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Disentangling the relative impacts of climate change and human activities on arid and semiarid grasslands in Central Asia during 1982–2015

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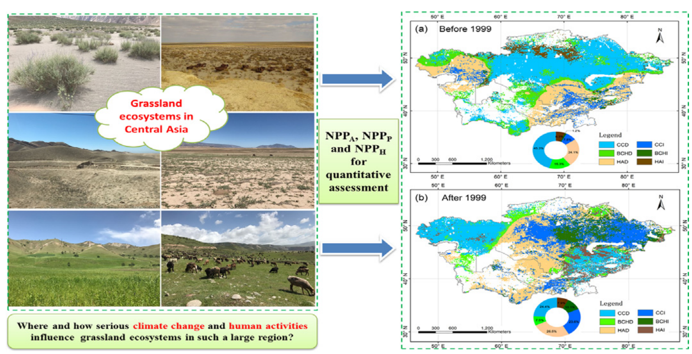
HIGHLIGHTS

- The relative impacts of climate change and human activities on grassland dynamics in Central Asia were studied.
- The change point of grassland NPP occurred in 1999.
- Precipitation was the main climatic factor controlling grassland dynamics in most areas of Central Asia.
- Human activities accelerated grassland degradation in Uzbekistan and Turkmenistan in the last three decades.
- Overgrazing was the main form of human activity accelerating grassland degradation.

GRAPHICAL ABSTRACT



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ABSTRACT

In recent decades, climate change and human activities have severely affected grasslands in Central Asia. Grassland regulation and sustainability in this region require an accurate assessment of the effects of these two factors on grasslands. Based on the abrupt change analysis, linear regression analysis and net primary productivity (NPP), the spatiotemporal patterns of grassland ecosystems in Central Asia during 1982–2015 were studied. Further, the potential NPP (NPP_P) was estimated using the Thornthwaite Memorial model and the human-induced NPP (NPP_H), which was the difference between NPP_P and actual NPP, were used to differentiate the effects of climate change and human activities on the grassland ecosystems, respectively. The grassland NPP showed a slight upward trend during 1982–2015, while two obvious decreasing periods were found before and after the mutation year 1999. Additionally, the main driving forces of the grassland NPP variation for the two periods were different. During 1982–1999, climate change was the main factor controlling grassland NPP increase or decrease, and 84.7% of grasslands experienced NPP reduction, while the regions experiencing an increase represented only 15.3% of the total area. During 1999–2015, the areas of increasing and decreasing grassland NPP represented 41.6% and 58.4% of the total area, respectively. After 1999, human activities became the main driving force of the NPP reduction, whereas climate change facilitated grassland restoration. The five Central Asian countries showed widely divergent relative impacts of climate change and human activities on NPP changes. In Uzbekistan and Turkmenistan, anthropogenic decreases in grassland NPP intensified during 1982–2015, while the negative anthropogenic effects on grassland NPP in Kyrgyzstan and Tajikistan moderated. Further analysis identified

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precipitation as the major climatic factor affecting grassland variation in most areas of Central Asia and overgrazing as the main form of human activity accelerating grassland degradation. This study improves the understanding of the relative impacts of climate change and human activities on grasslands in Central Asia.

1. Introduction

Terrestrial ecosystems have undergone dramatic changes, including changes in climate, atmospheric composition, and land-use management, during the past several decades (Stocker et al., 2014). The serious changes in global and regional terrestrial ecosystems are the consequences of both climate change and anthropogenic activities (Esser, 1987; Haberl, 1997). At present, terrestrial ecosystem dynamics can be accurately monitored to some extent, but it is difficult to directly discern the driving factors and their individual contributions to the terrestrial ecosystem changes (Fensholt et al., 2012; Wessels et al., 2007). Particularly in semiarid and arid ecosystems, intensified climate change and human activities could easily result in ecological degradation and significant ecological and economic losses (Wessels et al., 2008). Thus, accurate assessment and separation of the respective contributions of climate change and anthropogenic activities to the ecosystem changes are important for ecological management and regulation (Aldous et al., 2011; Dirnböck et al., 2003). As one of the most important terrestrial ecosystems, the grassland ecosystem accounts for nearly 30% of the Earth's land surface (Houghton, 1994). In addition, the grassland ecosystem is an important carbon reservoir that accounts for approximately 20% of the global soil carbon stock and plays an important role in global carbon cycles (Ahlström et al., 2015; Wang et al., 2008).

Central Asia is located in the hinterland of the Eurasian continent and has a fragile and vulnerable terrestrial ecosystem. Grassland is the most widespread land cover type in Central Asia, where it serves as a global carbon sink and is highly related to ecological security and social stability. Moreover, the grassland ecosystem in this region is sensitive to global climate change and anthropogenic activities due to its relatively sparse vegetation and infertile soil (Huang et al., 2016; Lioubimtseva and Henebry, 2009; Seddon et al., 2016). Previous research reported that grasslands in Central Asia were undergoing degradation and desertification due to intensifying climate change and human activities (Xi and Sokolik, 2015; Zhang et al., 2017). In general, the effect of climate change on terrestrial ecosystems mainly occurs through changes in temperature and precipitation (Byrne et al., 2017; Lehnert et al., 2016). Over the past three decades, temperatures throughout Central Asia showed a significantly increasing trend with a rate of 0.4 $°C\ 10a^{-1}$, which is higher than the average of the Northern Hemisphere (0.3 $°C\ 10a^{-1}$), and severe droughts occurred in Central Asia during the same period (Hu et al., 2014). Precipitation showed a slightly decreasing trend with strong spatial heterogeneity and significant inter-annual changes (Beurs et al., 2009; Gessner et al., 2013), although many uncertainties still exist in precipitation assessment. In addition to the climate change impacts on ecosystems in this region, due to the political and socio-economic instability of the Soviet Union, the ecosystems of this region are susceptible to human disturbances, such as land use and land cover change and overgrazing (Zhou et al., 2015). During the period of the Soviet Union, a large number of grasslands in northern Kazakhstan were converted to farmland, while these croplands were abandoned owing to the decrease in the population after the collapse of the Soviet Union. In addition, grazing activities and livestock numbers have had significant impacts on grasslands in this region since 1990 (Karnieli et al., 2008). Therefore, this region is ideal for distinguishing the impacts of climate change and human activity on grassland ecosystems. However, the potential effects of climate change and human activities on vegetation variations, especially in grasslands, remain uncertain (Boles et al., 2004; Lioubimtseva et al., 2005). Moreover, an accurate assessment of the carbon budget in Central Asia has great uncertainty (Ahlström et al., 2015). Thus, an objective and quantitative method is urgently needed to separate and monitor the relative impacts of climate change and human activities on grassland variation in such a large region.

In recent decades, numerous quantitative assessment methods have been employed to assess the relative roles of climate change and human activities on grassland ecosystems, such as partial derivatives analysis (Y. Zhang et al., 2016), multiple variable analysis (Li et al., 2018) and principal component analysis (Ma et al., 2007). However, these methods are primarily based on statistical analysis and assess the relative importance of climate change and human activities on grassland ecosystems by regression coefficients and variance rates while ignoring the true ecological significance, thereby easily resulting in uncertainties in the estimated results (Ma et al., 2007). Recently, some studies have used remotely sensed indices to identify climatic and anthropogenic influences on grassland dynamics in semiarid and arid regions, such as the normalized difference vegetation index (NDVI)-based residual trend (RESTREND) method (Li et al., 2012). However, there are still uncertainties associated with this method, and the effects of climate and human factors on ecosystems still cannot be fully distinguished (Chen et al., 2014). Net primary productivity (NPP) is defined as total photosynthesis minus losses due to vegetation respiration (Field, 1998) and is a robust indicator of ecosystem function and ecosystem health. Moreover, NPP, as a sensitive indicator of both climate change and human activities, has been widely used to differentiate climatic and anthropogenic influences on ecosystems (Schimel, 1995; Wessels et al., 2008; Zheng et al., 2006). In addition, based on NPP, an objective and quantitative method was developed in a previous study (Xu et al., 2010) that has been successfully used to assess and distinguish the effects of climate change and human activities on grassland ecosystems in many regions, such as Africa (Ugbaje et al., 2016), the Tibetan Plateau (Xu et al., 2016) and northwest China (Zhang et al., 2018). NPP reflects not only the scope of vegetation changes but also the degree of variation in vegetation or ecosystem carbon sequestration. Therefore, this method based on NPP variation may help explore the mechanism underlying vegetation change. Unfortunately, no reports have used this method to quantitatively assess and separate the individual effects of climatic and human factors on grasslands in Central Asia. To solve this problem, our work seeks to employ the method based on NPP to quantitatively identify the driving forces of grassland variation in Central Asia. Although many previous studies in Central Asia have analysed the spatial and temporal variation in grassland ecosystems and the relationship between grassland NPP and climatic factors (Li et al., 2015a; Propastin, 2008; C. Zhang et al., 2016; Zhang and Ren, 2017), those studies ignored the influences of human activities. Some studies estimated the effects of only grazing on grassland NPP variations, but the impacts of gazing on grassland changes under climate change are still unclear in this region (Han et al., 2016). Thus, there is a gap in the knowledge of where and the degree to which climate change and human activities influence grassland variations in this region.

Therefore, this paper aims to (1) explore the spatial and temporal variation in grassland NPP in Central Asia from 1982 to 2015; (2) quantitatively distinguish and assess the relative impacts of climate change and human activities on grassland variations; and (3) analyse the main driving forces of grassland dynamics in different time periods. We used a remote sensing-based model and a climate-driven model to estimate the actual NPP (NPP_A) and potential NPP (NPP_P),

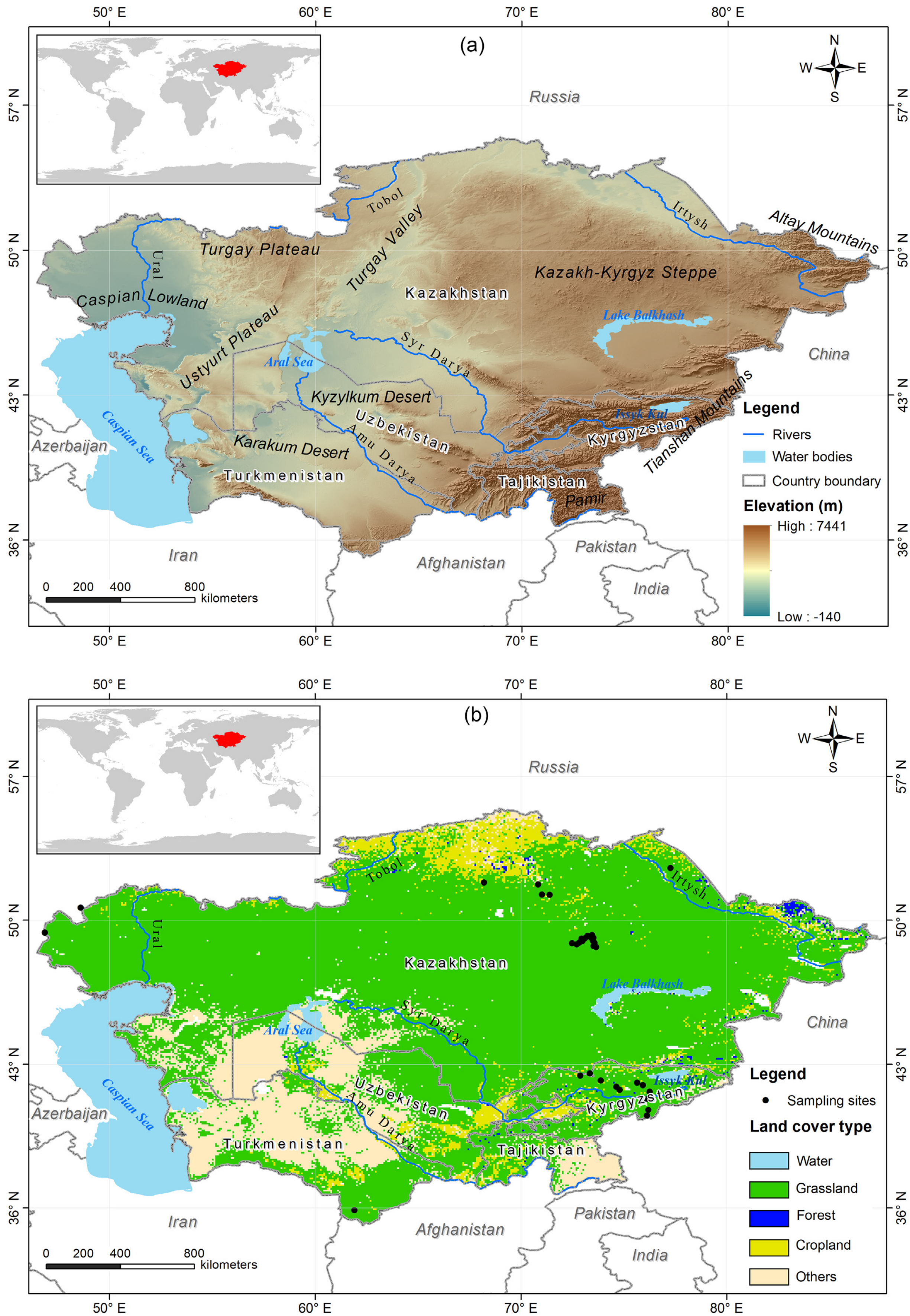

Fig. 1. Map showing the location of Central Asia and the spatial pattern of elevation (a) and the main types of land cover and spatial distribution of sampling sites throughout Central Asia (b).

respectively, and the human-induced NPP (NPP_H) was then calculated as the difference between the NPP_P and NPP_A. Six scenarios were considered in this study. By comparing the trends of NPP_P and NPP_H and interpreting them with respect to the six scenarios, we can differentiate the contributions of climatic and human factors to grassland variations. These results may provide reliable information for pastoral management and prevention of grassland degradation and desertification in Central Asia.

2. Materials and methods

2.1. Study area

Central Asia is situated in the middle Eurasia continent, where it borders China to the southeast, Russia to the north, and the Caspian Sea to the west, covers a latitudinal range of 35.13–55.44°N and a longitudinal range of 46.50–87.32°E, and consists of five independent countries: Kazakhstan, Uzbekistan, Tajikistan, Turkmenistan and Kyrgyzstan (Fig. 1a). The elevation gradually increases from the coast of the Caspian Sea in western Uzbekistan and Kazakhstan to the Altai Mountains of eastern Kazakhstan and across the Pamir Mountains and Tianshan Mountains in Tajikistan and Kyrgyzstan (de Beurs et al., 2015). This region is characterized by a temperate continental climate with hot summers and cold winters (Lioubimtseva et al., 2005). Long-term climate observations showed a 1.6 °C increase in temperature in the arid zone of Central Asia over the past century (Chen et al., 2012). The mean annual temperature ranges from 2 °C in northern Kazakhstan to >18 °C in Turkmenistan and southern Uzbekistan, and the annual average temperature of the mountainous regions and hills is below 0 °C (Mohammat et al., 2013). Mean annual precipitation is approximately 400 mm in northern Kazakhstan and below 100 mm in northern Turkmenistan and southern Uzbekistan, except in the mountainous areas, where precipitation is between 600 mm and 800 mm (Klein et al., 2012). Due to these unique climatic conditions, the main vegetation types in Central Asia are grassland (74.4%), cropland (6.7%), and forest (0.5%), with other land cover types including bare land, water body, etc., accounting for 18.4% (Fig. 1b).

2.2. Data sources

The datasets used in this study were mainly for model input, including NDVI data, gridded meteorological data, and grassland land cover data.

The latest version of the $NDVI3_g$ dataset produced by the Global Inventory Modeling and Mapping Studies (GIMMS) group using NOAA/AVHRR series satellites was used in this study (Tucker et al., 1994). The dataset was downloaded from the Ecological Forecasting Lab (ECOCAST) at the NASA Ames Research Center and spanned a time period of 1982–2015. The spatial and temporal resolution of the GIMMS $NDVI_{3g}$ dataset is 0.083° and half a month, respectively. This dataset has been corrected to decrease the noise resulting from calibration, volcanic eruptions, orbital drift and viewing geometry differences between the AVHRR/2 and AVHRR/3 instruments (Eastman et al., 2013; Pinzon and Tucker, 2014). To further remove the contamination by clouds, sandstorms, and haze, the monthly NDVI time series data were composited from biweekly time series data based on the maximum value composite (MVC) method (Holben, 1986).

Monthly precipitation, air temperature, and solar radiation data were extracted from the Climate Research Unit (CRU) version TS4.01 datasets, which have a 0.5° × 0.5° resolution and are available from 1901 to 2015 at the University of East Anglia. Recent studies (Guo et al., 2018; Li et al., 2015a; Miao et al., 2015; Poulter et al., 2014) have proven that the CRU dataset can capture real climatic conditions and be applicable and satisfactory for ecological and climatological studies in Central Asia.

The MODIS land cover product (MCD12Q1, V051) was obtained from the MODIS Land website and used to determine the grassland areas. The MCD12Q1 classifies the land cover into 17 sub-classes according to the definitions of the International Geosphere-Biosphere Programme (IGBP) land cover classification system. In our study, the class numbers 6 to 10 including open shrublands, savannas, and grasslands were extracted as a single grassland category (Yang et al., 2016). To avoid the impacts of other land cover types on the grassland, only grids with constant grassland type were selected as the grassland mask in this study (Forzieri et al., 2017).

To match the spatial resolution of the NDVI data, all the datasets were resampled to a resolution of 8 km based on the bilinear interpolation method (Chao et al., 2018).

2.3. Methods

2.3.1. Calculation of NPP_A, NPP_P, and NPP_H

To identify the impacts of climate change and human activities on grassland change, three kinds of NPP are defined: the NPP_A represents the real condition of grassland NPP and is calculated by using the Carnegie-Ames-Stanford Approach (CASA) model. NPP_P reflects the climate-driven state of grassland NPP and is calculated from the Thornthwaite Memorial model. The third type is NPP_H, which is defined as the difference between the NPP_P and the NPP_A, reflecting the loss of grassland NPP caused by human activities (Eq. (1)) (Xu et al., 2010).

$$NPP_H = NPP_P - NPP_A \tag{1}$$

In this study, monthly NPP_A was produced based on the CASA model. The CASA model is a light use efficiency model that uses remote sensing data, meteorological data and vegetation types as the input parameters. In the CASA model, the estimated NPP can be expressed by two factors: the absorbed photosynthetically active radiation (APAR) and the actual utilization of light energy (ε) (Eq. (2)) (Potter et al., 1993).

$$NPP_A(x,t) = APAR(x,t) \times \varepsilon(x,t) \tag{2}$$

$$APAR(x,t) = SOL(x,t) \times FPAR(x,t) \times 0.5 \tag{3}$$

$$\varepsilon(x,t) = T_1(x,t) \times T_2(x,t) \times \varepsilon^* \tag{4}$$

where x is the pixel location, and t is the time (in months). $APAR$ (x, t) represents the photosynthetically active radiation absorbed by the canopy of vegetation at pixel x in month t (MJ m^{-2}) (Eq. (3)). $\varepsilon(x,t)$ is the actual light use efficiency of pixel x in month t (g C MJ^{-1}) (Eq. (4)). SOL (x, t) represents the total monthly solar radiation at pixel x in month t (MJ m^{-2}); $FPAR$ (x, t) is the fraction of photosynthetically active radiation absorbed by the canopy of the vegetation of pixel x in month t; the constant value 0.5 denotes the ratio of photosynthetically active solar radiation to total solar radiation available for vegetation (0.37–0.71 μm); $T_1(x,t)$ and $T_2(x,t)$ denote the stress effects on light use efficiency at low temperature and high temperature, respectively; $W(x,t)$ is the coefficient of the effect of water stress; and ε^* is the maximum light use efficiency under ideal conditions (g C MJ^{-1}). Here, the ε^* of grasslands in Central Asia was set to 0.604 g C MJ^{-1} (Running et al., 2000), and more detailed information on the CASA model was provided by Yu et al. (2009, 2011).

The accuracy of NPP_A should be validated by measured NPP observations. Therefore, 32 sites from previous studies (Jiao et al., 2017; Propastin et al., 2012; C. Zhang et al., 2016) were used to directly validate the results of the CASA model. However, 32 is a small number of sites, and the sites were uneven, which may prevent detection of the spatial pattern of NPP. Thus, the remote-sensing MODIS NPP products were also included for further validation. Here, the yearly 500 m MODIS NPP dataset (MOD17A3H) from the Land Processes Distributed Active Archive Center (LP DAAC) was used to indirectly validate the CASA-estimated NPP during 2000–2014 at the pixel scale. To maintain consistency with the estimated NPP, the original MODIS NPP dataset was resampled from 500 m to 8 km.

NPP_P was calculated by the Thornthwaite Memorial model (Lieth and Box, 1972), which is driven by precipitation and temperature data. The Thornthwaite Memorial model was established based on the Miami model by incorporating Thornthwaite potential evaporation (Lieth, 1975). The Thornthwaite Memorial model can be used to calculate NPP_P as follows:

$$NPP_P = 3000\left[1-e^{-0.0009695(v-20)}\right] \tag{5}$$

$$V = \frac{1.05r}{\sqrt{1+(1+1.05r/L)^2}} \tag{6}$$

$$L = 3000 + 25t + 0.05t^3 \tag{7}$$

where NPP_P is the annual potential NPP (g C m^{-2} yr^{-1}); V is the annual actual evapotranspiration (mm); L represents the annual average evapotranspiration (mm); t is the annual average temperature (°C), and r indicates the annual precipitation (mm).

2.3.2. Abrupt change analysis

To check for potential switches in grassland NPP trends during 1982–2015, the non-parametric Mann-Kendall (M-K) test (Kendall, 1955; Mann, 1945) was adopted for change-point detection. In addition, the Pettitt test (Pettitt, 1979) was employed to validate the results from the M-K test. The Pettitt test is also a non-parametric test and has been widely used to detect change points in environmental and hydrological data (Bastia and Equeenuddin, 2016; Ma et al., 2008; Song et al., 2018). The Pettitt test uses the Mann-Whitney test statistic and divides the time series $(x_1, x_2, \ldots, x_n)$ into two sample sets, namely, $(x_1, x_2, \ldots, x_\tau)$ and $(x_{\tau+1}, x_{\tau+2}, \ldots, x_n)$, at time τ, as seen in Eqs. (8) and (9).

$$k_\tau = \sum_{i=1}^{\tau}\sum_{j=1}^{n} \operatorname{sgn}(x_i - x_j) \tag{8}$$

$$\operatorname{sgn}(x_i - x_j) = \begin{cases} 1 & if(xi-xj)>0 \\ 0 & if(xi-xj)=0 \\ -1 & if(xi-xj)<0 \end{cases} \tag{9}$$

where k_τ is the test statistic, and the abrupt change point most likely occurs during the time when the absolute value of τ reaches its maximum. The statistic K and relative probabilities (p) are used to test the significance of the abrupt change. The formulas of K and p are expressed as Eqs. (10) and (11), respectively.

$$K = \max_{1\le\tau\le n}|k_\tau| \tag{10}$$

$$p \approx 2\times \exp\left(\frac{-6K^2}{n^3+n^2}\right) \tag{11}$$

A significance level of 5% is used in the Pettitt test. A significant change point occurs when $p < 0.05$; the time series is split into two sections at the location of the abrupt change point τ.

2.3.3. Linear regression analysis

Linear regression analysis was used to detect the trend of inter-annual change in grassland NPP during 1982–2015 at the pixel scale based on least squares regression (Eq. (12)).

$$Slope = \frac{n\times\sum_{i=1}^{n}(i\times NPP_i) - \sum_{i=1}^{n} i\times\sum_{i=1}^{n} NPP_i}{n\times\sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{12}$$

where n is the number of the year, NPP_i represents the NPP in the ith year, and *Slope* is the trend of change in NPP at the pixel level. The slope can be both positive and negative to represent upward and downward trends, respectively.

In addition, the Pearson correlation coefficient was calculated by using linear regression to detect the relationship between NPP and climatic factors (precipitation and temperature). The significance of the coefficient was tested using Student's t-test at the 5% level (p).

2.3.4. Establishing scenarios and quantitative assessment method

The relative effects of climate change and human activities on grassland variations were assessed and separated by comparing the slopes of NPP_A, NPP_P, and NPP_H (Xu et al., 2009). All the slopes were calculated by Eq. (12), and six scenarios were established (Table 1). A slope of NPP_A ($SNPP_A$) > 0 suggests that grassland NPP increased, and vice versa. A slope of NPP_P ($SNPP_P$) > 0 denotes that climate change facilitated an increase in grassland NPP, while an $SNPP_P$ < 0 suggests that climate change caused a reduction in grassland NPP. A slope of NPP_H ($SNPP_H$) > 0 indicates that human activities caused a decline in grassland NPP. An $SNPP_H$ < 0 shows that human activities facilitated an increase in NPP.

Under the condition of $SNPP_A > 0$, if $SNPP_P < 0$ and $SNPP_H < 0$ (Scenario 1), then climate change promoted a decrease in grassland NPP, and human activities facilitated an increase in grassland NPP. Therefore, the grassland NPP increase is caused by human activities (HAI). If $SNPP_P > 0$ and $SNPP_H < 0$ (Scenario 2), then climate change and human activities both facilitated an increase in grassland NPP. In this scenario, the grassland NPP increase is caused by both climatic and human factors (BCHI). If $SNPP_P > 0$ and $SNPP_H > 0$ (Scenario 3), then climate change promoted an increase in grassland NPP, and human activities caused a decrease in grassland NPP. Thus, the grassland NPP increase is caused by climate change (CCI).

For the condition of $SNPP_A < 0$, if $SNPP_P > 0$ and $SNPP_H > 0$ (Scenario 4), then climate change promoted an increase in grassland NPP, and human activities caused a decrease in grassland NPP. Therefore, the decrease in grassland NPP is caused by human activities (HAD). If $SNPP_P < 0$ and $SNPP_H > 0$ (Scenario 5), then the decrease in grassland NPP was caused by both climatic and human factors (BCHD). If $SNPP_P < 0$ and $SNPP_H < 0$ (Scenario 6), then climate change caused a decrease in grassland NPP, and human activities facilitated an increase in grassland NPP. In this scenario, the grassland NPP decrease is caused by climate change (CCD).

3. Results

3.1. Validation of the CASA model

To evaluate the performance of the CASA model for simulating NPP_A in Central Asia, the simulated NPP was first compared with the MODIS NPP products for the period of 2000–2014. The CASA-estimated NPP was consistent with the MODIS NPP ($R^2 = 0.67$, $p < 0.001$) (Fig. 2a). In addition, the field-measured NPP and CASA-estimated NPP were even more consistent, with an R^2 of 0.74 ($p < 0.001$) (Fig. 2b). Hence, it can be concluded that the NPP estimated by the CASA model was reliable and can be applied in the next step of the analysis in Central Asia.

3.2. Change-year detection for grassland NPP from 1982 to 2015 in Central Asia

The overall linear trend cannot accurately capture the real temporal pattern of vegetation activities over a long time period (Piao et al., 2011). To further identify the actual variation in grassland NPP throughout the period, the M-K test (Kendall, 1955; Mann, 1945) and Pettitt test (Pettitt, 1979) were used to detect the abrupt change points of the variation in grassland NPP_A at the inter-annual scale. The actual periods of grassland NPP_A changes are crucial for further analysing the real contributions of different drivers at different stages. The abrupt change points

Table 1
Six scenarios were used to identify the reasons for NPP_A change. $SNPP_A$, $SNPP_P$, and $SNPP_H$ represent the slope of NPP_A, NPP_P, and NPP_H in each pixel, respectively.

Hypothesis	Scenario	$SNPP_P$	$SNPP_H$	Relative roles of climate change and human activities
$SNPP_A > 0$	Scenario 1	−	−	Human activities induced an NPP_A increase (HAI)
	Scenario 2	+	−	Both climatic and human factors induced an NPP_A increase (BCHI)
	Scenario 3	+	+	Climate change induced an NPP_A increase (CCI)
$SNPP_A < 0$	Scenario 4	+	+	Human activities caused an NPP_A decrease (HAD)
	Scenario 5	−	+	Both climatic and human factors induced an NPP_A decrease (BCHD)
	Scenario 6	−	−	Climate change induced an NPP_A decrease (CCD)

of grassland NPP_A during 1982–2015 were first detected using the M-K method (Fig. 3a). Several abrupt change points were found in approximately 1990 and in 1999. Given that false change points may be detected in results of the M-K test, the Pettitt test, a single change point-detection method, was further used to detect and validate the results of the M-K test. One abrupt change point was observed in 1999 at the 5% significance level when using the Pettitt test (Fig. 3b). Based on the results of these two methods, the change year for NPP_A in Central Asia was determined to be 1999 (Fig. 3a and b). Based on this change year, the grassland NPP_A time series (1982–2015) was divided into two periods: 1982–1999 and 1999–2015.

3.3. The spatiotemporal trends in NPP_A, NPP_P, and NPP_H

The results revealed that the mean annual NPP_A of grasslands in Central Asia was 181.9 g C m^{-2} yr^{-1}, the highest NPP was generated in 2002 (201.8 g C m^{-2} yr^{-1}), and the lowest value of 130.4 g C m^{-2} yr^{-1} occurred in 1997 (Fig. 4a). NPP_A showed a slight but nonsignificant uptrend at a rate of 0.18 g C m^{-2} yr^{-1} from 1982 to 2015 ($p = 0.430$). When the time series was divided into two phases based on the result of change-year detection, a significant downward trend with a rate of approximately −1.31 g C m^{-2} yr^{-1} ($p = 0.028$) appeared in the first period (1982–1999) (Fig. 4a), mainly occurring in the Kazakh-Kyrgyz Steppe, Turgay Valley and Turgay Plateau of Kazakhstan, the Kyzylkum Desert of Uzbekistan and the Karakum Desert of Turkmenistan, but the NPP_A during this time period exhibited a small increasing trend in the Caspian lowland, northern Kazakhstan plain and mountainous regions of Kyrgyzstan (Fig. 5a). From 1999 to 2015, the NPP_A decreased at a rate of approximately −0.46 g C m^{-2} yr^{-1} ($p = 0.389$) (Fig. 4a). During this period, NPP_A showed decreasing trends mainly in the Caspian lowland and Turgay Plateau and along the Tobol River, while it increased in the Kazakh-Kyrgyz Steppe of Kazakhstan (Fig. 5b).

For the NPP_P of the grasslands throughout Central Asia, the results of NPP_P simulation revealed decreasing trends in the periods of 1982–1999 and 1999–2015 with rates of −0.80 g C m^{-2} yr^{-1} ($p = 0.738$) and −0.03 g C m^{-2} yr^{-1} ($p = 0.989$), respectively (Fig. 4b). From 1982 to 1999, the decreasing trends mainly appeared in the Irtysh River Valley and Turgay Valley, and increasing trends occurred in the Caspian lowland, Moyinkum Desert and mountainous regions of Tianshan and Pamir (Fig. 5c). During 1999–2015, the NPP_P in most of the areas in Kazakhstan, Uzbekistan, and Turkmenistan exhibited an increasing trend, and a decreasing trend mainly appeared in western Kazakhstan and the Tianshan Mountains (Fig. 5d).

In contrast, NPP_H showed an increasing trend with a rate of 0.51 g C m^{-2} yr^{-1} ($p = 0.822$) and 0.43 g C m^{-2} yr^{-1} ($p = 0.833$) during the periods of 1982–1999 and 1999–2015, respectively (Fig. 4c). In addition, the regions with increased or decreased NPP_H were consistent with the spatial distribution of NPP_P (Fig. 5e–f).

3.4. Relative contributions of climate change and human activities to grassland NPP change

The spatial distribution of the relative impacts of climatic and human factors to changes in grassland NPP in Central Asia was assessed and separated by using the methods listed in Table 1 and Fig. S1. During the first period (1982–1999), decreased NPP_A in most areas was due to climate change; these areas were located across Kazakhstan from the west to the east. Human activities led to a decrease in grassland NPP_A mainly in southern Kazakhstan and some parts of Tajikistan and Kyrgyzstan. The increased NPP_A was caused by climate change and mainly occurred in the Tianshan Mountains and Pamir as well as in small parts of western Kazakhstan, while human activities contributed to a small increase in grassland NPP_A in the Northern Kazakhstan Plain (Fig. 6a). During 1999–2015, climate change resulted in a decrease in NPP_A in western Kazakhstan, large parts of the Tianshan Mountains and southern Lake Balkhash and caused an increase in NPP_A in the central and eastern Kazakhstan and western Tajikistan. Decreased NPP_A induced by human activities occurred in the Karakum Desert, Kyzylkum Desert and some parts of northern Kazakhstan, whereas in the south of Kazakhstan, small areas experienced increases resulting from human activities (Fig. 6b). However, the combinations of these two factors had little effect on the changes in grassland NPP_A in these areas in the two periods, although they did have effects in transitional regions between the areas with climate-induced and human-induced changes in NPP_A.

The change in the area of grassland with increased or decreased NPP_A caused by climatic and human factors was calculated for the two periods (Table 2). During 1982–1999, the total area in which grassland

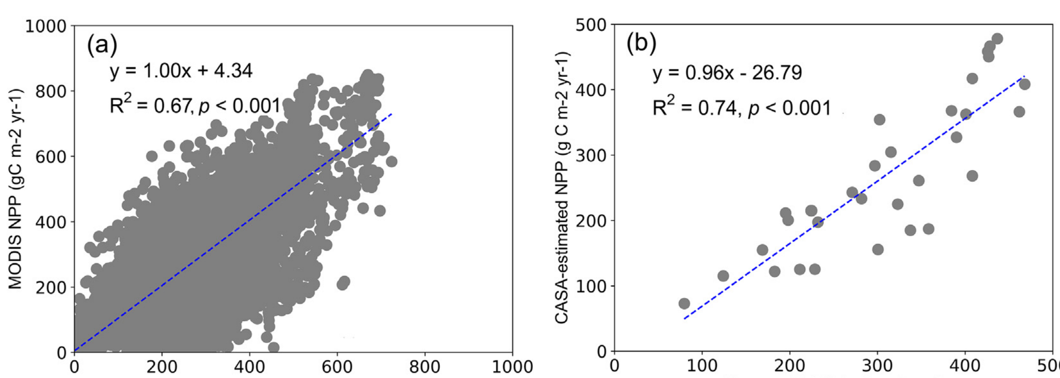

Fig. 2. (a) Scatterplot of CASA-estimated NPP and MODIS NPP and (b) scatterplot of CASA-estimated NPP and field-measured NPP.

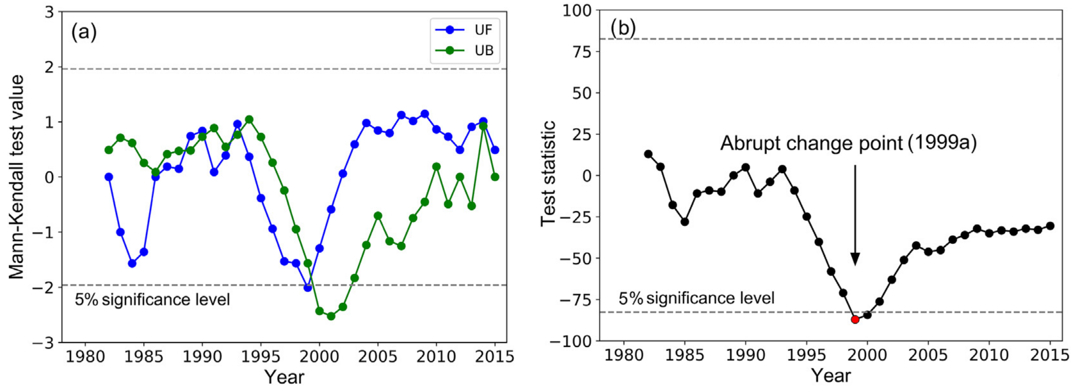

Fig. 3. Change-point detection for the NPP_A time series using a Mann-Kendall test (a) and Pettitt test (b) for 1982–2015 in Central Asia. The horizontal lines (dashed lines) denote the significance level of 5%. UF depicts the positive sequence statistics; UB depicts the inverse sequence statistics. The cross point of UF and UB represents the turning point in this time series of NPP_A (a). The black solid line depicts the test statistic for the Pettitt test (b).

NPP_A decreased accounted for 84.7% of the total study area (Fig. 6a). Of this area experiencing decreases, the area in which the decrease was caused by climate change accounted for approximately 53.5%, whereas the area in which the decrease was caused by human activities and the combination of the two factors was 28.5% and 18%, respectively (Table 2). From 1999 to 2015, the portion of the total area in which grassland NPP_A decreased was 58.4% (Fig. 6b). Human activities and climate change caused decreases in NPP_A in 45.3% and 41.8% of the total area, respectively, and the remaining area (12.9%) experienced decreases attributable to the combination of the two factors (Table 2). In all, the area in which grassland NPP_A decreased in Central Asia was larger than the area in which it increased during the two periods. However, climate change was the main driver of the decrease in grassland NPP_A in 1982–1999, whereas human activities primarily influenced the decrease in grassland NPP_A in 1999–2015.

The area in which NPP_A increased was 15.3% and 41.6% of the total study area in the first and second periods, respectively (Fig. 6a and b). During the first period, climate change caused the increase in NPP_A in 51.0% of the total area exhibiting an increase, which is more than the area influenced by human activities (41.4%) or both factors (7.6%) (Table 2). During the second period, climate change caused the increase in NPP_A in 56.7% of the total area exhibiting an increase, and human activities and both factors caused the increase in grassland NPP_A in 19.0% and 24.3% of the area with such increases, respectively (Table 2). Overall, unlike the driving force of reductions in grassland NPP_A, climate change was the dominant factor affecting increases in grassland NPP_A and promoted grassland restoration in these two periods.

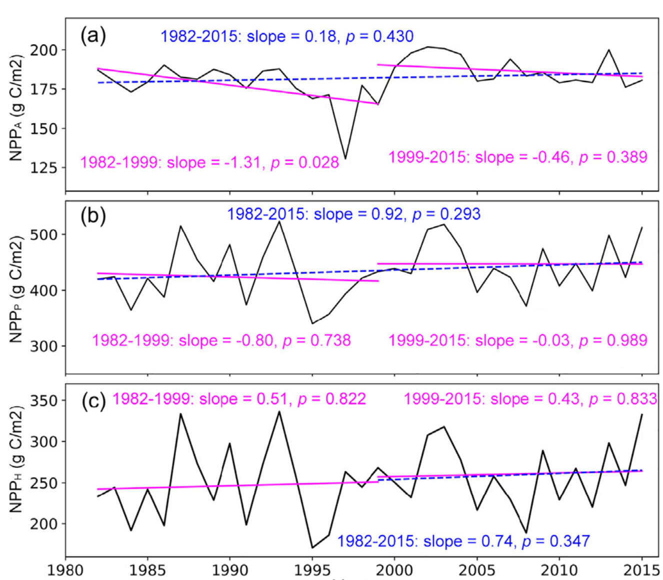

Fig. 4. Inter-annual variation in (a) CASA-simulated NPP_A, (b) Thornthwaite Memorial model-generated NPP_P, and (c) NPP_H in Central Asia from 1982 to 2015.

The relative impacts of climate change and human activities on changes in grassland NPP_A in the five countries of Central Asia varied greatly. Human activities mainly caused reductions in grassland NPP in the five countries during the two periods, especially in Kyrgyzstan and Tajikistan between 1982 and 1999, where the area experiencing a decrease in NPP_A caused by human activities was 14,528 km^2 and 10,128 km^2, respectively (Fig. 7a, Table 2). In contrast, the area experiencing a reduction in NPP_A caused by human activities after 1999 was reduced in these two countries (Fig. 7b). However, the effects of human activities on reductions in grassland NPP_A in Uzbekistan (increase in the corresponding area from 45.7% to 85.5%) and Turkmenistan (increase in the corresponding area from 10.1% to 92.6%) became more intense from the first period to the second period (Fig. 7a–b, Table 2). The reasons for increases in grassland NPP_A were very different among these five countries. The effect of climate on increases in NPP_A was greater than that of human activities in Uzbekistan, Tajikistan and Kyrgyzstan in 1982–1999, especially in Tajikistan, where the area experiencing a climate-induced increase in NPP_A accounted for 99.4% (5424 km^2) of the total area experiencing an increase (Fig. 7c). For the increases in grassland NPP in 1999–2015, the area with an NPP_A increase in Kyrgyzstan mainly due to human activities accounted for 92.2% (15,008 km^2) of the total area experiencing an increase. However, for the remaining four countries, namely, Kazakhstan, Uzbekistan, Tajikistan and Turkmenistan, climate change was the dominant driving force of the NPP_A increase (Fig. 7d).

4. Discussion

4.1. Climatic factors as dominant drivers of grassland NPP

In arid and semiarid regions, the fragile ecosystems are extremely sensitive to climate change (Lioubimtseva, 2004). Climate change could directly influence the vegetation growth in such regions because the changes in temperature and precipitation can determine the hydrothermal conditions of vegetation growth, especially for dryland ecosystems (Li et al., 2015b). Our results showed that the percentage of CCI increased from 7.8% to 23.6% and the percentage of CCD decreased from 45.3% to 24.4% during the first and second periods, respectively (Fig. 6a and b). This pattern suggests that climatic factors play a crucial role in grassland NPP dynamics in Central Asia.

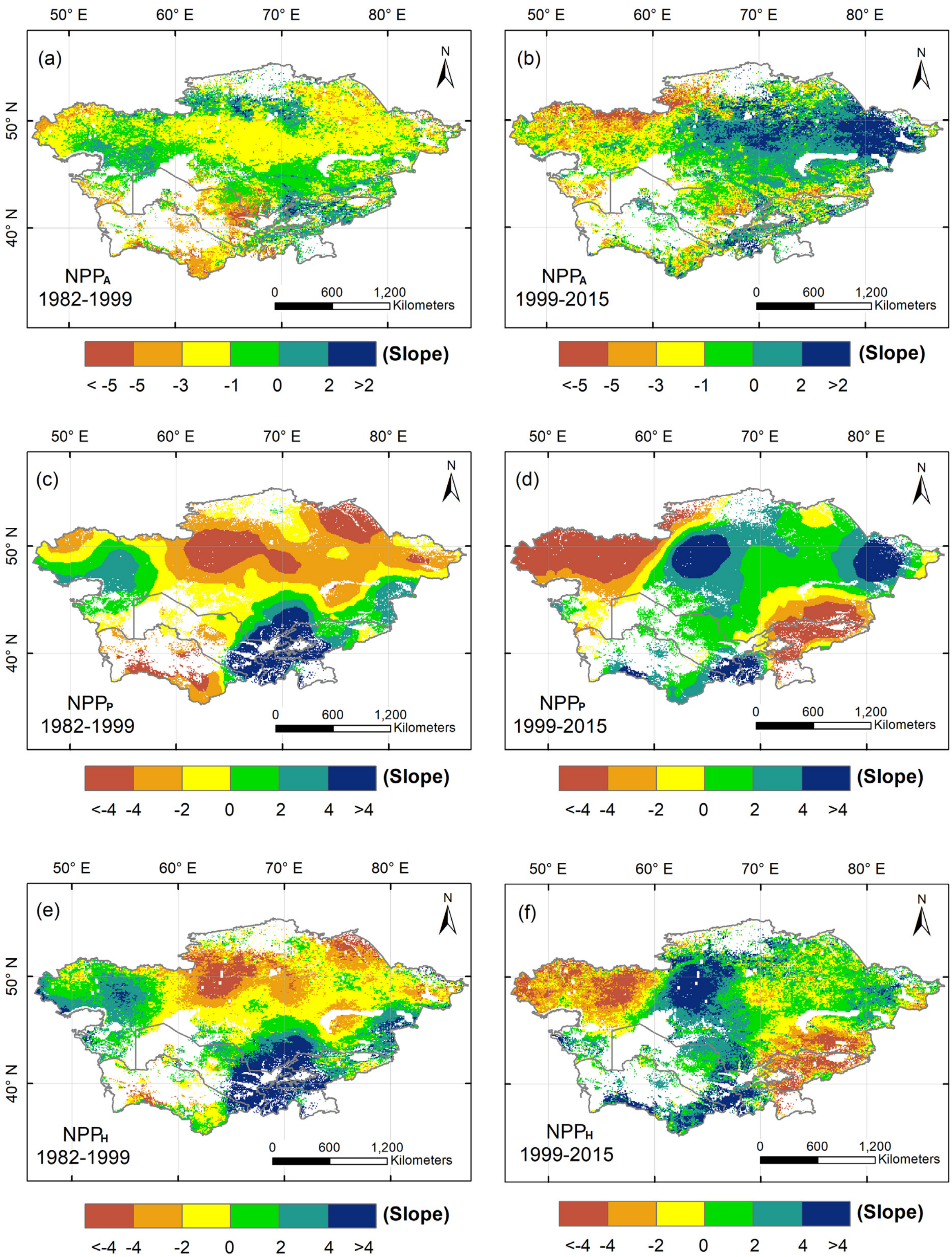

Fig. 5. The spatial distribution of trends in annual grassland NPP change in Central Asia during the periods of 1982–1999 and 1999–2015. (a) and (b) show the trend of NPP_A from 1982 to 1999 and from 1999 to 2015, respectively; (c) and (d) show the trend of NPP_P from 1982 to 1999 and from 1999 to 2015, respectively; (e) and (f) show the trend of NPP_H from 1982 to 1999 and from 1999 to 2015, respectively.

The spatial distributions of precipitation and temperature shifted significantly in the change year of 1999. Precipitation in most areas showed a decreasing trend before 1999, but it showed an uptrend after 1999 in all regions except western Kazakhstan and the Pamir Mountains and Tianshan Mountains (Fig. 8a and b). Temperature also displayed different trends before and after 1999 in most regions (Fig. 8c and d). For the climate-dominated regions, the grassland NPP displayed a decreasing trend with decreasing precipitation and increasing temperature. However, an increase

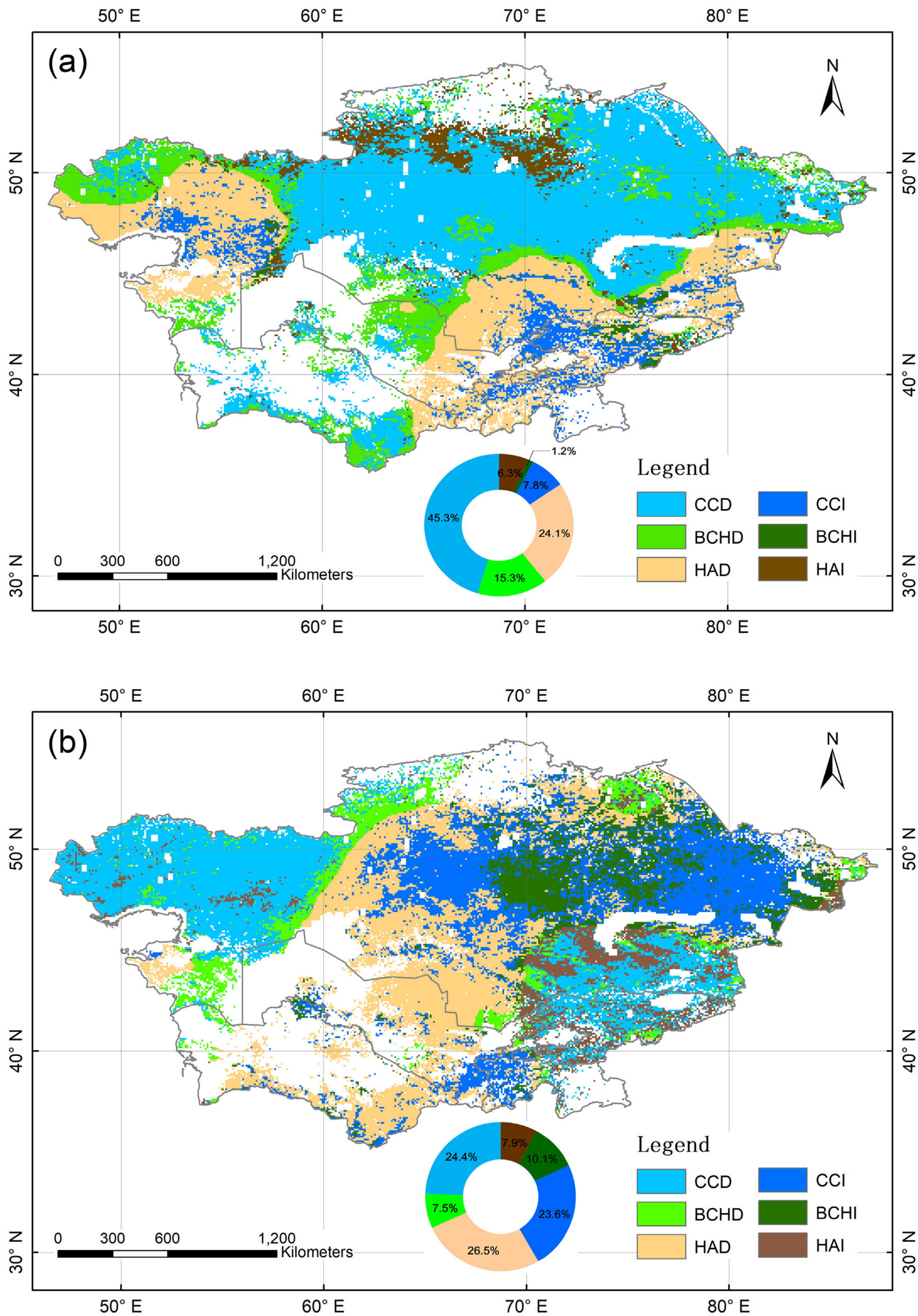

Fig. 6. Spatial distribution of relative effects of climate change and human activities on grassland NPP_A changes in different scenarios during the two periods of 1982–1999 (a) and 1999–2015 (b). HAI: NPP_A increase was induced by human activities; CCI: NPP_A increase was induced by climatic changes; BCHI: NPP_A increase was induced by both factors; HAD: NPP_A decrease was induced by human activities; CCD: NPP_A decrease was induced by climatic changes; BCHD: NPP_A decrease was induced by both factors.

in grassland NPP was recorded under the opposite patterns of precipitation and temperature. These results suggest that changes in hydrothermal conditions in these regions could determine the dynamics of grassland NPP. To better understand which climatic factor mainly controlled the change in grasslands, the correlations between grassland NPP and precipitation or temperature were further analysed.

Table 2
The percentage (%) and area (km^2) of grassland NPP increase and decrease induced by climate change, human activities, and both factors during the periods of 1982–1999 and 1999–2015.

		1982–1999						1999–2015					
		CA	KAZ	UZB	KGZ	TKM	TJK	CA	KAZ	UZB	KGZ	TKM	TJK
HAD	Area	185,680	135,296	19,152	14,528	4416	10,128	203,456	135,360	32,192	512	31,952	2736
	Percent	28.5	25.2	45.7	92.5	10.1	100.0	45.3	39.0	85.5	2.4	92.6	50.6
BCHD	Area	117,328	84,448	16,944	560	14,656	0	57,808	51,040	1776	1904	2032	736
	Percent	18.0	15.7	40.4	3.5	33.7	0.0	12.9	14.7	4.7	8.9	5.9	13.6
CCD	Area	348,384	317,456	5840	624	24,464	0	187,456	160,960	3680	18,992	528	1936
	Percent	53.5	59.1	13.9	4.0	56.2	0.0	41.8	46.3	9.8	88.7	1.5	35.8
HAI	Area	48,608	45,040	1296	1280	912	0	60,912	40,416	2272	15,008	224	2272
	Percent	41.4	55.6	18.2	5.8	72.2	0.0	19.0	14.9	19.9	92.2	2.2	22.3
BCHI	Area	8912	4336	448	3936	16	32	77,936	73,104	1104	288	2176	896
	Percent	7.6	5.4	6.3	17.9	1.2	0.6	24.3	27.0	9.7	1.8	21.2	8.8
CCI	Area	59,936	31,616	5360	16,752	336	5424	181,696	157,296	8016	976	7888	7008
	Percent	51.0	39.0	75.5	76.3	26.6	99.4	56.7	58.1	70.4	6.0	76.6	68.9

Note: CA: Central Asia; KAZ: Kazakhstan; UZB: Uzbekistan; KGZ: Kyrgyzstan; TKM: Turkmenistan; TJK: Tajikistan.

The area exhibiting positive correlation coefficients between grassland NPP and precipitation in Central Asia during the first and second periods accounted for 92.08% and 92.51% of the total area, respectively. The correlation was significant ($p < 0.05$) for approximately 48.99% and 45.97% of this area (Fig. 9a and b). In contrast, the area in which grassland NPP was negatively correlated with precipitation accounted for only 7.92% and 7.49% of the study area during the first and second periods, respectively, and was mainly distributed in mountainous regions (Fig. 9a and b). The significant positive correlations suggest that grassland NPP was sensitive to the variation in precipitation and confirmed that precipitation could be the major climatic factor affecting grassland changes in the study area, which is consistent with the findings of previous studies (Eisfelder et al., 2014; Zhang and Ren, 2017; Zhou et al., 2015). Unlike other mid-latitude and high-latitude regions, the dry ecosystem in Central Asia primarily depends on the supply of atmospheric precipitation (Zhang and Ren, 2017), which represents the maximum amount of water available for vegetation in this region. Decreased precipitation can lead to a reduction in photosynthetic efficiency, suppression of plant activity and reduction in organic matter production (Gourdji et al., 2013), thereby inhibiting grassland growth. Soil water content is a key element directly linking precipitation and NPP. Thus, increases in precipitation could increase soil water content and benefit grassland growth in these regions. However, precipitation variations have shown significant spatial heterogeneity in Central Asia (de Beurs et al., 2009; Gessner et al., 2013). Changes in the distribution, frequency, and intensity of precipitation have strong impacts on the water balance of the terrestrial ecosystem and vegetation productivity in this region. In this study, we detected negative responses of grassland NPP to precipitation variation in mountainous areas. This is because the photosynthetic activity of vegetation responds adversely to a reduction in the amount of radiation and an increase in the relative humidity when the precipitation increase exceeds the demand for vegetative growth (Ukkola et al., 2016). In addition, the rich water supply systems could decrease the dependence of the vegetation activity on atmospheric

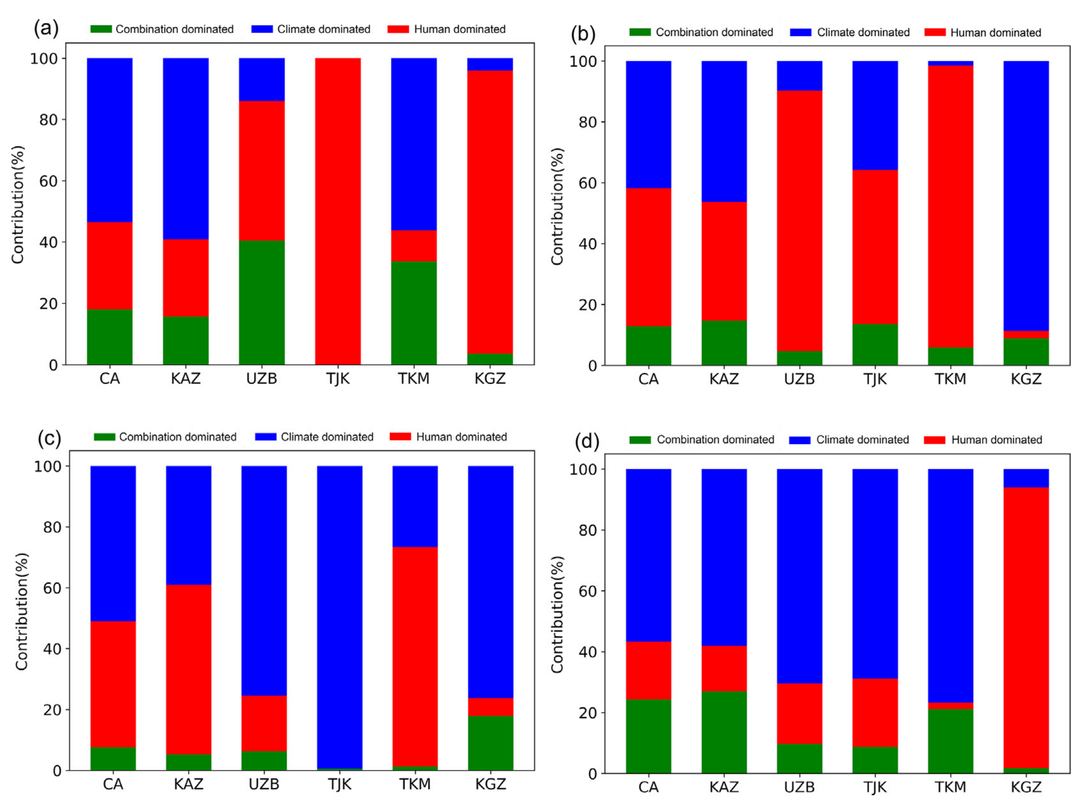

Fig. 7. Contributions of climatic and human factors to decreases in grassland NPP_A in 1982–1999 (a) and 1999–2015 (b) in the five countries of Central Asia and contributions of climatic and human factors to increases in grassland NPP_A in 1982–1999 (c) and 1999–2015 (d) in the five countries of Central Asia.

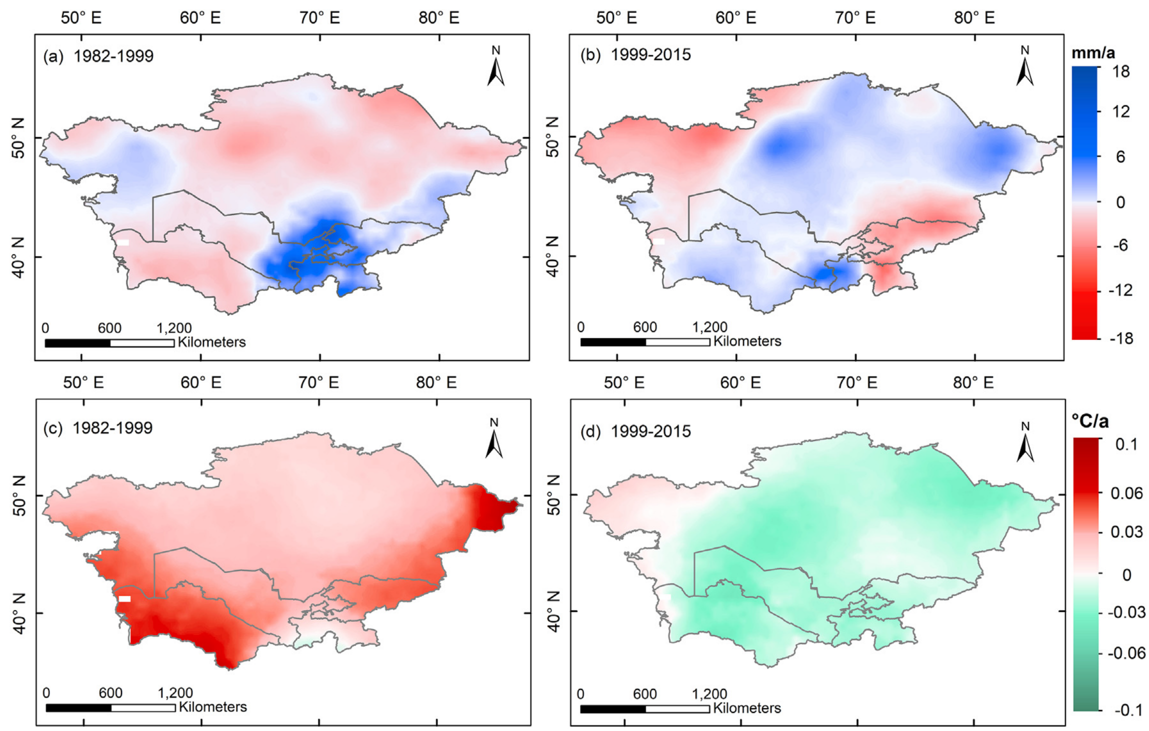

Fig. 8. Spatial distribution of the trends of annual total precipitation (PRE) in 1982–1999 (a) and 1999–2015 (b) and mean annual temperature (TEM) in 1982–1999 (c) and 1999–2015 (d).

precipitation in mountainous areas, and excessive precipitation will decrease the soil organic matter, aggravate soil erosion and flooding, and destroy the environment for vegetation (Qu et al., 2018).

The correlation between NPP and temperature was also analysed. Grassland NPP was negatively correlated with temperature in nearly 76.46% and 42.53% of the total area in 1982–1999 and 1999–2015,

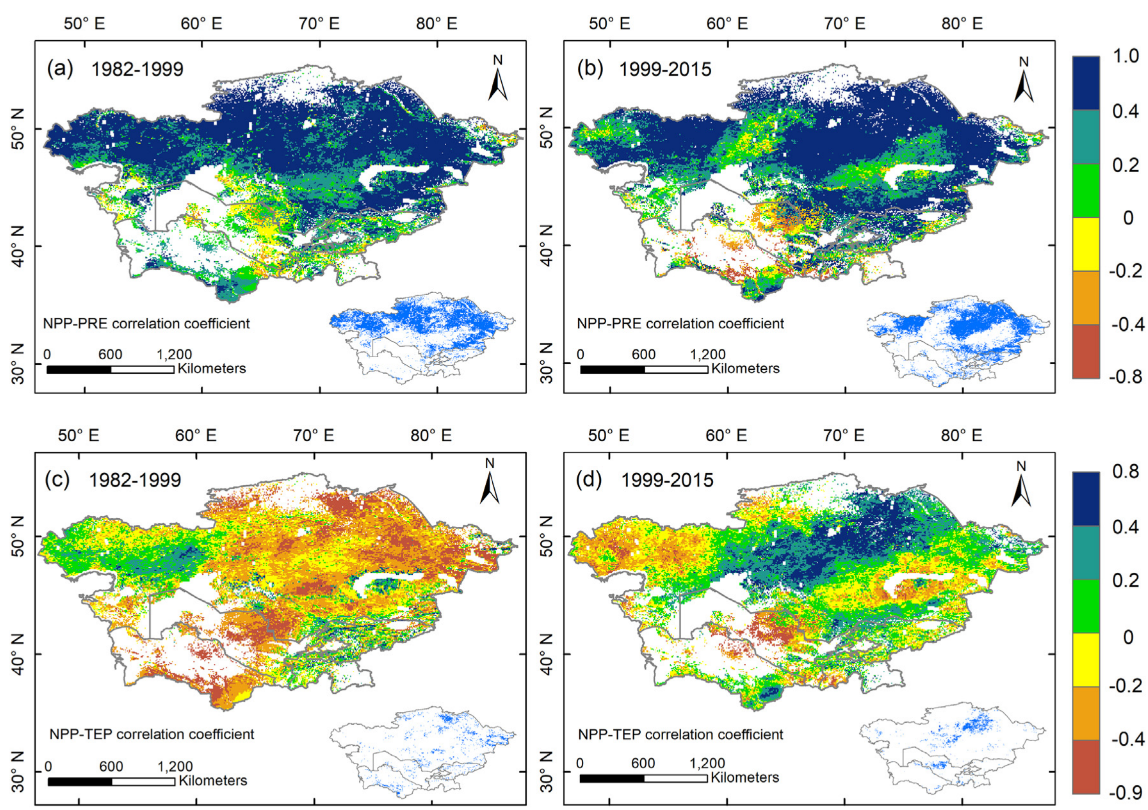

Fig. 9. Spatial distribution of the correlation coefficients between grassland NPP and climatic factors in Central Asia. (a) Correlation between annual grassland NPP and annual precipitation (PRE) during 1982–1999 and (b) 1999–2015; (c) correlation between annual grassland NPP and mean annual temperature (TEP) during 1982–1999 and (d) 1999–2015. Inset pictures show the regions with significant correlations ($p < 0.05$).

respectively (Fig. 9c and d). During the same periods, a positive correlation between grassland NPP and temperature was observed in 23.54% and 57.47% of the total area, respectively (Fig. 9c and d). However, few significant correlations were detected between grassland NPP and temperature (Fig. 9c and d). This suggested that grassland NPP is not sensitive to changes in temperature and that temperature may be not the decisive factor for grassland growth in most parts of Central Asia. This result is in agreement with those of previous studies showing that a change in temperature has no significant impact on vegetation biomass in Central Asia (de Beurs et al., 2009; C. Zhang et al., 2016).

In the past decades, the temperature rapidly rose in Central Asia, especially beginning in the middle of the 1990s (Li et al., 2015b; Mannig et al., 2013). With global warming, fire events also frequently occurred in the grassland ecosystems of Central Asia and further affected regional carbon sequestration (Smelansky and Tishkov, 2012; Sorg et al., 2012). As reported by Chen et al. (2017), the fire events mainly appeared in northern and southeastern Kazakhstan, Tajikistan and Kyrgyzstan. The grassland NPP is expected to significantly decrease with an increase in fire events, and the total consumption due to fire disturbances was 7.8 Tg C year^{-1} in the past decade in these regions. This indicates that the fire events in these areas may be another driving factor of decreases in grassland NPP. In addition, we found no significant correlation between changes in grassland productivity and climatic factors in some regions. This may be due to the impacts of human activities or the combined influences of climate change and human activities.

4.2. Human activities as a dominant driver of grassland NPP

Human disturbances are the most important driving forces of grassland NPP dynamics in Central Asia (Chen et al., 2017; Karnieli et al., 2008). We found that the area with human-induced changes in grassland NPP accounted for 30.5% and 34.4% of the total area during the first and second periods, respectively. This result was similar to that of Huang et al. (Huang et al., 2018), who found that the contribution of human activities to grassland NPP changes was 34% in Central Asia during 1979–2012. In addition, we found that the areas with reductions in grassland NPP due to human activities were mainly distributed in the Karakum Desert, Kyzylkum Desert, and Moyinkum Desert. This pattern occurred because the main grasslands in these areas are desert grasslands, which are more vulnerable to human activities than the temperate grasslands and alpine grasslands in other regions of Central Asia. Human activities, as an external driving force, could intensify grassland degradation to a certain extent in these regions.

Grazing was regarded as a major anthropogenic activity resulting in grassland NPP variations in Central Asia by previous studies (Chen et al., 2017; Han et al., 2016). Nearly 44% of land degradation in Central Asia was caused by overgrazing (Yusupov, 2003). In this study, data on the total number of livestock in Central Asia and its five countries were collected to analyse the grazing pressure in the grasslands and assess the impact of grazing on grasslands. Fig. 10 shows the change in the number of livestock in the five countries and all of Central Asia over the past three decades. The number of livestock in Central Asia changed dramatically before 2000, mainly due to the political disintegration of the Soviet Union. During the Soviet Union period, the animal husbandry industries of Kazakhstan, Tajikistan, and Kyrgyzstan obtained substantial funds from the government, and the number of livestock increased remarkably, even beyond the carrying capacity of the rangelands in these countries. Thus, heavy domestic grazing may be the reason for the observed grassland degradation and could have led to decreases in grassland NPP during this period. After the dissolution of the Soviet Union, the numbers of livestock in these countries decreased ranging between 32% and 64% (Fig. 10). Especially in Kyrgyzstan and Tajikistan, the livestock numbers have remained at a low level since the collapse of the Soviet Union. Furthermore, remote rangelands were abandoned and then converted into high-coverage grasslands, and the overgrazing was alleviated in these areas (Hauck et al., 2016; Robinson, 2016). This process may have promoted the changes in grasslands in these countries. The livestock numbers in Kazakhstan were also reduced due to the dissolution of the Soviet Union. However, the livestock numbers gradually recovered after 2000. The re-growth of pastures may be another human activity that caused grassland degradation during this period. Unlike the number of livestock in the abovementioned countries experiencing a significant shift during the two periods, the number of livestock in Uzbekistan and Turkmenistan continually increased over the past three decades (Fig. 10). Our results also revealed that the proportion of NPP reduction in Uzbekistan and Turkmenistan caused by human activities increased (Fig. 7a and b). Thus, overgrazing may be the human factor inducing decreases in grassland NPP in these two countries. Previous studies also reported that heavy domestic grazing was a main driving force of the grassland degradation and grassland carbon loss in Uzbekistan and Turkmenistan (Chen et al., 2017; Mirzabaev et al., 2016). Generally, overgrazing could cause the loss of biodiversity, reduce the proportion of dominant species, decrease leaf area and weaken photosynthetic capacity, which will damage the normal growth and development patterns of vegetation in grasslands and eventually intensify grassland desertification (Christiansen and Svejcar, 2010).

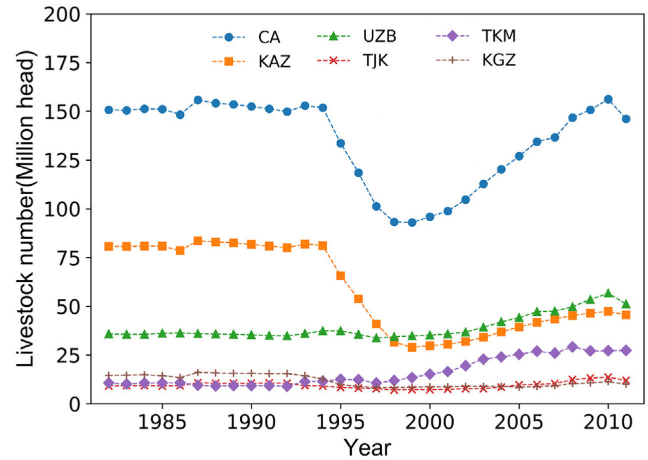

Fig. 10. The inter-annual variation in livestock numbers in Central Asia. The data on livestock inventories were obtained from the FAO (http://www.fao.org/faostat/en/#data/EK). All of the livestock were measured in terms of sheep units based on the "animal unit equivalent" (http://www.Chinaforage.com/standard/zaixuliang.htm).

However, the mechanisms underlying the relationship between grassland NPP and grazing under different grazing conditions are still unclear (Frank et al., 2002) because the impacts of grazing on grassland changes may vary spatially. These spatial differences may depend on grassland quality and productivity, grazing density, environmental variables (such as climate and soil) and plant community composition (Milchunas and Lauenroth, 1993). A previous study reported that NPP in European grasslands showed an increasing trend under grazing (Milchunas and Lauenroth, 1993). Luo et al. (2012) also indicated that moderate grazing can improve the grassland NPP in Central Asia due to significant overcompensation under moderate grazing. Hence, reasonable grazing could also promote grassland growth. In addition, overgrazing has attracted attention from the governments of Central Asian countries. Governments attempted to change their policies and invest more funds into various activities, such as drilling wells for pastoralists, providing water to livestock, and guiding pastoralists in the rational use of natural pastures. At the same time, governments applied the principles of a market economy to transform traditional animal husbandry and made widespread animal husbandry modern and efficient. These improvements may also have increased grassland NPP and promoted grassland reversion under suitable conditions. These results can explain why we found human-induced increases in grassland NPP in some regions (Fig. 6a and b).

Demographic dynamics and economic development are also regarded as two factors affecting human appropriation of grassland NPP in Central Asia (Ma et al., 2012). Generally, the population of Central Asia experienced rapid growth in the period of the Soviet Union and in the 21st Century. The growth of the population has led to an increase in the human appropriation of NPP in Central Asian grasslands during these periods. In addition, Central Asia has experienced rapid economic development, which could also affect the variation in grassland NPP because of increases in living standards that could lead to an increase in per capita food consumption (Huang et al., 2018). All these results may cause a reduction in grassland NPP due to the increase in the human appropriation of NPP. However, slow population growth and economic development were observed in the 1990s in Central Asia owing to the collapse of the Soviet Union, which decreased the human use of grassland NPP and helped mitigate the pressure on grasslands in Central Asia. In addition, the mining, petroleum, and chemical industries are widely distributed in the Ustyurt Plateau of Kazakhstan and the Karakum Desert of Turkmenistan and surround the Caspian Sea. To meet the needs of national economic development in Kazakhstan and Turkmenistan, numerous oil and gas plants and chemical industries have been established in these areas. Oil and gas exploitation may affect the desert grasslands in these places. For instance, vehicles and heavy equipment for oil and gas mining may damage the fragile desert grasslands (Jiang et al., 2017). These activities may lead to a decrease in grassland NPP and explain why human activities drove the reductions in grassland NPP in these regions (Fig. 6a and b).

In addition, some additional factors not considered in this work may also alter grassland NPP dynamics, such as carbon concentration, wind erosion, and nitrogen deposition. Future studies will consider these factors and further analyse the driving mechanisms of NPP dynamics.

5. Conclusions

The main purpose of this study was to quantitatively assess and distinguish the relative impacts of climate change and human activities on arid and semiarid grassland ecosystems in Central Asia by selecting NPP as an indicator. The results indicated that the actual NPP (NPP_A) showed a slight increasing trend from 1982 to 2015. A change point occurred in the grassland NPP time series in 1999. The main drivers of grassland NPP variations in Central Asia were different between the periods of 1982–1999 and 1999–2015.

Nearly 84.7% and 58.4% of the total grassland area experienced a decrease in NPP during the periods of 1982–1999 and 1999–2015, respectively. Climate change was the main driving force of the decrease in grassland NPP in 1982–1999, with the area experiencing climate change-driven decreases accounting for 53.5% of the total area experiencing decreases. In contrast, human activities were the major reason for decreases in grassland NPP during 1999–2015, with the area experiencing human-driven decreases accounting for 45.3% of the total area experiencing decreases. The area experiencing an increase in NPP_A during the first and second periods accounted for 15.3% and 41.6% of the total grassland area, respectively. Climate change was the main driving force of increases in grassland NPP during the two periods, with the area experiencing climate change-driven increases accounting for 51.0% and 56.7% of the total area experiencing increases in NPP, respectively. Overall, in Central Asia, climate change mainly facilitates grassland reversion, while human activities accelerate grassland degradation.

The relative impacts of climate change and human activities on changes in grassland NPP_A in the five countries of Central Asia varied greatly. Particularly in Uzbekistan and Turkmenistan, human activities causing decreases in grassland NPP intensified in the past three decades, while the negative impacts of human activities on grasslands in Kyrgyzstan and Tajikistan were mitigated. Additionally, the effects of human activities on grasslands in the five countries were closely related to changes in livestock numbers.

Further analysis found that precipitation was the main climatic factor controlling the grassland NPP variations in most areas of Central Asia. Moreover, grazing may be the major human activity explaining the grassland NPP changes in Central Asia; overgrazing, in particular, could explain the decrease in grassland NPP. Our results could provide reliable information for pastoral management and prevention of grassland degradation and desertification in Central Asia. In addition, the results of this study provided a new perspective on the relative impacts of climate change and human activities on grassland ecosystems in Central Asia.

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Author contributions

Guli Jiapaer designed this study. Tao Chen processed the data, analysed the results and wrote the manuscript. Anming Bao provided some constructive suggestions and expert advice. Hao Guo, Guoxiong Zheng, Liangliang Jiang, Cun Chang, and Latipa Tuerhanjiang provided analysis tools and technical assistance. All authors contributed to the final version of the manuscript by proofreading and providing constructive suggestions.

Conflicts of interest

The authors declare no conflict of interest.

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