Recent responses of grassland net primary productivity to climatic and anthropogenic factors in Kyrgyzstan

Abstract:

Net primary productivity (NPP) is an essential indicator of ecosystem function and sustainability and plays a vital role in the carbon cycle, especially in arid and semi-arid grassland ecosystems. Quantifying trends in NPP and identifying the contributing factors are important for understanding the relative impacts of climate change and human activities on grassland degradation. We quantified spatial and temporal patterns in potential NPP (NPP_P) and actual NPP (NPP_A) in Kyrgyzstan from 2000 to 2014 based on the Zhou Guangsheng model and MOD17A3 NPP data, respectively. By calculating the difference between NPP_P and NPP_A , we inferred human-induced NPP (NPP_H) and thereby characterised changes in grassland NPP attributable to anthropogenic activities. We found that over the past two decades, both climatic variation and anthropogenic activities have significantly affected Kyrgyzstan's grasslands. Grassland NPP decreased overall but patterns varied between provinces. Climate change, in particular changes in precipitation was the dominant factor driving grassland degradation in the north but human pressures also contributed. In the south however, human activities were associated with extensive areas of grassland recovery. The results provide important contextual understanding for supporting policy for grassland maintenance and restoration under climate change and intensifying human pressures.

Keywords: climate change, grassland, human activities, Kyrgyzstan, livestock, net primary productivity (NPP)

1. Introduction

Grasslands not only play a significant role in global biogeochemical cycles, but also contribute to carbon sequestration and maintaining climate stability (Zhang et al., 2013; Zhao & Running, 2010). Vegetation net primary productivity (NPP) quantifies the net accumulation of carbon in plant biomass through photosynthesis and underpins many biotic processes (Li & Pan, 2018). As a pivotal

indicator that encapsulates the effects on terrestrial vegetation of climate change and human activity, NPP can be used to reflect the productive capacity and sustainability of ecosystems and has become a focal point of global change research (Erb et al., 2009; Gang et al., 2018; Yang et al., 2017; Liu, Wang et al., 2019). Grassland degradation is largely attributable to increasing climatic and human pressures, with grazing and land cover change being dominant drivers in Kyrgyzstan, Central Asia—the focus of this study (Kraemer et al., 2015; Xu et al., 2016). Measuring the impact of climate change and anthropogenic activities in terrestrial ecosystems is essential to developing policies to improve ecosystem sustainability that account for increasing climatic and human pressures (Luo et al., 2018; Huang et al., 2016).

Kyrgyzstan is a landlocked country located in the arid region of central Asia well-known for its abundant grasslands. Complex mountain topography results in a highly heterogeneous composition of vegetation communities (Mamytov, 1982; Zhumanova et al., 2018), and grazing is a major human activity. Before the 1930s, semi-nomadic pastoralists were the dominant users of pasture areas. Under the Soviet government, large amounts of chemical fertilizer, artificial fodder and grazing subsidies severely impacted the sustainability of ecological and economic systems (Ludi, 2003). Vegetation degradation was a serious concern in the 1970s when more than one third of pastures were invaded by shrubs and unpalatable species (Borchardt et al., 2011). After the dissolution of the Soviet Union in 1991, Kyrgyzstan became an independent country and its economic system changed substantially. Land and livestock were privatized and a large number of small household enterprises appeared (Lerman & Zedik, 2009). The burgeoning human population and intensifying livestock grazing activities caused severe grassland degradation and by 2012, the area of degraded vegetation reached 49% (Pasture Department, 2014; Zhumanova et al., 2018). With its sensitive and fragile environment, effective management of Kyrgyzstan's grasslands is essential to prevent further degradation and promote ecological regeneration.

Quantifying the spatio-temporal variation in NPP is extremely important for ecosystem maintenance and related policy-making in Kyrgyzstan (Huang et al., 2017; Sagynbekova, 2017). NPP in terrestrial ecosystems has been widely investigated at both global and regional scales using integrated and advanced techniques (Awaya et al., 2004; Luo et al., 2018; Running et al., 2004). As field measurement of the terrestrial carbon cycle remains challenging over large scales (Han et al., 2018), different types of terrestrial ecosystem models have been developed to understand spatio-

temporal variations in NPP. A range of *climate-oriented* models have been developed to quantify NPP based on climatic data including the Miami model (Lieth, 1975), the Thornthwaite Memorial model (Lieth, 1972), the Zhou Guangsheng model (Zhou & Zhang, 1995; Zhou & Zhang, 1996). Several *process-oriented* models have been developed such as the Biome-Biogeochemical (BIOME-BGC) model (Running & Hunt Jr, 1993) and the CENTURY model (Parton et al., 1993) to evaluate regional-scale NPP from a complex combination of parameterizations and processes. In addition, *light-use efficiency* models such as the Carnegie-Ames-Stanford Approach (CASA) model (Potter et al., 1993) and the global production efficiency model (GLOPEM; Prince, 1991) have also be applied over large spatial extents due to easily obtainable model inputs (Gang et al., 2018).

To investigate the relative impact of anthropogenic pressures on terrestrial ecosystems, the most frequently used methods include the residual trend (RESTREND) method, the rain-use efficiency (RUE) method, and human appropriation of NPP (HANPP). The RESTREND algorithm is a difference comparison method first proposed by Evans and Geerken (2004). It has been used to detect human-induced land degradation from the effects of climate variability in South Africa (Wessels et al., 2007), and to accurately identify degradation and ecosystem change in drylands (Ma et al., 2017; Xu et al., 2018; Burrell et al., 2017). RUE is defined as the amount of biomass produced per unit of precipitation and is an important indicator for detecting the response of vegetation to rainfall (LeHouerou, 1984). Huang et al. (2013) used RUE measurements to evaluate the effects of grassland restoration programs on arid and semi-arid ecosystems, and illustrated the positive effect of restoration programs on grassland cover. However, due to the many uncertainties in RUE, its effectiveness as an indicator of vegetation degradation has been disputed (Chen et al., 2018). HANPP can be used to analyse the effects of land-use change and assess the impact of human activities on energy flows in terrestrial ecosystems (Gingrich et al., 2015; Baeza & Paruelo, 2018). Zhang et al. (2018) explored village-level patterns and dynamics of HANPP and its components in Tibet for the period 1989-2015, and the results reflected the complex impacts of anthropogenic activities on alpine ecosystems. Since the model requires data on human activity in a social environment, there are large uncertainties, and the influence of climatic factors is often neglected (Ren & Zhou, 2018; Vitousek et al., 1986).

In recent decades, studies have increasingly focussed on quantifying the relative impact of climatic factors and human activities on grassland ecosystems at multiple scales. Zhao and Running

(2010) concluded that large-scale droughts caused reductions in regional grassland NPP from 2000–2009, especially in the southern hemisphere. Gang et al. (2014) revealed the different roles of climate change and anthropogenic activities on grassland degradation at the continental level. Wang and et al. (2018) assessed the driving forces in vegetation dynamics in the semi-arid areas of the Loess Plateau in China, and quantified the contribution of human activities. In Central Asia, several elements influence vegetation productivity including rainfall, temperature, institutional transformation, and socioeconomic change (Zhou et al., 2019). Most studies on the drivers of vegetation dynamics in Central Asia have focused on the spatial and temporal variation in terrestrial ecosystems, the relationship between vegetation NPP and climatic factors, and vegetation responses under climate change (Xu et al., 2017; Propastin et al., 2008; Zhang et al., 2016). Dubovyk et al. (2016) quantified the broader influence of environmental drivers on vegetation dynamics over climatic and management gradients in Central Asia based on remote sensing data, and Chen et al. (2019) quantified the recent spatiotemporal patterns of grassland ecosystems and investigated the driving forces of grassland NPP variation. However, few studies have been made to quantify the relative contributions of climatic factors and anthropogenic activities on grassland productivity and land degradation.

In this study, we quantified and compared the spatial and temporal variation in potential NPP and actual NPP of grasslands in Kyrgyzstan from 2000 to 2014. We used a climate-driven model to calculate potential NPP representing maximum vegetation productivity. We used remote sensing to determine the actual NPP, which was influenced by both climatic factors and human activities. To assess the impact of anthropogenic activities on Kyrgyzstan's grasslands, human-induced NPP change was modelled as the difference between potential and actual NPP. In comparing the trends in actual NPP, climate-induced NPP, and human-induced NPP during the study period, six scenarios were established to illustrate the relative contributions of climatic and anthropogenic factors to trends in grassland NPP. Additionally, the correlation between grassland NPP and climatic and anthropogenic factors were explored to detect the major drivers of ecosystem variation. We discuss the implications of the results for the management of grasslands in Kyrgyzstan and Central Asia more broadly under the dual challenges of climate change and increased human pressures.

2. Materials and Methods

2.1 Study area

Covering an area of ~199,951 km², the Kyrgyz Republic (Fig. 1) in central Asia is a landlocked mountainous country, with 94% of its territory lying at more than 1,000 m above sea level (ASL) and peaks rising to ~7,500 m ASL (Kronenberg, 2014). Ice and snow cover is permanent in high-elevation areas. The population of Kyrgyzstan, as of 2017, was ~6.2 million people (World Bank, 2017a), of which more than 60% live in rural regions (Sagynbekova, 2017). While Kyrgyzstan experienced an economic upturn after 1996, political turmoil and large-scale ethnic violence have hindered development (Agadjanian & Gorina, 2019). Grasslands are one of the most significant natural resources in Kyrgyzstan, occupying 85% of the nation's agricultural land (Liechti, 2012; Wilson, 1997). As a traditional nomadic country, livestock husbandry dominates economic activities in Kyrgyzstan and animal products are a major commodity.

Fig. 1. Location of the study region (a) and the spatial distribution of different land cover types in Kyrgyzstan (b) The terrain map of the study region was from Esri, USGS and NOAA. Land cover data were obtained from the MODIS Terra Aqua Combined Land Cover product MCD12Q1 (<https://modis-land.gsfc.nasa.gov/landcover.html>).

2.2 Actual NPP

Actual NPP (NPP_A) reflects real grassland NPP and is influenced by both climatic factors and anthropogenic activities. The 1-km spatial resolution global Moderate Resolution Imaging Spectroradiometer (MODIS) NPP product MOD17A3 acquired from the National Aeronautics and Space Administration (NASA) MODIS Land Science team website (<https://modis.gsfc.nasa.gov/>) was used to calculate the NPP_A of grasslands in Kyrgyzstan from 2000 to 2014. MODIS NPP is a global dataset of terrestrial gross and net primary productivity based on the BIOME-BGC model, which is presented as follows:

$$NPP = \sum_t^{365} PSNet - (R_m + R_g) \quad (1)$$

$$PSNet = GPP - R_{lr} \quad (2)$$

where PSNet is net photosynthesis, R_m is annual maintenance respiration by all other living cells except leaves and roots, and R_g is growth respiration fixed by photosynthesis. R_{lr} represents daily leaves and roots maintenance respiration.

Compared with traditional regression models, MODIS NPP uses a more advanced method and additional parameters to estimate vegetation NPP. Data have been improved through temporally filling unreliable MOD15A2 data based on the maximum value of the fraction of absorbed photosynthetically active radiation (FPAR) and corresponding leaf area index (LAI). Spatial nonlinear interpolation was also conducted as well as using the biome parameter look-up table (BPLUT) recalibrated with more accurate parameters. MODIS NPP is inversely proportional to observed atmospheric CO_2 growth rates and the El Niño-Southern Oscillation index, indicating that the dataset is reliable (Bai & Dent, 2006; Zhao et al., 2005; Zhao et al., 2006). The dataset has been used widely in research on vegetation growth, biomass estimation, environmental monitoring, and global change at regional and global scales (Turner et al., 2006; Liu, Zhang et al., 2019; Zhang et al., 2009).

2.3 Potential NPP

We used the Zhou Guangsheng model (Zhou & Zhang, 1995; Zhou & Zhang, 1996) to calculate

potential NPP (NPP_P) from 2000 to 2014 based on climatic drivers. NPP_P , representing the maximum NPP of grasslands, was calculated using monthly precipitation and temperature data at 0.1 degree resolution obtained from NASA's Goddard Earth Sciences Data and Information Service Center (GES DISC) (McNally et al., 2017). The Zhou Guangsheng model is based on evapotranspiration, which is closely related to photosynthesis, and integrates interactions between empirical and modelled variables. The model equation is as follows:

$$NPP_P = RDI^2 * \frac{r * (1 + RDI + RDI^2)}{(1 + RDI)(1 + RDI^2)} * \exp(-\sqrt{9.87 + 6.25RDI}) \quad (3)$$

where RDI denotes the annual radiative dryness index and r is annual precipitation.

To understand the relationship between RDI and potential evapotranspiration rate, Zhou and Zhang (1996) used observed data from 671 meteorological stations in China and established the formula:

$$RDI = 0.629 + 0.23PER - 0.00313PER^2 (R^2 = 0.9) \quad (4)$$

$$PER = PET/r \quad (5)$$

where PER is potential evapotranspiration rate and PET is annual potential evapotranspiration.

We used annual biotemperature (BT) to calculate PET (Ren & Zhou, 2018), as proposed by Holdridge (1947). BT can be calculated from monthly mean temperature as follows:

$$PET = BT \times 58.93 \quad (6)$$

$$BT = \frac{\sum_{i=1}^{12} (T[i] \text{ if } 0 < T[i] < 30; \text{ else } 0)}{12} \quad (7)$$

where i is the months (from January to December) and $T[i]$ is the monthly mean temperature of a given month.

The Zhou Guangsheng model has been widely used to assess potential productivity of landscape systems (Song et al., 2009), the regional and global distribution of NPP (Chen et al., 2015), and the impacts of global change (Zhou & Zhang, 1996). The model has been shown to be more accurate than other empirical models in arid and semi-arid Asian grasslands (Pu et al., 2009; Ren & Zhou, 2018; Sun et al., 2012).

2.4 Human-induced change in NPP

Human-induced change in NPP (NPP_H) refers to the change in NPP resulting from human activities and is defined as the difference between potential and actual NPP (Haberl et al., 2007; Erb

et al., 2009; Chen et al., 2014; Tong et al., 2019). The formula for calculating NPP_H is as follows:

$$NPP_H = NPP_P - NPP_A \quad (8)$$

We computed human-induced NPP in Kyrgyzstan from 2000 to 2014. A positive value for NPP_H (i.e. where $NPP_A < NPP_P$) indicates a loss of NPP due to human activities (e.g. via harvesting, livestock grazing). A negative value of NPP_H (i.e. where $NPP_A > NPP_P$) indicates that NPP has been increased by human activities (e.g. via fertilisation, irrigation, livestock removal).

2.5 Trends in NPP

To detect trends in NPP_A , NPP_P and NPP_H from 2000 to 2014, we used linear regression analysis for each pixel based on least squares:

$$\text{Slope} = \frac{n \times \sum_{i=1}^n (i \times NPP_i) - \sum_{i=1}^n i \times \sum_{i=1}^n NPP_i}{n \times \sum_{i=1}^n i^2 - (\sum_{i=1}^n i)^2} \quad (9)$$

Where n is the number of years and NPP_i is annual NPP in the i^{th} year. A positive slope of NPP_A represents an increasing linear trend in the time series and vice versa. The slopes for NPP_P and NPP_H indicate the relative impact of climatic factors and human activities on grassland NPP.

2.6 Grassland NPP trend scenarios

To detect the effects of climate change and human activities on grasslands, six scenarios were established based on the results of linear trends in NPP_A , NPP_P and NPP_H (Fig. 2). The condition of grasslands (i.e. recovery or degradation trend) can be shown by the slope of actual NPP ($SNPP_A$). A positive value of $SNPP_A$ suggests that grassland NPP increased and grasslands are recovering. By contrast, a negative value of $SNPP_A$ indicates that grassland NPP decreased over the study period (i.e. degradation). The effects of climate factors and anthropogenic activities on grassland NPP were represented by the slope of potential NPP ($SNPP_P$) and human-induced NPP ($SNPP_H$), respectively. A positive value of $SNPP_P$ suggests that climate change promoted an increase in grassland NPP, while a negative value of $SNPP_P$ suggests climate change caused a decline in grassland NPP. A positive value of $SNPP_H$ suggests that human activities caused a reduction in grassland NPP and conversely, a negative value of $SNPP_H$ suggests human activities promoted an increase in grassland NPP.

We specified six scenarios (Fig. 2) to reflect the trend in NPP over the study period and capture the relative roles of climate change and anthropogenic activities on grassland NPP based on trends in $SNPP_P$ and $SNPP_H$. In areas of grassland recovery (i.e. where $SNPP_A > 0$), three scenarios were specified. Scenario 1 represents a net increase in NPP_A predominantly caused by human activities (IH). Here, climate change decreased grassland NPP (i.e. $SNPP_P < 0$) but human activities caused a stronger increase in grassland NPP (i.e. $SNPP_H < 0$ and $|SNPP_P| < |SNPP_H|$, remembering that positive values of NPP_H indicate a loss of grassland NPP). Scenario 2 represents a net increase in NPP_A predominantly caused by climate change (IC). Here, climate change promoted a strong increase in grassland NPP (i.e. $SNPP_P > 0$) while human activities caused a decrease (i.e. $SNPP_H > 0$ and $|SNPP_P| > |SNPP_H|$). Scenario 3 (IHC) represents a net increase in NPP_A caused both by human activities (i.e. $SNPP_H < 0$) and climate change (i.e. $SNPP_P > 0$).

Similarly, in areas of grassland degradation (i.e. where $SNPP_A < 0$), three scenarios were specified. Scenario 4 represents a decrease in NPP_A predominantly caused by human activities (DH). Here, climate change increased grassland NPP (i.e. $SNPP_P > 0$) but human activities caused a stronger reduction (i.e. $SNPP_H > 0$ and $|SNPP_P| < |SNPP_H|$). Scenario 5 represents a decrease in NPP_A predominantly caused by climate change (DC). Here, climate change strongly decreased grassland NPP (i.e. $SNPP_P < 0$) while human activities promoted an increase (i.e. $SNPP_H < 0$ and $|SNPP_P| > |SNPP_H|$). Scenario 6 (DHC) represents a net increase in NPP_A caused both by human activities (i.e. $SNPP_H > 0$) and climate change (i.e. $SNPP_P < 0$). The spatial distribution of the six trend scenarios was mapped over the study area.

Fig. 2. Six possible scenarios of NPP trend and dominant drivers over the study period. NPP_A : actual NPP, NPP_P : potential NPP, NPP_H : human-induced change in NPP. IH: NPP_A increase predominantly caused by human activities, IC: NPP_A increase predominantly caused by climate change, IHC: NPP_A increase caused by both human activities and climate change, DH: NPP_A decrease predominantly caused by human activities, DC: NPP_A decrease predominantly caused by climate change, DHC: NPP_A decrease caused by both human activities and climate change.

2.7 Correlation analysis

To provide some indication of the specific aspects of climate and human activities associated with changes in NPP in the study area we used correlation analysis. Although arid and semi-arid ecosystems are able to cope with restricted moisture availability and extreme temperatures (Johnson et al., 2012), vegetation growth in the study area is greatly influenced by changes of precipitation and temperature. From 2000 to 2014, mean precipitation showed a significant decreasing trend with a value of 4.94 mm yr^{-1} (Fig 3a). With the increase of greenhouse gases, the climate around the

world is getting warmer, while mean temperature in Kyrgyzstan showed a slight decreasing trend with an annual mean decrease of 0.01 °C (Fig 3b) during the research period. To identify the role of specific climatic factors in grassland NPP dynamics, we calculated the degree of correlation between actual NPP and precipitation and temperature in Kyrgyzstan from 2000 to 2014. We also analyzed the correlation between grassland NPP and human activities. Livestock grazing and human-induced land-cover change are the major anthropogenic activities leading to grassland variation in Central Asia (Kraemer et al., 2015; Xu et al., 2016). Previous research has indicated that livestock number can be used as an indicator to estimate the intensity of grazing on grasslands (Xu et al., 2011). We determined the number of livestock (cattle, cows, horses, sheep and goats) in each oblast from the National Statistical Committee of the Kyrgyz Republic (<http://www.stat.kg/en/>). Large animals (i.e. cattle, cows and horses) were standardized to sheep units with one large animal equating to four sheep.

Fig. 3. Spatial distribution of trends in climatic factors in Kyrgyzstan from 2000 to 2014. (a) Change in annual total precipitation (mm yr⁻¹) and (b) change in mean annual temperature (°C yr⁻¹). Meteorological data were obtained from NASA's GES DISC (<https://disc.gsfc.nasa.gov/>).

3. Results

3.1 Spatio-temporal patterns of net primary productivity

From 2000 to 2014, the mean annual actual NPP of grasslands in Kyrgyzstan was 235.7 g C m⁻² yr⁻¹, with the maximum value of 255.2 g C m⁻² yr⁻¹ occurring in 2011 and the minimum value of 192.3 g C m⁻² yr⁻¹ in 2014 (Fig. 4 and 5). Actual NPP showed a slight decrease over time at an

average rate of $-0.87 \text{ g C m}^{-2} \text{ yr}^{-1}$. The southern area in Kyrgyzstan, especially the Osh and Naryn Oblasts, showed upward trends with rates of $0.58 \text{ g C m}^{-2} \text{ yr}^{-1}$ and $0.24 \text{ g C m}^{-2} \text{ yr}^{-1}$, respectively (Fig. 8a). In the northern regions of Talas, Jalal-Abad and Chuy Oblasts, a significant decline in actual NPP was observed. The fastest decline occurred in Chuy Oblast, with a rate of $-3.11 \text{ g C m}^{-2} \text{ yr}^{-1}$. NPP_A around the Issyk-Kul Lake in the northeast also showed a declining trend.

Fig. 4. Potential net primary productivity (NPP_P), actual NPP (NPP_A), human-induced NPP (NPP_H), the number of livestock and climatic factors at the national scale and in seven oblasts in Kyrgyzstan from 2000 to 2014. Scenario 1: actual NPP increase caused by human activities (IH), Scenario 5: actual NPP decrease caused by climate change (DC), Scenario 6: actual NPP decrease caused by both human activities and climate change (DHC). r_l : correlation coefficient between grassland NPP and the number of livestock, r_p : correlation coefficient between grassland NPP and annual total precipitation, r_t : correlation coefficient between grassland NPP and mean annual temperature, PRE: precipitation, TEP: temperature.

Fig. 5. Actual net primary productivity (NPP_A) in Kyrgyzstan from 2000 to 2014.

At the national scale, mean potential NPP was $497.4 \text{ g C m}^{-2} \text{ yr}^{-1}$, ranging from $434.6 \text{ g C m}^{-2} \text{ yr}^{-1}$ in 2013 to $612.0 \text{ g C m}^{-2} \text{ yr}^{-1}$ in 2003 (Fig. 4 and 6). We found an overall downward trend in NPP_P not only at the national scale (with a rate of $-3.46 \text{ g C m}^{-2} \text{ yr}^{-1}$) but also in each province. The most distinct decreasing trends appeared in the eastern areas of Issyk-Kul Oblast and Naryn Oblast, with rates of $-7.53 \text{ g C m}^{-2} \text{ yr}^{-1}$ and $-3.67 \text{ g C m}^{-2} \text{ yr}^{-1}$, respectively (Fig. 8b). In contrast, only a few areas showed a positive trend, such as in the northern part of Chuy Oblast, the southern area of Jalal-Abad Oblast and the northwest and southwest regions of Osh Oblast.

Fig. 6. Potential net primary productivity (NPP_p) in Kyrgyzstan from 2000 to 2014.

Mean human-induced NPP of grassland was $261.70 \text{ g C m}^{-2} \text{ yr}^{-1}$ during 2000-2014 in Kyrgyzstan. The highest NPP_H occurred in 2003 ($372.64 \text{ g C m}^{-2} \text{ yr}^{-1}$), whereas the lowest value of $200.32 \text{ g C m}^{-2} \text{ yr}^{-1}$ was detected in 2007 (Fig. 4 and 7). Overall, NPP_H declined at a rate of $-2.58 \text{ g C m}^{-2} \text{ yr}^{-1}$. Regions with decreasing NPP_H matched the spatial distribution of potential NPP (Fig. 4, 7, 8c). Upward trends in NPP_H were observed in north-western areas including Chuy, Jalal-Abad and Talas Oblasts.

Fig. 7. Human-induced net primary productivity (NPP_H) in Kyrgyzstan from 2000 to 2014.

Fig. 8. Spatial patterns of trends over time in mean (a) actual net primary productivity (NPP_A), (b) potential net primary productivity (NPP_P), and (c) human-induced net primary productivity (NPP_H) in Kyrgyzstan from 2000 to 2014.

3.2 Relative roles of climate change and human activities in grassland net primary productivity

Based on the six trend scenarios, the spatial distribution of the effects of climate change and human activities on grassland recovery and degradation are shown in Fig. 9. The reasons for grassland NPP_A increases and decreases show distinct dissimilarities. 78,315 km² (59.4%) of the study area's grassland suffered degradation and climatic factors were the dominant driver. Climate alone resulted in degradation over 49,799 km² (37.8%) of the area, and both climate and human

drivers combined caused degradation in 25,087 km² (19.0%) of the area, while human factors alone caused degradation over just 3,429 km² (2.6%). Climate-dominated degradation occurred mostly in the northern half of the country. Conversely, grassland recovery occurred in 53,581 km² (40.6%) of the grassland area, mostly concentrated in the south, and most of this recovery (39.2%) was caused by human activities.

Fig. 9. Spatial patterns of the relative effects of climate change and human activities on grassland net primary productivity in Kyrgyzstan from 2000 to 2014. IH: NPP_A increase caused by human activities, IHC: NPP_A increase caused by both human activities and climate change, IC: NPP_A increase caused by climate change, DH: NPP_A decrease caused by human activities, DHC: NPP_A decrease caused by both human activities and climate change, DC: NPP_A decrease caused by climate change.

Overall, climate change was the dominant factor affecting decreases in grassland NPP_A, while human activities promoted grassland restoration in many areas. However, we found differences in the impacts of climatic factors and human activities on grassland NPP among provinces (Fig. 10, Table 1). In the north of Kyrgyzstan, most areas experienced grassland degradation dominated by climate change. In some of these areas, human activities compounded the negative effects of climate change while in other parts human activities had a positive effect on NPP, but the negative impact of climate change was stronger. By contrast, in much of the south, the effect of human activities on increasing grassland NPP_A was much greater than the largely negative impacts of climate change, especially in Naryn and Osh Oblasts. In Issyk-Kul and Naryn Oblasts the negative impacts of climate change was roughly offset by the positive impact of humans which resulted in little net change in grassland NPP.

Fig. 10. The (a) total areas of different effect caused by climate change and human activities in grassland, (b) average NPP trends caused by climate change and human activities, and (c) total NPP trend caused by climate change and human activities in seven oblasts and in Kyrgyzstan (KGZ) at the national scale. Note that here positive values of NPP_H indicate an increase in grassland NPP and vice versa.

Table 1. The area and percentage of grassland net primary productivity (NPP) increase and decrease from 2000 to 2014 explained by six scenarios for each oblast and at the national scale in Kyrgyzstan.

Oblast	Grassland recovery						Grassland degradation					
	Scenario1/IH		Scenario2/IC		Scenario3/IHC		Scenario4/DH		Scenario5/DC		Scenario6/DHC	
	Area (km²)	%	Area (km²)	%	Area (km²)	%	Area (km²)	%	Area (km²)	%	Area (km²)	%
Batken	2517	22.56	50	0.45	131	1.17	211	1.89	7239	64.88	1010	9.05
Jalal-abad	4052	14.42	157	0.56	188	0.67	1679	5.97	10034	35.71	11992	42.67
Issyk-kul	8561	50.08	0	0.00	0	0.00	0	0.00	8226	48.12	307	1.80
Naryn	22777	63.25	0	0.00	0	0.00	0	0.00	12001	33.33	1233	3.42
Osh	12407	64.86	287	1.50	1020	5.33	574	3.00	4169	21.79	672	3.51
Talas	247	2.69	12	0.13	11	0.12	690	7.51	4004	43.56	4227	45.99
Chuy	1156	10.31	1	0.01	7	0.06	275	2.45	4126	36.80	5646	50.36
KGZ	51717	39.21	507	0.38	1357	1.03	3429	2.60	49799	37.76	25087	19.02

* IH: actual net primary productivity (NPP_A) increase caused by human activities; IC: NPP_A increase caused by climate change; IHC: NPP_A increase caused by both human activities and climate change; DH: NPP_A decrease caused by human activities; DC: NPP_A decrease caused by climate change; DHC: NPP_A decrease caused by both human activities and climate change; KGZ: Kyrgyzstan (at national scale).

3.3 Correlates of change in grassland NPP

Climatic factors were associated with a negative effect on NPP across 126,603 km² (96.0%) of grasslands confirming that climate is a vital factor in grassland NPP decline in Kyrgyzstan. Grassland NPP was positively correlated with precipitation in 67.03% of the total area (Fig. 4 and 11a) and the correlation was significant ($p < 0.05$) for about 22.27% of the area (Fig. 11b). By contrast, the area showing negative correlation coefficients between NPP_A and precipitation accounted for 32.97% of the total area (Fig. 11a) but the correlation was significant ($p < 0.05$) for only 3.84% of the area (Fig. 11b). In addition, a positive correlation between grassland NPP and temperature was found in 71.21% of the region (Fig. 4 and 11c), but the correlation was significant ($p < 0.05$) for only 2.40% of the area (Fig. 11d). Conversely, a negative correlation between grassland NPP and temperature was found in 28.79% of the area (Fig. 11c) but significance levels were extremely low (Fig. 11d). Overall, in much of the study area climate change was associated with grassland degradation, and precipitation was the dominant climatic factor controlling the decrease in NPP.

Fig. 11. Spatial distribution of the correlation coefficients between grassland actual net primary productivity (NPP_A) and climatic factors in Kyrgyzstan from 2000 to 2014. (a) Correlation between annual actual NPP and annual precipitation. (b) Regions with significant correlations ($p < 0.05$) of NPP and precipitation. (c) Correlation between annual actual NPP and mean annual temperature. (d) Regions with significant correlations ($p < 0.05$) of NPP and temperature.

Fig. 4, 9 and Table 1 show that the area where human activities caused a negative effect in grassland NPP was about 29,023 km² (22.0 %) and was mainly distributed in the northwest of Chuy Oblast, southeast of Talas Oblast and in the southern area of Jalal-Abad Oblast. We found that grassland actual NPP in these areas was negatively correlated with the number of livestock ($p < 0.05$) (Fig. 3). Approximately 102,873 km² (78.0 %) grassland experienced NPP increases facilitated by human activities, mainly in the southern area of Kyrgyzstan and especially in Naryn Oblast. However, there was no correlation between grassland NPP and the number of livestock in these areas. This suggests that other human factors are at play in increasing grassland NPP in these areas.

4. Discussion

We have quantified the spatial and temporal variability of potential NPP, actual NPP and human-induced NPP in Kyrgyzstan from 2000 to 2014 and assessed the impacts of climatic factors and anthropogenic activities on grasslands. We found that grassland NPP generally decreased, with differences between oblasts. Through exploring the relative contributions of climatic and human factors associated with grassland NPP change, we found strong regional patterns in grassland degradation and recovery. Our results indicate that climate change resulted in a decrease in NPP over 96% of grasslands while human activities resulted in an increase in NPP over 78%. In most of the north, the negative effects of climate change (predominantly precipitation) was compounded by human pressures (predominantly intensification of livestock grazing). In other parts of the north, negative climate impacts more than offset positive gains brought on by human activities. In the south, the positive benefits of human activities tended to overwhelm the negative impacts of climate change.

4.1 Effects of climatic and human factors on NPP

Our analysis showed that grassland NPP was significantly and positively correlated with precipitation and precipitation was the primary climatic factor influencing grassland productivity in most of the study area. Conversely, correlation analysis between grassland and temperature was indeterminant. These results align with established understandings that climate change can influence

terrestrial vegetation growth (Li, Zhang, et al., 2015) and precipitation is viewed as the most significant factor driving NPP changes in arid and semi-arid regions (Knapp & Smith, 2001; Zeppel et al., 2014; Zhou et al., 2002). NPP increases with increasing mean annual precipitation across different sites and years in arid and semi-arid areas (Churkina et al., 1999; Huxman, Smith, et al., 2004; Peng et al., 2013). Precipitation has a direct effect on soil moisture (Weltzin et al., 2003; Xu et al., 2016). It is not only the major source of soil moisture content, but it also plays a crucial role in the regulation of biochemical processes in the soil environment, which directly affects soil respiration, especially in arid and semi-arid regions (Austin et al., 2004; Sponseller, 2007). Decreases in precipitation can cause serious soil moisture loss, influence the efficiency of photosynthesis and reduce organic matter production, such as the regeneration of photophosphorylation and ribulose 1,5-biphosphate (Huxman, Snyder, et al., 2004; Xu et al., 2016).

Some oblasts displayed significant negative correlations between grassland NPP and the number of livestock, reflecting the impact of grazing on grassland degradation. Kyrgyzstan was the third most important meat- and wool-producing region in the former Soviet Union and collective farms played a dominated role in that period. Under the centralised Soviet system, ‘sovkhozes’ and ‘kolkhozes’ became the specialized units in control of agricultural activities and livestock numbers increased considerably during that time. Under this management regime, pastures suffered serious damage (Ludi, 2003). Following Kyrgyzstan’s independence in 1991, traditional grazing patterns have been transformed into more intensive forms of agricultural land use (Hoppe et al., 2018). The number of livestock decreased and grazing pressure was relieved temporarily. Livestock numbers then gradually recovered to the original post-Soviet level in the 2000s (Levine et al., 2017). Overgrazing can cause grassland degradation in two ways. Excess livestock can cause severe damage to vegetation and the leaf area of pasture will decrease correspondingly, leading to a decline in photosynthesis. Overgrazing not only affects the growth of aboveground vegetation but it also affects root growth. Overgrazing can result in soil coarseness and soil properties variation and the concentration of organic carbon and nitrogen and microbial activities decrease. These processes accelerate soil erosion and grassland degradation (Xu & Zhao, 2001; Yong-Zhong et al., 2005). However, while livestock grazing increased in most oblasts over time, the dominant human impacts on grassland during the study area had a positive impact on NPP.

Mining is another anthropogenic activity causing localised grassland NPP decrease.

Kyrgyzstan is well-known for its abundant mineral resources and it was used by central authorities as a mineral resource base during the time of the former Soviet Union. Today, the mining industry is still a key part of the national economy of Kyrgyzstan. Kumtor is Kyrgyzstan's most significant company and contributes 10% of Kyrgyzstan's gross domestic product (Kronenberg, 2014). In the disturbed sites of mining industries, soil texture and moisture content can be significantly altered (Mummey et al., 2002) and some vegetation may be affected by heavy metal and metalloid contamination. Additionally, mining transportation (e.g. trucks) may damage vulnerable grasslands (Chen et al., 2019; Jiang et al., 2017).

However, on the whole, anthropogenic activities led to grassland recovery (i.e. increasing NPP_A) over 102,873 km² (78.0%) of the study area, largely located in southern Kyrgyzstan (Fig. 9 and 10). Over much of this area, climate change had an adverse influence on grassland as well, but this was more than offset by the positive effect of human factors. Anthropogenic activities, such as conservation and restoration efforts and environmental protection policy are likely to provide an explanation for this phenomenon. To improve the sustainability of pasture use, the Kyrgyz government enacted a number of environmental policies and laws. For instance, the *Law on Environmental Protection* and *Law on Ecological Expertise* were successively issued in 1999 and aimed to establish the legal and institutional framework for environmental and natural resources protection and prevent negative impacts on the environment and human health. In 2002, the *Law on Mountainous Territories* and the *Regulation on Allocation of Pastures for Rent and Use* were promulgated. Both laws were designed to regulate the management and allocation of pasture resources. Meanwhile, the Kyrgyz Republic intensified enforcement by related environmental law departments and reformed management methods. From 1999 to 2009, different ministries were responsible for pasture management according to the type of pasture: (1) pastures near villages belonging to community administrations, (2) intensive pastures (i.e. usually situated in the foothills) managed by districts, and (3) mid- and high-elevation and remote pastures under the administration of each oblast. To resolve the problem of fragmentation and rehabilitate rangeland, after the enactment of the *Kyrgyz Republic Law of Pasture* in 2009, the responsibility for managing pastures was converted to community-based user units from original management patterns (Crewett, 2012; Ludi, 2003). The establishment of ecological reserves and natural parks, such as the Karatal-Japyryk Reserve and Salkyn Tor National Park, has also reduced grazing intensity and led to a positive

510 impact on grassland restoration.

512 4.2 Implications for policy and governance

514 As a traditional grazing country, Kyrgyzstan has high quality pasture resources. During the
515 period of the Soviet Union, due to overgrazing and improper management of pastures, serious
516 grassland degradation occurred. After independence, the Kyrgyz Republic enacted a series of laws
517 to maintain the sustainability of grasslands. Although efforts have been made during the past few
518 years, the situation of grassland ecosystems in Kyrgyzstan is still austere. Establishing effective
519 policy to mitigate and adapt to the impact of climate change is urgent. It is important to strengthen
520 research on the influence of climate change on grasslands, quantitatively and dynamically
521 evaluating potential future grassland degradation and the efficacy of different adaptive management
522 strategies and approaches. To achieve more sustainable strategies for grassland restoration and
523 management, ecological, economic and social issues must be integrated into a comprehensive
524 framework (Jiang et al., 2006).

525 First, it is vital to educate local herders and managers in rangeland ecology and resource
526 management. Widespread education of herders on sustainable land management and grassland
527 ecology is required. There is a great need to use modern technology and methods to manage pasture.
528 Second, investments in infrastructure to increase flock mobility are urgent to ensure grazing pressure
529 is relieved seasonally from some grasslands (Foggin, 2018; Davies & Hagelberg, 2014). Seasonal
530 livestock mobility contributes to maintain a sustainable semi-arid grazing ecosystem and enable
531 natural pasture to recover. Furthermore, with more remote pasture, livestock can access higher
532 quality and more nutritious forage grass. In comparison with village-fed animals, the flock-fed
533 livestock have enough food in winter and their offspring are bigger and stronger (Kerven et al.,
534 2008). Generally, household decisions about flock mobility depend on herd size, the condition of
535 available pasture, and household financial and labour availability (Kerven et al., 2004). Most herders
536 in Kyrgyzstan are only willing to graze near their home and show scant interest in remote grasslands
537 because of inconvenient access and lack of services (Crewett, 2012). Therefore, improving
538 infrastructure and services may facilitate greater flock migration. Third, improving the legal
539 provision for seasonal migration is of paramount importance. So far, there is no enforcement of

seasonal migration and no sanctions in existing regulations. Due to the low cost of pasture rent and non-standard operation, this results in fewer restrictions for pasture lease (Crewett, 2012). Thus, legal efforts to establish management methods and enforcement of related regulation would have practical significance.

Controlling the impact of mining on grasslands is also important. The energy industry is rapidly becoming the mainstay of Kyrgyzstan's economy and energy cooperation will become the main component of trade with other countries under the "One Belt One Road Initiative". The impact caused by the mining industry could introduce significant environmental and ecological problems and increase the conflict between resource demand, environmental protection and sustainable development. To combat the problem, government organisations and mining enterprises need to cooperate with researchers to assess grassland and environmental disruption by mining and minimize damage on vegetation. Periodically monitoring grassland condition in mining areas and developing governance and restoration plans is also essential.

4.3 Innovation and generalisability

Some large-scale studies have been conducted on the impacts of climate change and anthropogenic activities on Central Asian grasslands but few studies have attempted to disentangle the contributions of climate and anthropogenic factors. Previous studies reported that climate variation played a dominant role in grassland ecosystems in Central Asia, with precipitation intensity and duration showing large effects on grassland growth (Han et al., 2018; Li, Chen, et al., 2015; Propastin et al., 2008) and changes in temperature showing no obvious impacts on vegetation biomass in Central Asia (Chen et al., 2019; Zhang & Ren, 2017). Our results are not only consistent with the results of previous studies but also using more high resolution data to detect recent response of grassland NPP on climatic effects in Kyrgyzstan. We found that with a significant decreasing trend in mean precipitation, there was an overall degradation of grasslands at the national scale but there were differences in grassland changes at the provincial scale. Regarding the impact of anthropogenic activities on grasslands, our results support the conclusions of recent studies (Chen et al., 2019). In most parts of southern Kyrgyzstan, human activities led an increase in grassland NPP, while some northwest areas underwent grassland degradation by anthropogenic activities. In

comparison with previous research, we discussed the effects of climate change and human activities on grassland at the national scale and in seven oblasts. We found the response of grassland dynamics to anthropogenic activities were not equal in each oblast.

Our study offers a new perspective for research into the responses of grassland dynamics to global change and proposed significant suggestions for environmental conservation and sustainable development based on the impact of climate change and anthropogenic activities. We have distinguished the relative roles of climate change and human activities in grassland productivity and ecosystem health. Our approach has broad applicability in identifying the impacts of climatic variation, livestock grazing, socio-economic change, and land cover change in arid and semi-arid grassland areas. Additionally, we provided new evidence for grassland recovery potentially related to the enactment of environmental protection policies and enforcement in Kyrgyzstan, and offer a theoretical and practical basis for maintaining grassland and agricultural sustainability for other Central Asian countries. Our findings substantially improve the understanding of the role of environmental protection and management as potential drivers of grassland recovery in Central Asia.

4.4 Limitations and uncertainty

Although the Zhou Guangsheng model used to simulate grassland NPP_P in this study has been shown to be more precise and effective than other empirical models (Pu et al., 2009; Ren & Zhou, 2018; Sun et al., 2012), simulated potential NPP is still fairly coarse resolution both because of the simplicity of the algorithm itself and the resolution of the input data. As a climate-driven model, it uses precipitation, temperature and evaporation to simulate potential NPP and the satellite-derived climatic data sets for Central Asia have limitations both in accuracy and potential use (Hu et al., 2016). Beyond climate, the Zhou Guangsheng model does not consider the influence of other factors on NPP such as terrain, soil condition, solar radiation, and vegetation type (Ren & Zhou, 2018). Similarly, the MODIS NPP applied in our study and it has the advantages on detecting grassland variation. However, due to the coarse temporal resolution and uncertainties of meteorological inputs, it also has its drawbacks (Zhao et al., 2005).

We also did not consider the effects of other factors on NPP such as variation in grassland species, fire, plant diseases, and insect pests in this study. For instance, grassland species

composition and abundance are affected by climate change, invasive species, and disturbance such as preferential grazing, which may cause variation in grassland NPP and introduce model errors. Huenneke et al. (2002) found that grassland was replaced by desert scrub in the Chihuahuan Desert in the USA, with little change in aboveground biomass. In past decades, some areas in Kyrgyzstan have experienced invasion by shrubs and other vegetation species (Zhumanova et al., 2018).

Finally, we only assessed the correlation between grassland NPP and climatic and anthropogenic factors. This enabled us to discuss associative relationships between potential drivers and NPP. The analysis of the causal impact of the factors on NPP presents an opportunity for future research. Further, a strong effect identified in this study is the positive impact of human activities on NPP recovery in southern Kyrgyzstan. Evaluating and quantifying the causal impact of environmental policies on grassland NPP in Kyrgyzstan is also a very promising avenue for further investigation to guide future policy approaches especially given the multiple pressures anticipated under the Belt and Road program of infrastructure investment.

5. Conclusion

We used MODIS NPP and the Zhou Guangsheng model to estimate actual (NPP_A), potential (NPP_P) and human-induced NPP (NPP_H). Our results show that 59.4% of Kyrgyzstan's grassland area underwent a decrease in NPP_A mostly in the northern parts of the country, while grassland NPP_A increased over 40.6% of the study area, occurring mostly in the south. Human activities facilitated an increase in grassland NPP over 78.0% of the study area, while climate change led to grassland degradation over 96.0%. Precipitation was the dominant climatic factor contributing to the decrease in grassland NPP. Livestock grazing is likely to be the major anthropogenic activity influencing grassland degradation in the northwest in recent years, while in southern Kyrgyzstan grassland recovery may be due to the enactment and vigorous enforcement of several environmental protection policies such as grazing prohibition. The results have implications for policy and governance to strengthen the local economy and livelihoods while protecting the environment and achieving sustainable development. Importantly, further research is needed to extend our associative analysis and quantify the causal impact of climatic and human drivers on grassland NPP, in particular the effect of environmental policies in southern Kyrgyzstan.

Acknowledgements

This research was supported by the funding from China Scholarship Council (grant number: 201806270117).

Author contributions

BB, YW and SH designed the study and planned the analysis. YW, HY, QP, and CH did the data analysis. YW drafted the manuscript. All authors contributed to the interpretation of findings, provided revisions to the manuscript, and approved the final manuscript.

Conflicts of interest

The authors declare no conflict of interest.

References:

- Agadjanian, V., & Gorina, E. (2019). Economic Swings, Political Instability and Migration in Kyrgyzstan. *European Journal of Population*, 35(2), 285-304. <https://doi.org/10.1007/s10680-018-9482-4>
- Austin, A. T., Yahdjian, L., Stark, J. M., Belnap, J., Porporato, A., Norton, U., ... & Schaeffer, S. M. (2004). Water pulses and biogeochemical cycles in arid and semiarid ecosystems. *Oecologia*, 141(2), 221-235. <https://doi.org/10.1007/s00442-004-1519-1>
- Awaya, Y., Kodani, E., Tanaka, K., Liu, J., Zhuang, D., & Meng, Y. (2004). Estimation of the global net primary productivity using NOAA images and meteorological data: changes between 1988 and 1993. *International Journal of Remote Sensing*, 25(9), 1597-1613. <https://doi.org/10.1080/0143116031000139782>
- Baeza, S., & Paruelo, J. M. (2018). Spatial and temporal variation of human appropriation of net primary production in the Rio de la Plata grasslands. *ISPRS journal of photogrammetry and remote sensing*, 145, 238-249. <https://doi.org/10.1016/j.isprsjprs.2018.07.014>
- Bai, Z. G., & Dent, D. L. (2006). Global assessment of land degradation and improvement: pilot study in Kenya. *ISRIC Report*.
- 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(3), 363-373. <https://doi.org/10.1007/s11629-011-2121-8>
- Burrell, A. L., Evans, J. P., & Liu, Y. (2017). Detecting dryland degradation using time series segmentation and residual trend analysis (TSS-RESTREND). *Remote sensing of environment*, 197, 43-57. <http://dx.doi.org/10.1016/j.rse.2017.05.018>
- Chen, A., Li, R., Wang, H., & He, B. (2015). Quantitative assessment of human appropriation of aboveground net primary production in China. *Ecological modelling*, 312, 54-60. <http://dx.doi.org/10.1016/j.ecolmodel.2015.05.017>
- Chen, B., Zhang, X., Tao, J., Wu, J., Wang, J., Shi, P., ... & Yu, C. (2014). The impact of climate change and anthropogenic activities on alpine grassland over the Qinghai-Tibet Plateau. *Agricultural and Forest Meteorology*, 189, 11-18. <http://dx.doi.org/10.1016/j.agrformet.2014.01.002>
- Chen, H., Liu, X., Ding, C., & Huang, F. (2018). Phenology-Based Residual Trend Analysis of MODIS-NDVI Time Series for Assessing Human-Induced Land Degradation. *Sensors*, 18(11), 3676. <https://doi.org/10.3390/s18113676>
- Chen, T., Bao, A., Jiapaer, G., Guo, H., Zheng, G., Jiang, L., ... & Tuerhanjiang, L. (2019). Disentangling the relative impacts of climate change and human activities on arid and semiarid grasslands in Central Asia during 1982–2015. *Science of The Total Environment*, 653, 1311-1325. <https://doi.org/10.1016/j.scitotenv.2018.11.058>
- Churkina, G., Running, S. W., Schloss, A. L., The Participants of the Potsdam NPP Model intercomparison. (1999). Comparing global models of terrestrial net primary productivity (NPP): the importance of water availability. *Global Change Biology*, 5(S1), 46-55. <https://doi.org/10.1046/j.1365-2486.1999.00006.x>
- Crewett, W. (2012). Improving the sustainability of pasture use in Kyrgyzstan. *Mountain Research and Development*, 32(3), 267-275. <http://dx.doi.org/10.1659/MRD-JOURNAL-D-11-00128.1>
- Davies, J., & Hagelberg, N. (2014). Sustainable Pastoralism and the Post 2015 Agenda: Opportunities and Barriers to Pastoralism for Global Food Production and Environmental Stewardship. *United Nations Environment Programme (UNEP)*, 2.
- Dubovyk, O., Landmann, T., Dietz, A., & Menz, G. (2016). Quantifying the impacts of environmental factors on vegetation dynamics over climatic and management gradients of central Asia. *Remote Sensing*, 8(7), 600.

<https://doi.org/10.3390/rs8070600>
 Erb, K. H. , Krausmann, F. , Gaube, V. , Gingrich, S. , Bondeau, A. , & Fischer-Kowalski, M. , et al. (2009).
 Analyzing the global human appropriation of net primary production — processes, trajectories,
 implications. an introduction. *Ecological Economics*, 69(2), 250-259.
<https://doi.org/10.1016/j.ecolecon.2009.07.001>
 Evans, J., & Geerken, R. (2004). Discrimination between climate and human-induced dryland degradation. *Journal*
of Arid Environments, 57(4), 535-554. [https://doi.org/10.1016/S0140-1963\(03\)00121-6](https://doi.org/10.1016/S0140-1963(03)00121-6)
 Foggin, J. M. (2018). Environmental conservation in the Tibetan Plateau region: lessons for China's Belt and Road
 Initiative in the mountains of Central Asia. *Land*, 7(2), 52. <https://doi.org/10.3390/land7020052>
 Gang, C., Zhao, W., Zhao, T., Zhang, Y., Gao, X., & Wen, Z. (2018). The impacts of land conversion and management
 measures on the grassland net primary productivity over the Loess Plateau, Northern China. *Science of the*
Total Environment, 645, 827-836. <https://doi.org/10.1016/j.scitotenv.2018.07.161>
 Gang, C., Zhou, W., Chen, Y., Wang, Z., Sun, Z., Li, J., ... & Odeh, I. (2014). Quantitative assessment of the
 contributions of climate change and human activities on global grassland degradation. *Environmental*
earth sciences, 72(11), 4273-4282. <https://doi.org/10.1007/s12665-014-3322-6>
 Gingrich, S., Niedertscheider, M., Kastner, T., Haberl, H., Cosor, G., Krausmann, F., ... & Vadineanu, A. (2015).
 Exploring long-term trends in land use change and aboveground human appropriation of net primary
 production in nine European countries. *Land Use Policy*, 47, 426-438.
<https://doi.org/10.1016/j.landusepol.2015.04.027>
 Haberl, H., Erb, K. H., Krausmann, F., Gaube, V., Bondeau, A., Plutzer, C., ... & Fischer-Kowalski, M. (2007).
 Quantifying and mapping the human appropriation of net primary production in earth's terrestrial
 ecosystems. *Proceedings of the National Academy of Sciences*, 104(31), 12942-12947.
<https://doi.org/10.1073/pnas.0704243104>
 Han, Q., Luo, G., Li, C., & Li, S. (2018). Response of Carbon Dynamics to Climate Change Varied among Different
 Vegetation Types in Central Asia. *Sustainability*, 10(9), 3288. <https://doi.org/10.3390/su10093288>
 Holdridge, L. R. (1947). Determination of world plant formations from simple climatic data. *Science*, 105(2727),
 367-368. <https://doi.org/10.1126/science.105.2727.367>
 Hoppe, F., Schickhoff, U., & Oldeland, J. (2018). Plant species diversity of pastures in the Naryn Oblast (Kyrgyzstan).
DIE ERDE—Journal of the Geographical Society of Berlin, 149(4), 214-226. DOI:10.12854/erde-2018-
 384
 Hu, Z., Hu, Q., Zhang, C., Chen, X., & Li, Q. (2016). Evaluation of reanalysis, spatially interpolated and satellite
 remotely sensed precipitation data sets in central Asia. *Journal of Geophysical Research: Atmospheres*,
 121(10), 5648-5663. <https://doi.org/10.1002/2016JD024781>
 Huang, K., Zhang, Y., Zhu, J., Liu, Y., Zu, J., & Zhang, J. (2016). The influences of climate change and human
 activities on vegetation dynamics in the Qinghai-Tibet Plateau. *Remote Sensing*, 8(10), 876.
<https://doi.org/10.3390/rs8100876>
 Huang, L., Xiao, T., Zhao, Z., Sun, C., Liu, J., Shao, Q., ... & Wang, J. (2013). Effects of grassland restoration
 programs on ecosystems in arid and semiarid China. *Journal of environmental management*, 117, 268-275.
<https://doi.org/10.1016/j.jenvman.2012.12.040>
 Huang, X., Luo, G., He, H., Wang, X., & Amuti, T. (2017). Ecological Effects of Grazing in the Northern Tianshan
 Mountains. *Water*, 9(12), 932. <https://doi.org/10.3390/w9120932>
 Huenneke, L. F., Anderson, J. P., Remmenga, M., & Schlesinger, W. H. (2002). Desertification alters patterns of
 aboveground net primary production in Chihuahuan ecosystems. *Global Change Biology*, 8(3), 247-264.
<https://doi.org/10.1046/j.1365-2486.2002.00473.x>

- Huxman, T. E., Smith, M. D., Fay, P. A., Knapp, A. K., Shaw, M. R., Loik, M. E., ... & Pockman, W. T. (2004). Convergence across biomes to a common rain-use efficiency. *Nature*, 429(6992), 651. <https://doi.org/10.1038/nature02561>
- Huxman, T. E., Snyder, K. A., Tissue, D., Leffler, A. J., Ogle, K., Pockman, W. T., ... & Schwinning, S. (2004). Precipitation pulses and carbon fluxes in semiarid and arid ecosystems. *Oecologia*, 141(2), 254-268. <https://doi.org/10.1007/s00442-004-1682-4>
- Jiang, G., Han, X., & Wu, J. (2006). Restoration and management of the Inner Mongolia grassland require a sustainable strategy. *AMBIO: A Journal of the Human Environment*, 35(5), 269-271. <https://doi.org/10.1579/06-S-158.1>
- Jiang, L., Bao, A., Guo, H., & Ndayisaba, F. (2017). Vegetation dynamics and responses to climate change and human activities in Central Asia. *Science of the Total Environment*, 599, 967-980. <https://doi.org/10.1016/j.scitotenv.2017.05.012>
- Johnson, S. L., Kuske, C. R., Carney, T. D., Housman, D. C., Gallegos - Graves, L. V., & Belnap, J. (2012). Increased temperature and altered summer precipitation have differential effects on biological soil crusts in a dryland ecosystem. *Global Change Biology*, 18(8), 2583-2593. <https://doi.org/10.1111/j.1365-2486.2012.02709.x>
- Kerven, C., Alimaev, I. I., Behnke, R., Davidson, G., Franchois, L., Malmakov, N., ... & Wright, I. (2004). Retraction and expansion of flock mobility in Central Asia: costs and consequences. *African Journal of Range and Forage Science*, 21(3), 159-169. <https://doi.org/10.2989/10220110409485848>
- Kerven, C., Shanbaev, K., Alimaev, I., Smailov, A., & Smailov, K. (2008). Livestock mobility and degradation in Kazakhstan's semi-arid rangelands. *The socio-economic causes and consequences of desertification in Central Asia* (pp. 113-140). Springer, Dordrecht.
- Knapp, A. K., & Smith, M. D. (2001). Variation among biomes in temporal dynamics of aboveground primary production. *Science*, 291(5503), 481-484. <https://doi.org/10.1126/science.291.5503.481>
- Kraemer, R., Prishchepov, A. V., Müller, D., Kuemmerle, T., Radeloff, V. C., Dara, A., ... & Friühauf, M. (2015). Long-term agricultural land-cover change and potential for cropland expansion in the former Virgin Lands area of Kazakhstan. *Environmental Research Letters*, 10(5), 054012. <https://doi.org/10.1088/1748-9326/10/5/054012>
- Kronenberg, J. (2014). Viable Alternatives for Large-Scale Unsustainable Projects in Developing Countries: The case of the Kumtor gold mine in Kyrgyzstan. *Sustainable Development*, 22(4), 253-264. <https://doi.org/10.1002/sd.1529>
- LeHouerou, H. N. (1984). Rain use efficiency: a unifying concept in arid-land ecology. *Journal of arid Environments*.
- Lerman, Z., & Zedik, D. (2009). Agrarian reform in Kyrgyzstan: Achievements and the unfinished agenda (No. 888-2016-65098).
- Levine, J., Isaeva, A., Eddy, I., Foggin, M., Gergel, S., Hagerman, S., & Zerriffi, H. (2017). A cognitive approach to the post-Soviet Central Asian pasture puzzle: new data from Kyrgyzstan. *Regional environmental change*, 17(3), 941-947. <https://doi.org/10.1007/s10113-017-1122-8>
- Li, C., Zhang, C., Luo, G., Chen, X., Maisupova, B., Madaminov, A. A., ... & Djenbaev, B. M. (2015). Carbon stock and its responses to climate change in Central Asia. *Global change biology*, 21(5), 1951-1967. <https://doi.org/10.1111/gcb.12846>
- Li, Z., Chen, Y., Li, W., Deng, H., & Fang, G. (2015). Potential impacts of climate change on vegetation dynamics in Central Asia. *Journal of Geophysical Research: Atmospheres*, 120(24), 12345-12356. <https://doi.org/10.1002/2015JD023618>
- Li, Z., & Pan, J. (2018). Spatiotemporal changes in vegetation net primary productivity in the arid region of Northwest China, 2001 to 2012. *Frontiers of earth science*, 12(1), 108-124.

777 <https://doi.org/10.1007/s11707-017-0621-8>
 778 Liechti, K. (2012). The meanings of pasture in resource degradation negotiations: evidence from post-socialist rural
 779 Kyrgyzstan. *Mountain Research and Development*, 32(3), 304-313. <https://doi.org/10.1659/MRD->
 780 JOURNAL-D-11-00113.1
 781 Lieth, H. (1975). Modeling the primary productivity of the world. In *Primary productivity of the biosphere* (pp. 237-
 782 263). Springer, Berlin, Heidelberg.
 783 Lieth, H. (1972). Evapotranspiration and primary productivity: CW Thornthwaite memorial model. *Pub. in*
 784 *Climatology*, 25, 37-46.
 785 Liu, Y., Wang, Q., Zhang, Z., Tong, L., Wang, Z., & Li, J. (2019). Grassland dynamics in responses to climate
 786 variation and human activities in China from 2000 to 2013. *Science of The Total Environment*, 690, 27-39.
 787 <https://doi.org/10.1016/j.scitotenv.2019.06.503>
 788 Liu, Y., Zhang, Z., Tong, L., Khalifa, M., Wang, Q., Gang, C., ... & Sun, Z. (2019). Assessing the effects of climate
 789 variation and human activities on grassland degradation and restoration across the globe. *Ecological*
 790 *Indicators*, 106, 105504. <https://doi.org/10.1016/j.ecolind.2019.105504>
 791 Ludi, E. (2003). Sustainable pasture management in Kyrgyzstan and Tajikistan: Development needs and
 792 recommendations. *Mountain Research and Development*, 23(2), 119-124. <https://doi.org/10.1659/0276->
 793 4741(2003)023[0119:SPMIKA]2.0.CO;2
 794 Luo, Z., Wu, W., Yu, X., Song, Q., Yang, J., Wu, J., & Zhang, H. (2018). Variation of Net Primary Production and
 795 Its Correlation with Climate Change and Anthropogenic Activities over the Tibetan Plateau. *Remote*
 796 *Sensing*, 10(9), 1352. <https://doi.org/10.3390/rs10091352>
 797 Ma, W., Wang, X., Zhou, N., & Jiao, L. (2017). Relative importance of climate factors and human activities in
 798 impacting vegetation dynamics during 2000–2015 in the Otindag Sandy Land, northern China. *Journal of*
 799 *Arid Land*, 9(4), 558-567. <https://doi.org/10.1007/s40333-017-0062-y>
 800 Mamytov, A. (1982). Mountain soils in Central Asia and Southern Kazakhstan. In: Frunze.
 801 McNally, A., Arsenault, K., Kumar, S., Shukla, S., Peterson, P., Wang, S., ... & Verdin, J. P. (2017). A land data
 802 assimilation system for sub-Saharan Africa food and water security applications. *Scientific data*, 4, 170012.
 803 <https://doi.org/10.1038/sdata.2017.12>
 804 Mummey, D. L., Stahl, P. D., & Buyer, J. S. (2002). Soil microbiological properties 20 years after surface mine
 805 reclamation: spatial analysis of reclaimed and undisturbed sites. *Soil Biology and Biochemistry*, 34(11),
 806 1717-1725. [https://doi.org/10.1016/S0038-0717\(02\)00158-X](https://doi.org/10.1016/S0038-0717(02)00158-X)
 807 Parton, W. J., Scurlock, J. M. O., Ojima, D. S., Gilmanov, T. G., Scholes, R. J., Schimel, D. S., ... & Kamnalrut, A.
 808 (1993). Observations and modeling of biomass and soil organic matter dynamics for the grassland biome
 809 worldwide. *Global biogeochemical cycles*, 7(4), 785-809. <https://doi.org/10.1029/93GB02042>
 810 Pasture Department, 2014. Annual Report on Pasture Department Activities for 2014 (In Kyrgyz). Bishkek.
 811 Peng, S., Piao, S., Shen, Z., Ciais, P., Sun, Z., Chen, S., ... & Chen, A. (2013). Precipitation amount, seasonality and
 812 frequency regulate carbon cycling of a semi-arid grassland ecosystem in Inner Mongolia, China: a
 813 modeling analysis. *Agricultural and Forest Meteorology*, 178, 46-55.
 814 <https://doi.org/10.1016/j.agrformet.2013.02.002>
 815 Potter, C. S., Randerson, J. T., Field, C. B., Matson, P. A., Vitousek, P. M., Mooney, H. A., & Klooster, S. A. (1993).
 816 Terrestrial ecosystem production: a process model based on global satellite and surface data. *Global*
 817 *Biogeochemical Cycles*, 7(4), 811-841. <https://doi.org/10.1029/93GB02725>
 818 Prince, S. D. (1991). A model of regional primary production for use with coarse resolution satellite data.
 819 *International Journal of Remote Sensing*, 12(6), 1313-1330. <https://doi.org/10.1080/01431169108929728>
 820 Propastin, P. A., Kappas, M., & Muratova, N. R. (2008). Inter-Annual Changes in Vegetation Activities and Their

- Relationship to Temperature and Precipitation in Central Asia from 1982 to 2003. *Journal of Environmental Informatics*, 12(2). <https://doi.org/10.3808/jei.200800126>
- Pu, Z. C., Zhang, S. Q., & Wang, S. L. (2009). Response of NPP to climate change over last 47 years in Tianshan Mountain areas. *Chin. J. Agrometeorol*, 30, 283-288. <https://doi.org/10.3969/j.issn.1000-6362.2009.03.002>
- Ren, H., & Zhou, G. (2018). Measuring the impacts of anthropogenic activities on Inner Mongolian temperate grassland. *Land degradation & development*, 29(9), 2942-2950. <https://doi.org/10.1002/ldr.3055>
- Running, S. W., & Hunt Jr, E. R. (1993). Generalization of a forest ecosystem process model for other biomes, BIOME-BCG, and an application for global-scale models. *Scaling Physiological Processes*, 141-158. <http://dx.doi.org/10.1016/B978-0-12-233440-5.50014-2>
- Running, S. W., Nemani, R. R., Heinsch, F. A., Zhao, M., Reeves, M., & Hashimoto, H. (2004). A continuous satellite-derived measure of global terrestrial primary production. *Bioscience*, 54(6), 547-560. [https://doi.org/10.1641/0006-3568\(2004\)054\[0547:ACSMOG\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2004)054[0547:ACSMOG]2.0.CO;2)
- Sagynbekova, L. (2017). Environment, rural livelihoods, and labor migration: a case study in Central Kyrgyzstan. *Mountain research and development*, 37(4), 456-464. <https://doi.org/10.1659/MRD-JOURNAL-D-17-00029.1>
- Song, F. Q., Kang, M. Y., Chen, Y. R., Yang, P., Liu, Y., & Wang, Q. (2009). Estimation of vegetation net primary productivity on North Shaanxi Loess Plateau. *Chinese Journal of Ecology*, 28(11), 2311-2318. <https://doi.org/10.13292/j.1000-4890.2009.0362>
- Sponseller, R. A. (2007). Precipitation pulses and soil CO₂ flux in a Sonoran Desert ecosystem. *Global Change Biology*, 13(2), 426-436. <https://doi.org/10.1111/j.1365-2486.2006.01307.x>
- Sun, J., Guan, D., Wu, J., Jin, C., & Yuan, F. (2012). Research advances in net primary productivity of terrestrial vegetation. *World Forestry Research*, 25(1), 1-6.
- Tong, L., Liu, Y., Wang, Q., Zhang, Z., Li, J., Sun, Z., & Khalifa, M. (2019). Relative effects of climate variation and human activities on grassland dynamics in Africa from 2000 to 2015. *Ecological Informatics*, 53, 100979. <https://doi.org/10.1016/j.ecoinf.2019.100979>
- Turner, D. P., Ritts, W. D., Cohen, W. B., Gower, S. T., Running, S. W., Zhao, M., ... & Ahl, D. E. (2006). Evaluation of MODIS NPP and GPP products across multiple biomes. *Remote Sensing of Environment*, 102(3-4), 282-292. <https://doi.org/10.1016/j.rse.2006.02.017>
- Vitousek, P. M., Ehrlich, P. R., Ehrlich, A. H., & Matson, P. A. (1986). Human appropriation of the products of photosynthesis. *BioScience*, 36(6), 368-373. <https://doi.org/10.2307/1310258>
- Wang, H., Liu, G., Li, Z., Wang, P., & Wang, Z. (2018). Assessing the driving forces in vegetation dynamics using net primary productivity as the indicator: A case study in Jinghe river basin in the Loess Plateau. *Forests*, 9(7), 374. <https://doi.org/10.3390/f9070374>
- Weltzin, J. F., Loik, M. E., Schwinning, S., Williams, D. G., Fay, P. A., Haddad, B. M., ... & Pockman, W. T. (2003). Assessing the response of terrestrial ecosystems to potential changes in precipitation. *Bioscience*, 53(10), 941-952. [https://doi.org/10.1641/0006-3568\(2003\)053\[0941:ATROTE\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2003)053[0941:ATROTE]2.0.CO;2)
- Wessels, K. J., Prince, S. D., Malherbe, J., Small, J., Frost, P. E., & VanZyl, D. (2007). Can human-induced land degradation be distinguished from the effects of rainfall variability? A case study in South Africa. *Journal of Arid Environments*, 68(2), 271-297. <https://doi.org/10.1016/j.jaridenv.2006.05.015>
- Wilson, R. T. (1997). Livestock, pastures, and the environment in the Kyrgyz Republic, central Asia. *Mountain Research and Development*, 57-68. <https://doi.org/10.2307/3673914>
- WorldBank. (2017a) Kyrgyzstan; Population; (<https://data.worldbank.org/indicator/SP.POP.TOTL?end=2017&-locations=KG&start=1960&view=chart>)

- Xu, H. J. , Wang, X. P. , & Yang, T. B. . (2017). Trend shifts in satellite-derived vegetation growth in central eurasia, 1982–2013. *Science of The Total Environment*, 579, 1658-1674. <https://doi.org/10.1016/j.scitotenv.2016.11.182>
- Xu, H. J., Wang, X. P., & Zhang, X. X. (2016). Decreased vegetation growth in response to summer drought in Central Asia from 2000 to 2012. *International journal of applied earth observation and geoinformation*, 52, 390-402. <https://doi.org/10.1016/j.jag.2016.07.010>
- Xu, L., Tu, Z., Zhou, Y., & Yu, G. (2018). Profiling Human-Induced Vegetation Change in the Horqin Sandy Land of China Using Time Series Datasets. *Sustainability*, 10(4), 1068. <https://doi.org/10.3390/su10041068>
- Xu, W., Gu, S., Zhao, X., Xiao, J., Tang, Y., Fang, J., ... & Jiang, S. (2011). High positive correlation between soil temperature and NDVI from 1982 to 2006 in alpine meadow of the Three-River Source Region on the Qinghai-Tibetan Plateau. *International Journal of Applied Earth Observation and Geoinformation*, 13(4), 528-535. <https://doi.org/10.1016/j.jag.2011.02.001>
- Xu, Z., & Zhao, M. (2001). Influence of overgrazing on soil erosion of grassland. *Grassland of China*, (6), 59-63.
- Yang, J., Zhang, X., Luo, Z., & Yu, X. (2017). Nonlinear variations of net primary productivity and its relationship with climate and vegetation phenology, China. *Forests*, 8(10), 361. <https://doi.org/10.3390/f8100361>
- Yong-Zhong, S., Yu-Lin, L., Jian-Yuan, C., & Wen-Zhi, Z. (2005). Influences of continuous grazing and livestock exclusion on soil properties in a degraded sandy grassland, Inner Mongolia, northern China. *Catena*, 59(3), 267-278. <https://doi.org/10.1016/j.catena.2004.09.001>
- Zeppel, M. J. B. , Wilks, J. V. , & Lewis, J. D. . (2014). Impacts of extreme precipitation and seasonal changes in precipitation on plants. *Biogeosciences*, 11(11), 3083-3093. <https://doi.org/10.5194/bg-11-3083-2014>
- Zhang, C., Lu, D., Chen, X., Zhang, Y., Maisupova, B., & Tao, Y. (2016). The spatiotemporal patterns of vegetation coverage and biomass of the temperate deserts in Central Asia and their relationships with climate controls. *Remote Sensing of Environment*, 175, 271-281. <https://doi.org/10.1016/j.rse.2016.01.002>
- Zhang, C., & Ren, W. (2017). Complex climatic and CO2 controls on net primary productivity of temperate dryland ecosystems over central Asia during 1980–2014. *Journal of Geophysical Research: Biogeosciences*, 122(9), 2356-2374. <https://doi.org/10.1002/2017JG003781>
- Zhang, Y., Pan, Y., Zhang, X., Wu, J., Yu, C., Li, M., & Wu, J. (2018). Patterns and dynamics of the human appropriation of net primary production and its components in Tibet. *Journal of environmental management*, 210, 280-289. <https://doi.org/10.1016/j.jenvman.2018.01.039>
- Zhang, Y., Song, C., Zhang, K., Cheng, X., & Zhang, Q. (2013). Spatial–temporal variability of terrestrial vegetation productivity in the Yangtze River Basin during 2000–2009. *Journal of Plant Ecology*, 7(1), 10-23. <https://doi.org/10.1093/jpe/rtt025>
- Zhang, Y., Xu, M., Chen, H., & Adams, J. (2009). Global pattern of NPP to GPP ratio derived from MODIS data: effects of ecosystem type, geographical location and climate. *Global Ecology and Biogeography*, 18(3), 280-290. <https://doi.org/10.1111/j.1466-8238.2008.00442.x>
- Zhao, M., Heinsch, F. A., Nemani, R. R., & Running, S. W. (2005). Improvements of the MODIS terrestrial gross and net primary production global data set. *Remote sensing of Environment*, 95(2), 164-176. <https://doi.org/10.1016/j.rse.2004.12.011>
- Zhao, M., Running, S. W., & Nemani, R. R. (2006). Sensitivity of Moderate Resolution Imaging Spectroradiometer (MODIS) terrestrial primary production to the accuracy of meteorological reanalyses. *Journal of Geophysical Research: Biogeosciences*, 111(G1). <https://doi.org/10.1029/2004JG000004>
- Zhao, M., & Running, S. W. (2010). Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science*, 329(5994), 940-943. <https://doi.org/10.1126/science.1192666>
- Zhou, G. S. , Wang, Y. H. , Jiang, Y. L. , & Xu, Z. Z. . (2002). Carbon balance along the northeast china transect

909 (nect-igbp). *Science in China*, 45(S1), 18-29. <https://doi.org/10.3969/j.issn.1674-7305.2002.z1.004>

910 Zhou, G., & Zhang, X. (1995). A natural vegetation NPP model. *Acta Phytoecological Sinica*, 19(3), 193-200.

911 Zhou, G., & Zhang, X. (1996). Study on NPP of natural vegetation in China under global climate change. *Acta*

912 *Phytoecological Sinica*, 20(1), 11-19.

913 Zhou, Y., Zhang, L., Xiao, J., Williams, C. A., Vitkovskaya, I., & Bao, A. (2019). Spatiotemporal transition of

914 institutional and socioeconomic impacts on vegetation productivity in Central Asia over last three decades.

915 *Science of the Total Environment*, 658, 922-935. <https://doi.org/10.1016/j.scitotenv.2018.12.155>

916 Zhumanova, M., Männig, C., Hergarten, C., Darr, D., & Wrage-Männig, N. (2018). Assessment of vegetation

917 degradation in mountainous pastures of the Western Tien-Shan, Kyrgyzstan, using eMODIS NDVI.

918 *Ecological indicators*, 95, 527-543. <https://doi.org/10.1016/j.ecolind.2018.07.060>