in the MS and the KS.

Sub-region	MS			KS		
Correlation coefficient (r)	LAI	NPP	NEP	LAI	NPP	NEP
SPEI	0.79***	0.91***	0.65**	0.59**	0.46	0.75***
LN	0.28	0.4	−0.3	−0.08	−0.27	−0.32
SPEI	0.73***	0.74***	0.55**	0.73***	0.64**	0.79***
agGDP	−0.26	0.43	−0.32	−0.67**	−0.71**	−0.29

*p < 0.05, **p < 0.01, ***p < 0.001

and Zhang and Ren (2017). The regional aggregated value of NEP was higher than that from Biome-BGC. A possible reason for the difference is that Han's study included all vegetation types, while in this study, we only considered the condition of grasslands. For the MS, our results were very similar to those from the grassland landscape productivity model (GLPM), but were higher than the output from the TEM model. One possible reason for the difference is the longer study period in the study of Sui et al. (2013) (1951–2007), which covered the earlier several decades and during which NEP was lower than in recent times.

The general similarity in modeling NEP using different models should be partly from the share of a similar modeling strategy, *i.e.*, the first-order C decomposition scheme. Based on this general framework, the feedback of soil C decomposition to climate variations is similar. However, this scheme has long been criticized for ignoring some well-supported microbial-related soil mechanisms such as the priming effect (Kuzyakov, 2010; Feng et al., 2017) and microbial acclimation to global warming (Luo et al., 2001; Peng et al., 2009), which contribute to the large uncertainty in modeling and predicting SOC dynamics. The land use and cover change (LUCC) factor was not considered in the current study. In this study, we tried to avoid the significant LUCC period over the region such as the collapse of the former USSR and the huge land degradation in Inner Mongolia in the early 1990s. However, LUCC, especially the recovery of grasslands, has occurred recently. For example, Chen et al. (2013) reported that some grasslands were reclaimed from 2000 to 2009 in Central Asia. Mu et al. (2013) and Huang et al. (2013) reported that new growth of grassland from the conservation programs in China promoted production increases of grasslands. In addition, new expansions of LUCC such as energy production and urbanization are potential factors influencing the land use pattern in the region. Hence, these factors should be considered in future studies.

5. Conclusions and perspectives

Understanding the drivers of ecosystem service dynamics is important in predicting their spatio-temporal patterns and providing recommendations for sustainable management in the future. The results from this study indicated significant negative correlations between

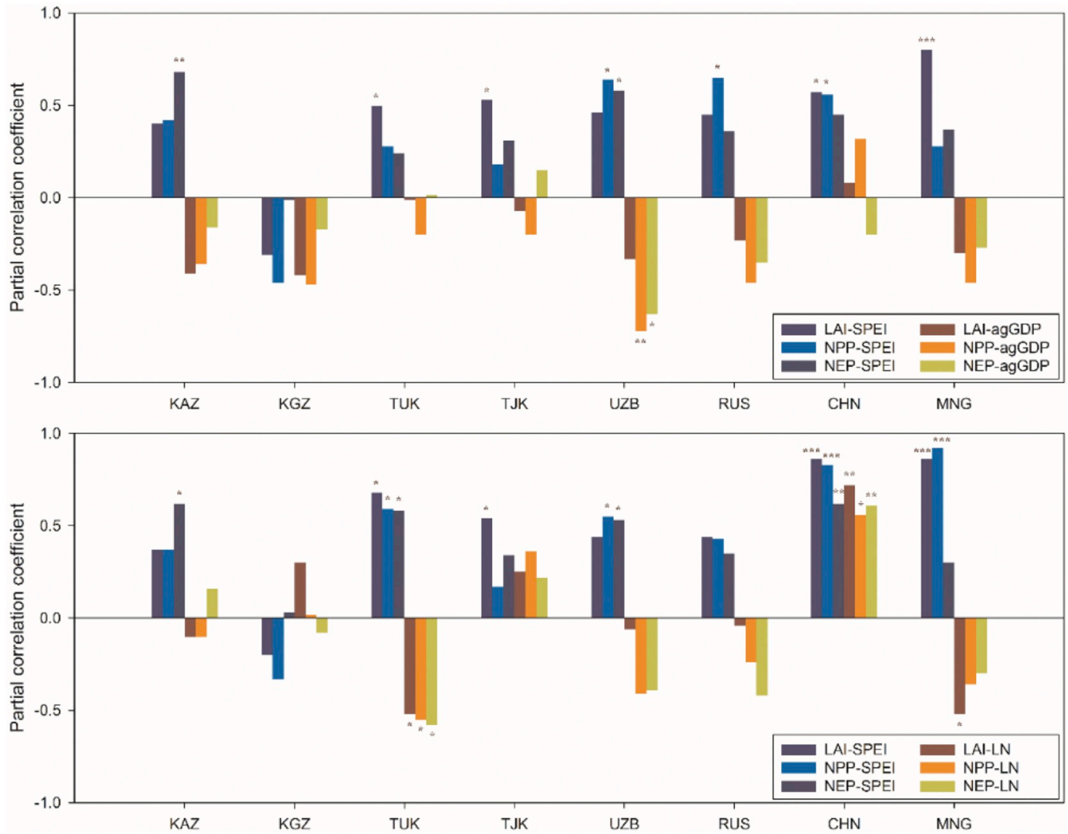

Fig. 8. Partial correlation analysis of ecosystem service indexes to climate and human appropriation indexes at the country level.

HAIs and EIs in the KS, especially from the two Southern countries, Uzbekistan and Turkmenistan. Significant positive correlations were found for the Chinese regions in the past two decades, where large sustainable development has been implemented. The contrasting sub-regional consequences shows that top-down institutional or policy changes modify the relationship between human appropriation and EIs. Therefore, our study emphasizes the importance of sustainable development in managing pasture systems. The spatially-explicit information provided in this study has potential implications for sustainable regional management.

Semi-arid ecosystems play an important role in determining the trend and IAV of global terrestrial C sinks (Poulter et al., 2014; Ahlström et al., 2015). This means that the potential impact from policy or institutional shifts may play a more important role in the global pattern of C sinks as previously expected. Therefore, our results also emphasize the necessity to explicitly consider socio-economic factors in studying the determinants of the IAV of global C sinks in response to global change.

Table 2
Recent model results of grassland in Temperate Eurasian Steppe and comparison with this study.

Study area	Study period	Method	Model type of carbon assimilation[a]	Results ($gC\,m^{-2}\,yr^{-1}$)	Corresponding results in this study ($gC\,m^{-2}\,yr^{-1}$)[b]	Reference
Mongolia	2000–2005	Improved CASA model	LUE	NPP: 125.33	108.3	Xing et al. (2010)
Northern China	2000–2005	Improved CASA model	LUE	NPP:153.26	123.8 (for Inner Mongolia and Xinjiang)	
China	2000	CASA CEVSA GLOPEM GEOLUE GEOPRO	LUE Farquhar **LUE** LUE Farquhar	NPP:245 NPP:208 NPP:145 NPP:178 NPP:168	138.1 (for Inner Mongolia and Xinjiang)	Gao and Liu (2008)
China	2007	BEPS	Farquhar	NPP: 122.6	121.23 (for Inner Mongolia)	Feng et al. (2007)
Eastern Kazakhstan	2004	Modified light use efficiency (LUE) model	LUE	NPP:168	152.1	Propastin et al. (2012)
Xilinhot, Inner Mongolia	2002	GLPM	Farquhar	NEP:1.91	3.1	Zhang et al. (2009)
Inner Mongolia	1951–2007	TEM model	Farquhar	NEP:11.25	13.7 for the period of 1999 to 2007	Sui et al. (2013)
Central Asia	1979–2011	BIOME-BGC	Farquhar	NEP: ~ −13.5	−6.7	Han et al. (2016)

[a] LUE: light use efficiency model; Farquhar: Farquhar biochemical model.
[b] The results are extracted from the simulated map in this study with the same spatiotemporal scale to the corresponding recent studies.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2019.102679.

References

Ahlström, A., Raupach, M.R., Schurgers, G., Smith, B., Arneth, A., Jung, M., Reichstein, M., Canadell, J.G., Friedlingstein, P., Jain, A.K., 2015. The dominant role of semi-arid ecosystems in the trend and variability of the land CO2 sink. Science 348, 895–899.
Arora, V.K., 2003. Simulating energy and carbon fluxes over winter wheat using coupled land surface and terrestrial ecosystem models. Agric. For. Meteorol. 118, 21–47.
ASK, 2003. Republic of Kazakhstan: 50 Years since the Beginning of Virgin Lands Campaign. Statistical digest 1953–2003. Agency of Statistics of the Republic of Kazakhstan, Almaty.
Bai, Y., Wu, J., Xing, Q., Pan, Q., Huang, J., Yang, D., Han, X., 2008. Primary production and rain use efficiency across a precipitation gradient on the Mongolia plateau. Ecology 89, 2140–2153.
Bain, I., 2010. Sustainable development in western China: managing people, livestock and grasslands in pastoral areas[J]. Mountain Research and Development 30 (1), 59–61.
Baydildina, A., Akshinbay, A., Bayetova, M., Mkrytichyan, L., Haliepesova, A., Ataev, D., 2000. Agricultural policy reforms and food security in Kazakhstan and Turkmenistan. Food Policy 25, 733–747.
Bonan, G.B., 1995. Land-atmosphere CO2 exchange simulated by a land surface process model coupled to an atmospheric general circulation model. J. Geophys. Res. 100, 2817–2831.
Bulygina, O., Groisman, P.Y., Razuvaev, V., Korshunova, N., 2011. Changes in snow cover characteristics over Northern Eurasia since 1966. Environ. Res. Lett. 6, 045204.
Chen, J.M., Lui, J., Cihlar, J., Goulden, M., 1999. Daily canopy photosynthesis model through temporal and spatial scaling for remote sensing applications. Ecol. Model. 124, 99–119.
Chen, J.M., Mo, G., Yuen, C.-W., Margolis, H., Higuchi, K., Chan, D., 2007. Modeling and scaling coupled energy, water, and carbon fluxes based on remote sensing: an application to Canada's landmass. J. Hydrometeorol. 8, 123–143.
Chen, X., Bai, J., Li, X., Luo, G., Li, J., Li, B.L., 2013. Changes in land use/land cover and ecosystem services in Central Asia during 1990–2009. Curr. Opin. Environ. Sustain. 5, 116–127.
Chen, B., Zhang, X., Tao, J., Wu, J., Wang, J., Shi, P., Zhang, Y., Yu, C., 2014. The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet plateau. Agric. For. Meteorol. 189, 11–18.
Chen, J., John, R., Shao, C., Fan, Y., Zhang, Y., Amarjargal, A., Brown, D.G., Qi, J., Han, J., Lafortezza, R., 2015a. Policy shifts influence the functional changes of the CNH systems on the Mongolian plateau. Environ. Res. Lett. 10, 085003.
Chen, J., John, R., Zhang, Y., Shao, C., Brown, D.G., Batkhishig, O., Amarjargal, A., Ouyang, Z., Dong, G., Wang, D., Qi, J., 2015b. Divergences of two coupled human and natural systems on the Mongolian plateau. Bioscience 65, 559–570.
Chen, Y., Wang, K., Lin, Y., Shi, W., Song, Y., He, X., 2015c. Balancing green and grain trade. Nat. Geosci. 8, 739.
Chen, Y., Ju, W., Groisman, P., et al., 2017. Quantitative assessment of carbon sequestration reduction induced by disturbances in temperate Eurasian steppe[J]. Environmental Research Letters 12 (11), 115005.
Chuai, X., Huang, X., Wang, W., Bao, G., 2013. NDVI, temperature and precipitation changes and their relationships with different vegetation types during 1998–2007 in Inner Mongolia, China. Int. J. Climatol. 33, 1696–1706.
Chun-Yu, Z., Ying, W., Xiao-Yu, Z., Yan, C., Yu-Lian, L., Da-Ming, S., Hong-Min, Y., Yu-Ying, L., 2013. Changes in climatic factors and extreme climate events in Northeast China during 1961–2010. Adv. Clim. Chang. Res. 4, 92–102.
Conant, R.T., 2010. Challenges and Opportunities for Carbon Sequestration in Grassland Systems. Food and Agriculture Organization of the United Nations.
Dudwick, N., Fock, K., Sedik, D., 2007. Land Reform and Farm Restructuring in Transition Countries: The Experience of Bulgaria, Moldova, Azerbaijan, and Kazakhstan. The World Bank.
Erb, K.-H., Kastner, T., Plutzar, C., Bais, A.L.S., Carvalhais, N., Fetzel, T., Gingrich, S., Haberl, H., Lauk, C., Niedertscheider, M., 2018. Unexpectedly large impact of forest management and grazing on global vegetation biomass. Nature 553, 73.
Farquhar, G., von Caemmerer, S.v., Berry, J., 1980. A biochemical model of photosynthetic CO2 assimilation in leaves of C3 species. Planta 149, 78–90.
Feng, X., Liu, G., Chen, J., Chen, M., Liu, J., Ju, W., Sun, R., Zhou, W., 2007. Net primary productivity of China's terrestrial ecosystems from a process model driven by remote sensing. J. Environ. Manag. 85, 563–573.
Feng, W., Liang, J., Hale, L.E., Jung, C.G., Chen, J., Zhou, J., Xu, M., Yuan, M., Wu, L., Bracho, R., 2017. Enhanced decomposition of stable soil organic carbon and microbial catabolic potentials by long-term field warming. Glob. Chang. Biol. 23, 4765–4776.
Fetzel, T., Havlik, P., Herrero, M., Kaplan, J.O., Kastner, T., Kroisleitner, C., Rolinski, S., Searchinger, T., Van Bodegom, P.M., Wirsenius, S., Erb, K.H., 2017. Quantification of uncertainties in global grazing systems assessment. Glob. Biogeochem. Cycles 31, 1089–1102.
Fujimori, S., Hasegawa, T., Masui, T., Takahashi, K., Herran, D.S., Dai, H., Hijioka, Y., Kainuma, M., 2017. SSP3: AIM implementation of shared socioeconomic pathways. Glob. Environ. Chang. 42, 268–283.
Gang, C., Zhou, W., Chen, Y., Wang, Z., Sun, Z., Li, J., Qi, J., Odeh, I., 2014. Quantitative assessment of the contributions of climate change and human activities on global grassland degradation. Environ. Earth Sci. 72, 4273–4282.
Gao, Z., Liu, J., 2008. Simulation study of China's net primary production. Chin. Sci. Bull. 53, 434–443.
Groisman, P., Bulygina, O., Henebry, G., et al., 2018. Dryland belt of Northern Eurasia: contemporary environmental changes and their consequences[J]. Environmental Research Letters 13 (11), 115008.
Groisman, P., Shugart, H., Kicklighter, D., Henebry, G., Tchebakova, N., Maksyutov, S., Monier, E., Gutman, G., Gulev, S., Qi, J., 2017. Northern Eurasia Future Initiative (NEFI): facing the challenges and pathways of global change in the twenty-first century. Prog. Earth Planet. Sci. 4, 41.
Han, Q., Luo, G., Li, C., Shakir, A., Wu, M., Saidov, A., 2016. Simulated grazing effects on carbon emission in Central Asia. Agric. For. Meteorol. 216, 203–214.
Huang, L., Xiao, T., Zhao, Z., Sun, C., Liu, J., Shao, Q., Fan, J., Wang, J., 2013. Effects of grassland restoration programs on ecosystems in arid and semiarid China. J. Environ. Manag. 117, 268–275.
Jangid, K., Williams, M.A., Franzluebbers, A.J., Sanderlin, J.S., Reeves, J.H., Jenkins, M.B., Endale, D.M., Coleman, D.C., Whitman, W.B., 2008. Relative impacts of land-use, management intensity and fertilization upon soil microbial community structure in agricultural systems. Soil Biol. Biochem. 40, 2843–2853.
Ju, W., Chen, J.M., Black, T.A., Barr, A.G., Liu, J., Chen, B., 2006. Modelling multi-year coupled carbon and water fluxes in a boreal aspen forest. Agric. For. Meteorol. 140, 136–151.
Ju, W.M., Chen, J.M., Harvey, D., Wang, S., 2007. Future carbon balance of China's forests under climate change and increasing CO2. J. Environ. Manag. 85, 538–562.
Ju, W., Chen, J.M., Black, T.A., Barr, A.G., McCaughey, H., 2010. Spatially simulating changes of soil water content and their effects on carbon sequestration in Canada's forests and wetlands. Tellus B 62, 140–159.
Knapp, A., Hoover, D., Blair, J., Buis, G., Burkepile, D., Chamberlain, A., Collins, S., Fynn, R., Kirkman, K., Smith, M., 2012. A test of two mechanisms proposed to optimize grassland aboveground primary productivity in response to grazing. J. Plant Ecol. 5, 357–365.
Kraemer, R., Prishchepov, A.V., Müller, D., Kuemmerle, T., Radeloff, V.C., Dara, A., Terekhov, A., Frühauf, M., 2015. Long-term agricultural land-cover change and potential for cropland expansion in the former virgin lands area of Kazakhstan. Environ. Res. Lett. 10, 054012.
Kuzyakov, Y., 2010. Priming effects: interactions between living and dead organic matter. Soil Biol. Biochem. 42, 1363–1371.
Leriche, H., LeRoux, X., Gignoux, J., Tuzet, A., Fritz, H., Abbadie, L., Loreau, M., 2001. Which functional processes control the short-term effect of grazing on net primary production in grasslands? Oecologia 129, 114–124.
Lerman, Z., Roth, Z., 2007. Uzbekistan: Sustainable Livestock Sector Development/Technical Report/The Hebrew University of Jerusalem. pp. 18.
Lerman, Z., Prikhodko, D., Punda, I., Sedi, D., Serova, E., Swinnen, J., Sedik, D., Serova, E., Swinnen, J., 2012. Turkmenistan Agricultural Sector Review. Rome, Italy, FAO.
Li, A., Wu, J., Huang, J., 2012. Distinguishing between human-induced and climate-driven vegetation changes: a critical application of RESTREND in inner Mongolia. Landsc. Ecol. 27, 969–982.
Li, Z., Chen, Y., Fang, G., Li, Y., 2017. Multivariate assessment and attribution of droughts in Central Asia. Sci. Rep. 7, 1316.
Liang, S., Yi, Q., Liu, J., 2015a. Vegetation dynamics and responses to recent climate change in Xinjiang using leaf area index as an indicator. Ecol. Indic. 58, 64–76.
Liang, W., Bai, D., Wang, F., Fu, B., Yan, J., Wang, S., Yang, Y., Long, D., Feng, M., 2015b. Quantifying the impacts of climate change and ecological restoration on streamflow changes based on a Budyko hydrological model in China's loess plateau. Water Resour. Res. 51, 6500–6519.
Liu, J., Chen, J.M., Cihlar, J., Park, W., 1997. A process-based boreal ecosystem productivity simulator using remote sensing inputs. Remote Sens. Environ. 62, 158–175.
Liu, J., Chen, J.M., Cihlar, J., 2003. Mapping evapotranspiration based on remote sensing: an application to Canada's landmass. Water Resour. Res. 39.
Liu, Y., Liu, R., Chen, J.M., 2012. Retrospective retrieval of long-term consistent global leaf area index (1981–2011) from combined AVHRR and MODIS data. J. Geophys. Res. Biogeosci. 117 (2005–2012).
Liu, Y., Ju, W., He, H., Wang, S., Sun, R., Zhang, Y., 2013. Changes of net primary

productivity in China during recent 11 years detected using an ecological model driven by MODIS data. Front. Earth Sci. 7, 112–127.
Liu, Z., Wu, C., Peng, D., Wang, S., Gonsamo, A., Fang, B., Yuan, W., 2017. Improved modeling of gross primary production from a better representation of photosynthetic components in vegetation canopy. Agric. For. Meteorol. 233, 222–234.
Liu, M., Dries, L., Heijman, W., Huang, J., Zhu, X., Hu, Y., Chen, H., 2018. The impact of ecological construction programs on grassland conservation in Inner Mongolia. China. Land Degrad. Dev. 29, 326–336.
Luo, Y., Wan, S., Hui, D., Wallace, L.L., 2001. Acclimatization of soil respiration to warming in a tall grass prairie. Nature 413, 622–625.
Luo, G., Han, Q., Zhou, D., Li, L., Chen, X., Li, Y., Hu, Y., Li, B.L., 2012. Moderate grazing can promote aboveground primary production of grassland under water stress. Ecol. Complex. 11, 126–136.
Matches, A.G., 1992. Plant response to grazing: a review. J. Prod. Agric. 5, 1–7.
Mátyás, C., Berki, I., Bidló, A., Csóka, G., Czimber, K., Führer, E., Gálos, B., Gribovszki, Z., Illés, G., Hirka, A., 2018. Sustainability of forest cover under climate change on the temperate-continental xeric limits. Forests 9, 489.
Meyfroidt, P., Schierhorn, F., Prishchepov, A.V., Müller, D., Kuemmerle, T., 2016. Drivers, constraints and trade-offs associated with recultivating abandoned cropland in Russia, Ukraine and Kazakhstan. Glob. Environ. Chang. 37, 1–15.
Milchunas, D.G., Lauenroth, W.K., 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments: ecological archives M063-001. Ecol. Monogr. 63, 327–366.
Monier, E., Kicklighter, D.W., Sokolov, A.P., Zhuang, Q., Sokolik, I.N., Lawford, R., Kappas, M., Paltsev, S.V., Groisman, P.Y., 2017. A review of and perspectives on global change modeling for northern Eurasia. Environ. Res. Lett. 12, 083001.
Mu, S.J., Zhou, S.X., Chen, Y.Z., Li, J.L., Ju, W.M., Odeh, I.O.A., 2013. Assessing the impact of restoration-induced land conversion and management alternatives on net primary productivity in Inner Mongolian grassland, China. Glob. Planet. Chang. 108, 29–41.
Norman, J.M., 1982. Simulation of microclimates. Biometeorol. Integr. Pest Manag. 65–99.
O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Chang. 122, 387–400.
Peng, S., Piao, S., Wang, T., Sun, J., Shen, Z., 2009. Temperature sensitivity of soil respiration in different ecosystems in China. Soil Biol. Biochem. 41, 1008–1014.
Piao, S., Yin, G., Tan, J., Cheng, L., Huang, M., Li, Y., Liu, R., Mao, J., Myneni, R.B., Peng, S., 2015. Detection and attribution of vegetation greening trend in China over the last 30 years. Glob. Chang. Biol. 21, 1601–1609.
Pomfret, R., 2008. Tajikistan, Turkmenistan, and Uzbekistan. Distortions to agricultural incentives in Europe's transition economies. pp. 297–338.
Pongratz, J., Reick, C.H., Houghton, R., House, J., 2014. Terminology as a key uncertainty in net land use and land cover change carbon flux estimates. Earth Syst. Dyn. 5, 177–195.
Post, W.M., Kwon, K.C., 2000. Soil carbon sequestration and land-use change: processes and potential. Glob. Chang. Biol. 6, 317–327.
Poulter, B., Frank, D., Ciais, P., Myneni, R.B., Andela, N., Bi, J., Broquet, G., Canadell, J.G., Chevallier, F., Liu, Y.Y., 2014. Contribution of semi-arid ecosystems to interannual variability of the global carbon cycle. Nature 509, 600.
Prishchepov, A.V., Müller, D., Dubinin, M., Baumann, M., Radeloff, V.C., 2013. Determinants of agricultural land abandonment in post-soviet European Russia. Land Use Policy 30, 873–884.
Prishchepov, A.V., Müller, D., Baumann, M., Kuemmerle, T., Alcantara, C., Radeloff, V.C., 2017. Underlying drivers and spatial determinants of post-soviet agricultural land abandonment in temperate Eastern Europe. In: Land-Cover and Land-Use Changes in Eastern Europe after the Collapse of the Soviet Union in 1991. Springer, pp. 91–117.
Propastin, P., Kappas, M.W., Herrmann, S.M., Tucker, C.J., 2012. Modified light use efficiency model for assessment of carbon sequestration in grasslands of Kazakhstan: combining ground biomass data and remote-sensing. Int. J. Remote Sens. 33, 1465–1487.
Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Chang. 42, 153–168.
Schwalm, C.R., Williams, C.A., Schaefer, K., Anderson, R., Arain, M.A., Baker, I., Barr, A., Black, T.A., Chen, G., Chen, J.M., 2010. A model-data intercomparison of CO2 exchange across North America: results from the North American Carbon Program site synthesis. J. Geophys. Res. Biogeosci. 115 (2005–2012).
Schwartz, M.D., Ahas, R., Aasa, A., 2006. Onset of spring starting earlier across the northern hemisphere. Glob. Chang. Biol. 12, 343–351.
Sui, X., Zhou, G., Zhuang, Q., 2013. Sensitivity of carbon budget to historical climate variability and atmospheric CO_2 concentration in temperate grassland ecosystems in China. Clim. Chang. 117, 259–272.
van der Werf, G.R., Randerson, J.T., Giglio, L., Collatz, G.J., Kasibhatla, P.S., Arellano Jr., A.F., 2006. Interannual variability in global biomass burning emissions from 1997 to 2004. Atmos. Chem. Phys. 6, 3423–3441.
Wang, G., You, L., 2004. Delayed impact of the North Atlantic oscillation on biosphere productivity in Asia. Geophys. Res. Lett. 31.
Wang, X., Lu, C., Fang, J., Shen, Y., 2007. Implications for development of grain-for-green policy based on cropland suitability evaluation in desertification-affected North China. Land Use Policy 24, 417–424.
Wang, Y., Zhou, G., Jia, B., 2008. Modeling SOC and NPP responses of meadow steppe to different grazing intensities in Northeast China. Ecol. Model. 217, 72–78.
Wang, J., Brown, D.G., Agrawal, A., 2013. Climate adaptation, local institutions, and rural livelihoods: a comparative study of herder communities in Mongolia and Inner Mongolia, China. Glob. Environ. Chang. 23, 1673–1683.
White, R.P., Murray, S., Rohweder, M., Prince, S., Thompson, K., 2000. Grassland Ecosystems. World Resources Institute, Washington, DC, USA.
Wu, C., Chen, J.M., Gonsamo, A., Price, D.T., Black, T.A., Kurz, W.A., 2012. Interannual variability of net carbon exchange is related to the lag between the end-dates of net carbon uptake and photosynthesis: evidence from long records at two contrasting forest stands. Agric. For. Meteorol. 164, 29–38.
Xiao, J., 2014. Satellite evidence for significant biophysical consequences of the “Grain for Green” program on the loess plateau in China. J. Geophys. Res. Biogeosci. 119, 2261–2275.
Xiao, J., Zhou, Y., Zhang, L., 2015. Contributions of natural and human factors to increases in vegetation productivity in China. Ecosphere 6, 1–20.
Xing, X., Xu, X., Zhang, X., Zhou, C., Song, M., Shao, B., Ouyang, H., 2010. Simulating net primary production of grasslands in northeastern Asia using MODIS data from 2000 to 2005. J. Geogr. Sci. 20, 193–204.
Xu, D., Li, C., Zhuang, D., Pan, J., 2011. Assessment of the relative role of climate change and human activities in desertification: a review. J. Geogr. Sci. 21, 926.
Yao, Y., Wang, X., Li, Y., Wang, T., Shen, M., Du, M., He, H., Li, Y., Luo, W., Ma, M., 2018. Spatiotemporal pattern of gross primary productivity and its covariation with climate in China over the last thirty years. Glob. Chang. Biol. 24, 184–196.
Zhang, C., Ren, W., 2017. Complex climatic and CO2 controls on net primary productivity of temperate dryland ecosystems over Central Asia during 1980–2014. J. Geophys. Res. Biogeosci. 122, 2356–2374.
Zhang, N., Zhao, Y.-S., Yu, G.-R., 2009. Simulated annual carbon fluxes of grassland ecosystems in extremely arid conditions. Ecol. Res. 24, 185–206.
Zhang, G., Kang, Y., Han, G., Sakurai, K., 2011. Effect of climate change over the past half century on the distribution, extent and NPP of ecosystems of Inner Mongolia. Glob. Chang. Biol. 17, 377–389.
Zhang, S.W., Zhao, D., Dai, E., 2013. Temporal-spatial changes in inner Mongolian grassland degradation during past three decades. Agric. Sci. Technol. 14, 7.
Zhang, X., Luo, H., Hou, X., Badgery, W., Zhang, Y., Jiang, C., 2014. Effect of restricted time at pasture and indoor supplementation on ingestive behaviour, dry matter intake and weight gain of growing lambs. Livest. Sci. 167, 137–143.
Zhou, Y., Zhu, Q., Chen, J.M., Wang, Y.Q., Liu, J., Sun, R., Tang, S., 2007. Observation and simulation of net primary productivity in Qilian Mountain, western China. J. Environ. Manag. 85, 574–584.
Zhou, W., Yang, H., Huang, L., Chen, C., Lin, X., Hu, Z., Li, J., 2017. Grassland degradation remote sensing monitoring and driving factors quantitative assessment in China from 1982 to 2010. Ecol. Indic. 83, 303–313.