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Quantitative Assessment of the Effects of Climate Change and Human Activities on Grassland NPP in Altay Prefecture

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Abstract: Grassland degradation in Altay Prefecture is of considerable concern as it is a threat that hinders the sustainable development of the local economy and the stable operation of the livestock industry. Quantitative assessment of the relative contributions of climate change and human activities, which are considered as the dominant triggers of grassland degradation, to grassland variation is crucial for understanding the grassland degradation mechanism and mitigating the degraded grassland in Altay Prefecture. In this paper, the Carnegie-Ames-Stanford Approach model and the Thornthwaite memorial model were adopted to simulate the actual net primary productivity (NPP_A) and potential net primary productivity (NPP_P) in the Altay Prefecture from 2000 to 2019. Meanwhile, the difference between potential NPP and actual NPP was employed to reflect the effects of human activities (NPP_H) on the grassland. On this basis, we validated the viability of the simulated NPP using the Pearson correlation coefficient, investigated the spatiotemporal variability of grassland productivity, and established comprehensive scenarios to quantitatively assess the relative roles of climate change and human activities on grassland in Altay prefecture. The results indicate three main points. (1) The simulated NPP_A was highly consistent with the MOD17A3 dataset in spatial distribution. (2) Regions with an increased NPP_A accounted for 70.53% of the total grassland, whereas 29.47% of the total grassland area experienced a decrease. At the temporal scale, the NPP_A presented a slightly increasing trend (0.83 g C m^{-2} yr^{-1}) over the study period, while the trends of NPP_P and NPP_H were reduced (–1.31 and –2.15 g C m^{-2} yr^{-1}). (3) Compared with climate change, human activities played a key role in the process of grassland restoration, as 66.98% of restored grassland resulted from it. In contrast, inter-annual climate change is the primary cause of grassland degradation, as it influenced 55.70% of degraded grassland. These results could shed light on the mechanisms of grassland variation caused by climate change and human activities, and they can be applied to further develop efficient measures to combat desertification in Altay Prefecture.

Key words: grassland degradation; net primary productivity; climate change; human activities; Altay Prefecture

1 Introduction

As the most widespread terrestrial vegetation type in the world, grassland plays a key role in global climate change, food security, and ecological balancing, so it is a critical

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component of the terrestrial ecosystem (Yu et al., 2005). The grassland in China covers approximately 3.93×10^6 km^2, which is nearly 40% of the domestic land area and 13% of the total grassland worldwide (Ni, 2002). However, global climate change has significantly affected the natural ecosystem in many regions worldwide because of increased temperatures and altered precipitation patterns (Ravi et al., 2010). Meanwhile, as the population keeps growing, grassland ecosystems have suffered serious degradation caused by long-term unsustainable human activities, including overgrazing, land conversion, and overcutting (Wang and Zhu, 2003). In China, most of the grassland areas have experienced varying degrees of degeneration, especially in the northwestern part, where the degradation process is often affected by climate change and human activities. Altay Prefecture, one of the key pastoral areas in China, has abundant natural grassland resources and accounts for nearly 15% of the available grassland areas in the Xinjiang Uygur Autonomous Region. In recent years, grassland in Altay Prefecture has experienced severe damage induced by extreme climate, excessive land use, and population growth. Grassland degradation not only threatens the ecological processes, but also introduces severe obstacles to the stable operation of the livestock industry and the local economic development. Meanwhile, the grassland ecosystem in Altay Prefecture is extremely sensitive to climate change and human activities due to its vulnerability and the geographical conditions. Therefore, using a precise quantitative method to assess the individual effects of these two factors on grassland dynamics is crucial for the control and rehabilitation of degradation in Altay Prefecture.

In recent years, the methodologies applied to distinguish the individual contributions of these driving factors have included three types. Firstly, the mathematical statistical methods, which mainly include principal component analysis and the statistical technique of multiple variable analysis, have been employed to assess the contributions of climate change and human activities (Du et al., 2014; Gollnow and Lakes, 2014; Schweizer and Matlack, 2014). However, these methods neglect the true ecological significance and lack the ability to reveal the discrepancies in spatial distributions among the various factors (Yan et al., 2019). Secondly, as the common approach of quantitative analysis, the residual trend of normalized difference vegetation index (NDVI) method has been used to investigate the contributions of climate change and human activities in numerous studies (Jiang et al., 2017; Li et al., 2017). Nevertheless, an adjustment of the parameters used in residual analysis must be carried out before it can be applied to different periods or areas within the same region (Zheng et al., 2019). Thirdly, the net primary productivity (NPP) refers to the amount of new carbon fixed through photosynthesis by the plant community per unit of time and space, which exerts great influence on the carbon cycle in the global biosphere (Piao et al., 2006; Liang et al., 2015). Specifically, NPP is not only vulnerable to climate change and sensitive to human activities, but it also can precisely reflect the responses of vegetation growth to driving factors (Potter et al., 2012; Chen et al., 2015). Thus, many researchers have selected NPP as an indicator for investigating the dynamic characteristics of vegetation and determining the primary drivers of vegetation variation (Liu et al., 2019b). In particular, according to the assumption that the difference between the potential and actual vegetation productivity can reflect the impact of human activities on vegetation variation, recent studies have compared the potential vegetation productivities with the actual one to determine the impact of human appropriation on vegetation productivity (Chen et al., 2014; Li et al., 2018; Yan et al., 2019). Specifically, actual NPP (NPP_A) refers to the real situation of vegetation productivity, which is impacted by both climate change and human activities. For potential NPP (NPP_P), the only impact factor is climate change, so it indicates the potential vegetation productivity in the hypothetical condition. Additionally, the human-induced vegetation NPP (NPP_H), which assumes that the productivity difference between potential and actual vegetation productivity indicates the influence of human activities on the ecological environment, can be estimated by comparing the NPP_P and NPP_A. Then, an exhaustive study regarding the respective effects of climate change and human activities on vegetation variations can be carried out by comparing the variation tendencies of NPP_A, NPP_P, and NPP_H (Wu et al., 2017).

Based on the above framework, many studies used the method that couples NPP with scenario simulation to further quantify the individual impacts of climate change and human activities on vegetation variation. For example, Xu et al. developed a quantitative method to evaluate the relative roles of the driving factors in desertification using the slopes of the three types of NPP in the Ordos Plateau (Xu et al., 2010). According to the different timescales, Xu et al. emphasized evaluating the reactions of grassland dynamics to climate change and human activities in Qinghai-Tibet Plateau, and established the method based on the tendencies of several NPP and scenario simulations (Xu et al., 2016). Zhang et al. focused on the variations of grassland dynamics in Xinjiang, and assessed the respective effects of primary driving factors during 2000–2014 in the same way (Zhang et al., 2018). Additionally, the studies of Yang et al. and Liu et al. (Yang et al., 2016; Liu et al., 2019b) expanded the study areas to the regional and global scale, which showed that these methods based on NPP coupled scenario simulation have been employed to detect grassland variation worldwide. As shown by these studies, the NPP combined with a scenario simulation method has been widely and successfully applied to quantitatively distinguish the relative effects of climate change and human activities in grassland dynamics.

In order to quantitively distinguish the dominant contributions in grassland restoration or degradation in Altay Prefecture, the Thornthwaite Memorial and Carnegie-Ames-Stanford Approach (CASA) models were employed to simulate potential and actual NPP from 2000 to 2019, respectively. Then, this paper estimated the human appropriation of grassland productivity by comparing the potential NPP with the actual NPP, and the variation tendencies of the various NPP were described in detail. The present study primarily aims to: 1) examine the spatial-temporal patterns and dynamics of grassland NPP in Altay Prefecture from 2000 to 2019; 2) discriminate the relative roles of climate change and human activities in grassland dynamics in Altay Prefecture, and quantitatively evaluate the spatial distribution of NPP variation induced by either climate change or human activities in various types of grassland; and 3) further analyze the patterns of these two dominant factors in effecting grassland restoration or degradation according to the impact factors of climate change and human activities. All these efforts are designed to offer a scientific basis for grassland ecological conservation policy making and optimizing ecosystem management, especially in the ecologically fragile regions and ecosystem transition zones.

2 Data and methods

2.1 Study area

Altay Prefecture is located between 45°00′00″–49°10′45″N and 85°31′36″– 91°04′23″E (Fig. 1a), and situated in the heartland of Eurasia, bordered by Mongolia, Russia, and Kazakhstan. The Prefecture is characterized by an arid and semi-arid continental climate, with a mean annual temperature of 1.22–4.51 ℃ and mean annual precipitation of 173–390 mm (Fu et al., 2017). The climate in the Altay Prefecture varies considerably. Low temperature and high precipitation occur in the northern mountains, which are attributable to the blockage of the Arctic and Atlantic monsoons by the Altay Mountains and their special topography. Meanwhile, with the effect of the Gurbantunggut Desert, the southern plain has a dry climate and scarce precipitation. In addition, Altay Prefecture has a total area of 1.18×10^5 km^2, grassland is the main type of vegetation in Altay Prefecture, where it covers an area greater than 9×10^4 km^2, which making it one of the largest grasslands in Xinjiang, accounting for nearly 11% of the pasture in key grazing areas nationwide (Chao, 2004). As the altitude increases, grassland types change between temperate desert (TD), temperate steppe (TS), mountain meadow (MM), alpine steppe (AS), and alpine meadow (AM) with obvious vertical zonality (Fig. 1b). Furthermore, owing to the impacts of the geographical conditions and climate changes, the temperate desert has gradually become the dominant grassland type in the study area.

2.2 Data sources

2.2.1 Remote sensing data

The remote sensing data used in this study are NPP (MOD17A3, 500 m, 1 year) and NDVI (MOD13Q1, 500 m, 16 days) products from 2000 to 2019, which were derived from the Level 1 and Atmosphere Archive and Distribution System Web of NASA (https://ladsweb.nascom.nasa.gov/data/search/html). In this study, the NPP data (MOD17A3, 500 m, 1 year) were applied to validate the grassland NPP estimated from the CASA model. Moreover, the Google Earth Engine was employed to deal with the MODIS datasets. In order to generate monthly data, the maximum value composite method that reduces the noise was employed to merge the 16 days of NDVI data. The coordinate and

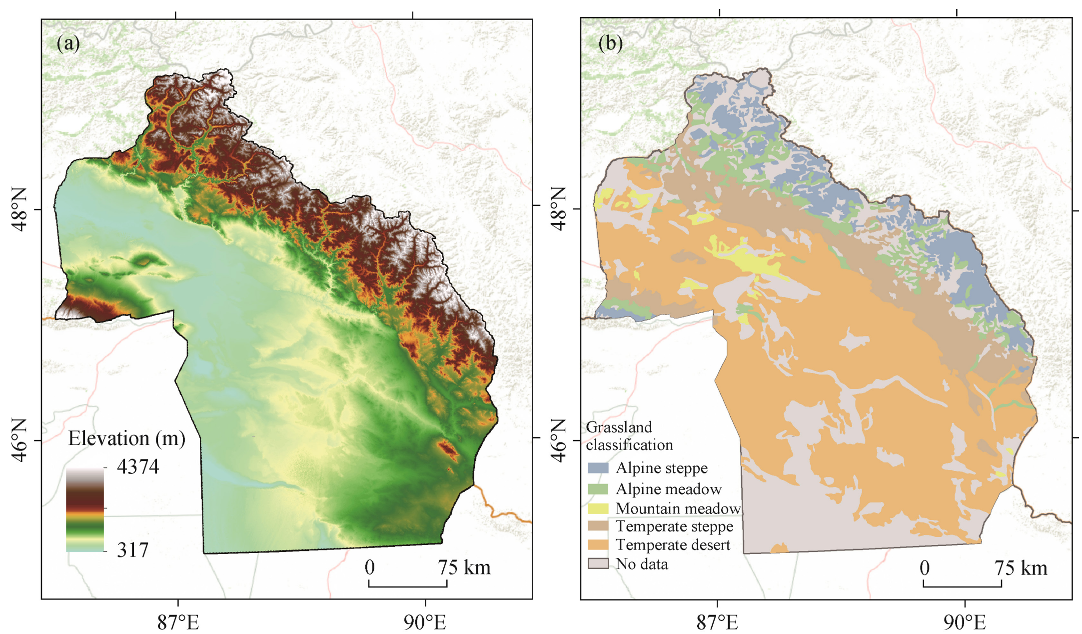

Fig. 1 Location of the study area: (a) The base map is 500 m DEM; (b) Grassland type map used in the study.

projection systems used in this study were the World Geodetic System 1984 and the Lambert Conformal Conic projection, respectively.

2.2.2 Meteorological data

The meteorological data, including daily precipitation, temperature, and daily sunshine duration from 2000 to 2019 for 20 nationally standard meteorological stations around and within the study area, were obtained from the China Meteorological Data Sharing Service System (http://data.cma.cn/). Meanwhile, the Angstrom-Prescott model was employed to calculate total solar radiation. Additionally, under the considerations of latitude, longitude, and elevation, the ANUSPLIN software was adopted to interpolate the meteorological data into a grid with the same spatial resolution and coordinate system as the remote sensing data.

2.2.3 Other data

A 1:1000000 scale vegetation distribution map of China was produced by a domestic partnership which consisted of 53 research groups guided by the Chinese Academy of Sciences. Based on it, we divided the grasslands in Altay Prefecture into five categories according to the grassland classification standards issued by the Ministry of Agriculture in 2017. The DEM data (SRTM, 500 m) used in this study were obtained from Resource and Environment Science and Data Center (https://www.resdc.cn/Default.aspx). Moreover, statistical data for population and livestock in the study region from 2000 to 2019 were collected from the Altay Prefecture statistical yearbook.

2.3 Methods

2.3.1 Calculation of grassland NPP

(1) Calculation of actual NPP

The improved Carnegie-Ames-Stanford Approach model (Zhu, 2005), a light use efficiency model based on the resource-balance theory, was adopted to simulate NPP_A in this study. The CASA model is very effective at evaluating the NPP variations across various regions owing to the fact that it simulates NPP with fewer blank values. In this model, absorbed photosynthetically active radiation (*APAR*) and light energy conversion (ε) were the primary variables employed to calculate NPP, and the main equations are as follows:

$$NPP = APAR \times \varepsilon \tag{1}$$

where *NPP* is the annual net primary productivity (g C m^{-2} yr^{-1}; *APAR* represents the canopy-absorbed incident solar radiation; and ε represents the actual light use efficiency.

$$APAR = SOL \times FPAR \times 0.5 \tag{2}$$

where *SOL* represents the total solar radiation (MJ m^{-2}); *FPAR* is the fraction of photosynthetically active radiation absorbed by vegetation, which is calculated from the NDVI; and 0.5 stands for the fraction of total solar radiation that can be used by the vegetation.

$$\varepsilon = T_{\varepsilon 1} \times T_{\varepsilon 2} \times W_{\varepsilon} \times \varepsilon^* \tag{3}$$

where $T_{\varepsilon 1}$ and $T_{\varepsilon 2}$ denote the stress effects on light use efficiency at low temperature and high temperature respectively; W_{ε} stands for the effects of water stress; and ε^* is the maximum possible efficiency, with an ε^* value for grassland of 0.542 (g C MJ^{-1}) used in this study.

(2) Calculation of NPP_P and NPP_H

Certain models, including the Thornthwaite Memorial model, Miami model, and Chikugo model, are widely used by scholars all over the world to estimate NPP_P. The Thornthwaite Memorial model, with meteorological data as the input, was established according to the data used in the Miami model and modified by Thornthwaite's potential evaporation model (Lieth and Whittaker, 1975). Compared to the basic model, the Thornthwaite Memorial model has more precision because it estimates the NPP_P from evapotranspiration by using temperature and precipitation data as the driving parameters based on the relationship of evapotranspiration and carbon uptake (Liu et al., 2019b). In this study, the Thornthwaite Memorial model was adopted to simulate the grassland NPP_P. The basic principle of this model can be expressed as follows:

$$NPP_P = 3000 \times [1 - e^{-0.0009695 \times (v-20)}] \tag{4}$$

where NPP_P represents the annual total NPP (g C m^{-2} yr^{-1}); and v represents the annual actual evapotranspiration (mm). The value of v can be calculated as follows:

$$v = \frac{1.05r}{\sqrt{1+(1+1.05r/L)^2}} \tag{5}$$

$$L = 3000 + 25q + 0.05q^3 \tag{6}$$

where r represents the annual precipitation (mm); q represents the annual temperature (℃); and L stands for the annual average evapotranspiration (mm).

Then, as mentioned earlier, we measured the variation of grassland NPP induced by human disturbance according to the difference between NPP_P and NPP_A. Hence, the computational formula of NPP_H can be expressed as follows (Yang et al., 2016):

$$NPP_H = NPP_P - NPP_A \tag{7}$$

2.3.2 Grassland dynamic assessment

The ordinary least-squares method was utilized to estimate the linear trend of NPP over time, which could reflect the changing trend of grassland NPP more reasonably and precisely (Han et al., 2018). The calculation for the statistics is expressed as follows:

$$Slope = \frac{n \times \sum_{i=1}^{n} \left(i \times NPP_i\right) - \sum_{i=1}^{n} i \times \sum_{i=1}^{n} NPP_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{8}$$

where i is the sequence number of the year; NPP_i is the total annual NPP in year i; and n is 20 in this paper.

In order to represent the confidence level of the variation, the *F*-test was used to determine the significance of the variation tendency. The formula is expressed as follows:

$$F = (n-2) \times \frac{Q}{P} \tag{9}$$

$$Q = \sum_{i=1}^{n} \left(\hat{x}_i - \overline{x} \right)^2 \tag{10}$$

$$P = \sum_{i=1}^{n} \left(x_i - \hat{x}_i \right)^2 \tag{11}$$

where Q represents the residual sum of the squares; P represents the regression sum; $\hat{x}_i$ stands for the regression value; and $\overline{x}$ stands for the mean data over the years. As shown in Table 1, combined with the *F*-test results, the variation tendency was classified into six levels in this study.

Table 1 Significance test of the NPP_A change trend and classification levels

P and *Slope* values	Classification level
Slope<0, *P*<0.01	Extremely Significant Decrease (ESD)
Slope<0, 0.01 ≤*P*<0.05	Significant Decrease (SD)
Slope<0, 0.05 ≤*P*	Not Significant Decrease (NSD)
Slope>0, *P*<0.01	Extremely Significant Increase (ESI)
Slope>0, 0.01 ≤*P*<0.05	Significant Increase (SI)
Slope>0, 0.05 ≤*P*	Not Significant Increase (NSI)

2.3.3 Establishing scenarios

In this study, the slopes of NPP_A, NPP_P, and NPP_H were calculated to discriminate the relative contributions of climate change and human activities to grassland restoration or degradation, and were represented by S_A, S_P, and S_H, respectively. We calculated the slopes of the three kinds of NPP and established the scenarios (Table 2). A changing trend of S_A indicates dynamic vegetation, with the positive or negative value of S_A representing that grassland restoration or degradation occurs in the grassland, respectively. A positive S_P indicates that the inter-annual climate change during this period is beneficial to grass growth, whereas a negative S_P demonstrates that inter-annual climate change reduces grass growth. Additionally, the effects of human activities on grass growth can be assessed based on the slope of S_H. A negative S_H indicates that human activities during this period are beneficial to grassland growth, which implies that human interventions promote grassland restoration. Conversely, a positive S_H indicates that grassland productivity decreased and grassland degradation was dominated by human activities (Li et al., 2016).

Furthermore, there exist some uncertain circumstances in which the magnitudes and directions of the relative contributions of climate change and human activities are different when the tendencies of S_P and S_H are both either positive or negative. These conditions will lead to confusion in distinguishing the dominant factors that caused grassland restoration or degradation. Therefore, based on common scenarios (Gang et al., 2014), the absolute values of S_P and S_H were compared to further identify the vital roles of climate change and human activities in this study. Moreover, some situations like the opposite of scenario 3 or scenario 6, where neither climate change nor human activities were responsible for grassland restoration or degradation, were not taken into consideration in this paper to avoid uncertainties.

Table 2 Methods for assessing the relative contributions of climate change and human activities to grassland restoration or degradation

Hypothesis	Scenario	S_P	S_H	Relative relation	Relative roles of climate change and human activities
S_A>0 (Restoration)	Scenario 1	>0	>0	$\|S_P\|>\|S_H\|$	Climate is the dominant trigger responsible for grassland restoration (CDR)
	Scenario 2	<0	<0	$\|S_P\|<\|S_H\|$	Human activities are the dominant factor that controls the grassland restoration (HDR)
	Scenario 3	>0	<0		Climate change and human activities act together to promote grassland restoration (BDR)
S_A<0 (Degradation)	Scenario 4	>0	>0	$\|S_P\|<\|S_H\|$	Grassland degradation is mainly caused by human activities such as overgrazing, over-reclamation (HDD)
	Scenario 5	<0	<0	$\|S_P\|>\|S_H\|$	Climate plays a dominant role in grassland degradation (CDD)
	Scenario 6	<0	>0		Climate change and human activities are both responsible for grassland (BDD)

3 Results

3.1 Validating the estimated NPP_A and the spatial distribution of NPP_A

In this study, the Pearson correlation coefficient was employed to reflect the relationship between NPP_A simulated by the CASA model and the MOD17A3 dataset. As shown in Fig. 2a, the correlation coefficients that exceed 0.5 occupied nearly 52% of the study area, which indicated that the CASA model exhibited reliable accuracy in estimating NPP_A to some extent. Meanwhile, a high similarity of spatial distribution characteristics existed between the CASA model and MOD17A3 dataset when their annual mean NPP values from 2000 to 2019 were compared (Fig. 2b and 2c).

In general, the value of NPP_A exhibited a slightly increasing trend over the research period, and its spatial distribution showed a gradual rise from south to north in the study area (Fig. 2b). The highest NPP_A values were found in the Altay Mountains and Sawuer Mountains, with mean values greater than 400 g C m^{-2} yr^{-1} in the major parts of these regions. Areas with NPP_A values ranging from 100 to 300 g C m^{-2} yr^{-1} were found to be widespread throughout the study area, and the mean grassland NPP_A was 189.09 g C m^{-2} yr^{-1} from 2000 to 2019. In addition, the smallest NPP_A values were evidently found in parts of the southern desert, with a mean value of less than 80 g C m^{-2} yr^{-1}. Owing to the effects of climate change and human activities, the NPP_A values of various grassland types exhibited significant differences. Grassland types in the mountain regions primarily include alpine steppe, alpine meadow, and mountains meadow, with annual mean NPP_A values of 578.76, 427.8, and 267.3 g C m^{-2} yr^{-1}, respectively. The annual mean NPP_A of temperate steppe in the central Irtysh River Basin was 300.59 g C m^{-2} yr^{-1}. Additionally, temperate desert grassland in the southern desert region had the lowest annual mean NPP_A, which was only 64.25 g C m^{-2} yr^{-1}.

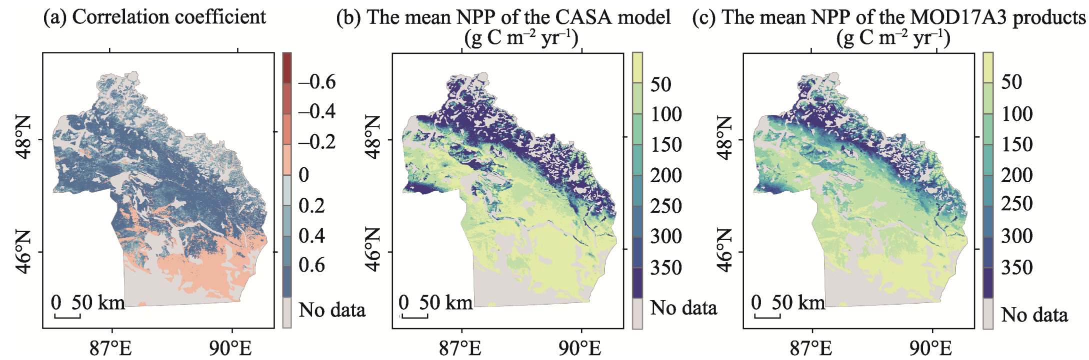

Fig. 2 Comparison between the mean NPP of the CASA model and the mean NPP of the MOD17A3 products from 2000 to 2019: (a) Correlation analysis of the two data sources; (b) The mean NPP of the CASA model; (c) The mean NPP of the MOD17A3 products.

3.2 Dynamic analysis of grassland net primary productivity

Based on the pixels, a combination of the ordinary least squares with the *F*-test method was employed to calculate the variation tendency of grassland NPP_A in the study area from 2000 to 2019. The result (Fig. 3a) shows a significant spatial heterogeneity. While the values of NPP_A showed an increasing trend overall of 0.83 g C m^{-2} yr^{-1}, a decreasing trend only occurred in certain areas. Regions with the increased NPP_A accounted for 70.53% of the total grassland. The extremely significant increase (ESI) and significant increase (SI) areas accounted for 9.91% of the Altay Prefecture grassland, and were primarily located in Irtysh River Basin, Ulungur River Basin, and Sawuer Mountains regions, which have either good irrigation conditions or abundant precipitation. By contrast, regions with the decreased NPP_A occupied 29.47% of the total grassland. Similarly, extremely significant decrease (ESD) and significant decrease (SD) regions accounted for 2.06% of the total grassland and were sporadically distributed throughout the study area. Furthermore, the grassland without significant changes in NPP_A occupied 7.0452×10^4 km^2, equivalent to 88.03% of the total grassland area. The not significant increase (NSI) and not significant decrease (NSD) regions accounted for 60.62% and 27.41% of the total grassland, respectively.

In order to investigate the evolving direction of NPP_A in Altay Prefecture grassland in this study, the slope value of NPP_A was combined with the Hurst index, which is based on Rescaled Range Analysis (R/S analysis). The directions of the evolving tendency in future NPP_A were classified into six types (Table 3): Strong favorable direction (SFD) and weak favorable direction (WFD) mean that the future NPP_A has a sustainable growth in different extents; strong unfavorable direction (SUD) and weak unfavorable direction (WUD) reflect the opposite scenarios; moreover, uncertain direction (UD) and continuously unchanged (CU) denote that the evolving direction of NPP_A is uncertain or unchanged, respectively. In total, 35.7% of the study area was continuously unchanged and 57.4% was of an uncertain direction (Fig. 3b); moreover, the weak favorable direction and weak unfavorable direction accounted for 0.26% and 0.43%, respectively. Furthermore, there existed few areas that presented either strong favorable direction or strong unfavorable direction in Altay Prefecture.

Table 3 Classified results of evolving tendency of NPP_A from 2000 to 2019 in Altay Prefecture

H and *Slope* value	Classification level
Slope<0, *H*<0.1 and *Slope*>0, 0.9≤*H*	Strong Favorable Direction (SFD)
Slope<0, 0.1≤*H*<0.3 and *Slope*>0, 0.7≤ *H*<0.9	Weak Favorable Direction (WFD)
Slope<0, 0.9≤ *H* and *Slope*>0, *H*<0.1	Strong Unfavorable Direction (SUD)
Slope<0, 0.7≤ *H*<0.9 *and Slope*>0, 0.1≤*H*<0.3	Weak Unfavorable Direction (WUD)
Slope<0, 0.5≤*H*<0.7 *and Slope*>0, 0.3≤*H*<0.5	Uncertain Direction (UD)
Slope<0, 0.3≤*H*<0.5 and *Slope*>0, 0.5<*H*<0.7	Continuously Unchanged (CU)

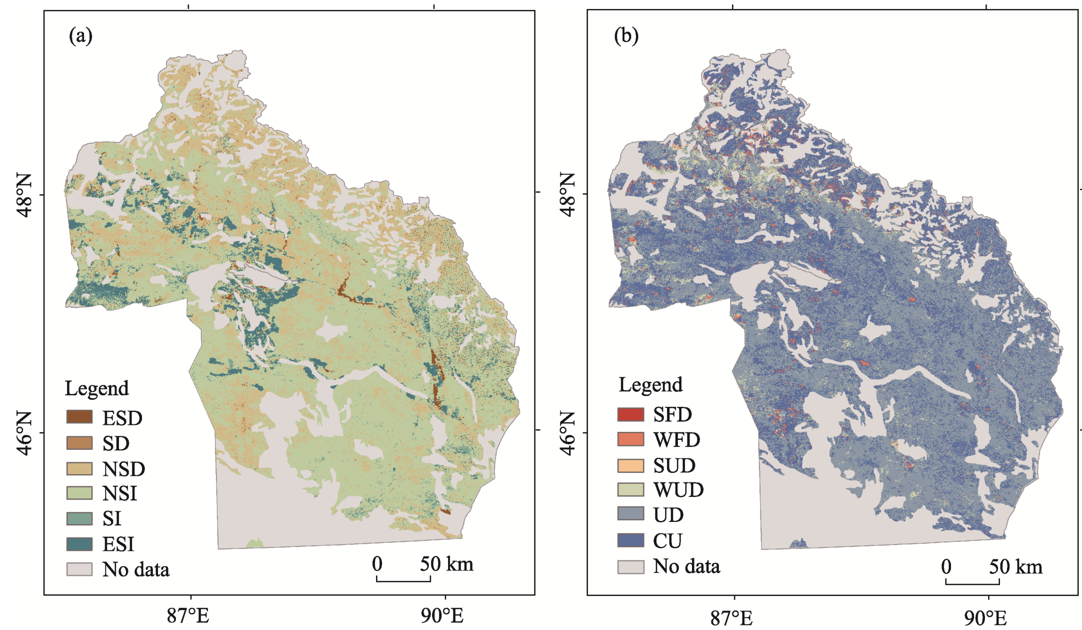

Fig. 3 Dynamic analysis of grassland net primary productivity in Altay Prefecture: (a) Significance test of NPP_A change trend from 2000 to 2019; (b) Spatial distribution of the direction of the evolving tendency.
Note: The abbreviations in figure see in Table 1 and Table 3.

The Linear Regression Analysis was employed to calculate the NPP_P and NPP_H inter-annual variation tendency (Fig. 4). In general, both the NPP_P influenced by climate change and the NPP_H affected by human activities appeared to show a decreasing tendency, and their rates of decrease were 1.31 g C m^{-2} yr^{-1} and 2.15 g C m^{-2} yr^{-1}, respectively. These results implied that human activities may facilitate the increase of grassland productivity, whereas climate factors played a negative role. Moreover, the change rate of NPP_H was higher than NPP_P, which indicated that human activities may be mainly responsible for the grassland restoration in Altay Prefecture.

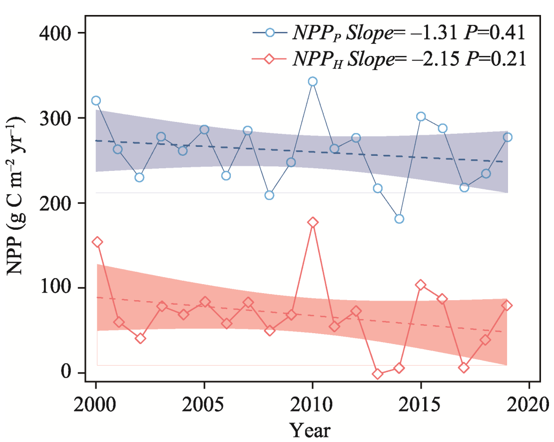

Fig. 4 The trends of NPP_P and NPP_H from 2000 to 2019

3.3 Relative contributions of climate change and human activities to grassland variation

According to the scenarios in Table 2, the relative effects of climate change and human activities were simulated in this paper. In total, the restored grassland areas were larger than the degraded areas in Altay Prefecture grassland from 2000 to 2019. As can be seen in Fig. 5a, human activities contributed mostly to the restoration. The regions of human- dominated restoration (HDR) occupied 66.98% of the total grassland restoration area. The regions with restoration induced by human activities were widespread throughout the study area, especially in the border zone between the Altay Mountains and the plain, and some regions distributed in Fuyun and Qinghe counties. Meanwhile, the climate- dominated restoration (CDR) region accounted for 18.43%, which were scattered across the west of Ulungur Lake, and the border zone between Jimunai County and other counties. Additionally, the regions where both of these two drivers contributed to grassland restoration (BDR) were found to occupy 14.59%, mainly in the east of Ulungur Lake, and some regions of Altay.

Grassland degradation induced by either the individual or combined effects of climate change and human activities were also analyzed (Fig. 5b). The regions where climate change contributed to grassland degradation (CDD) accounted for up to 55.70% of the total grassland degradation area, and were mainly distributed in Altay Mountains, and scattered around the east of the Altay Prefecture. The human-dominated degradation (HDD) regions accounted for 29.91% of the total degradation area, and were primarily concentrated in the west of the study area and around Ulungur Lake. Furthermore, the regions where grassland degradation was induced by both factors (BDD) only occupied a small proportion (14.39%) of the degraded grassland. Moreover, the regions where the combined factors contrib-

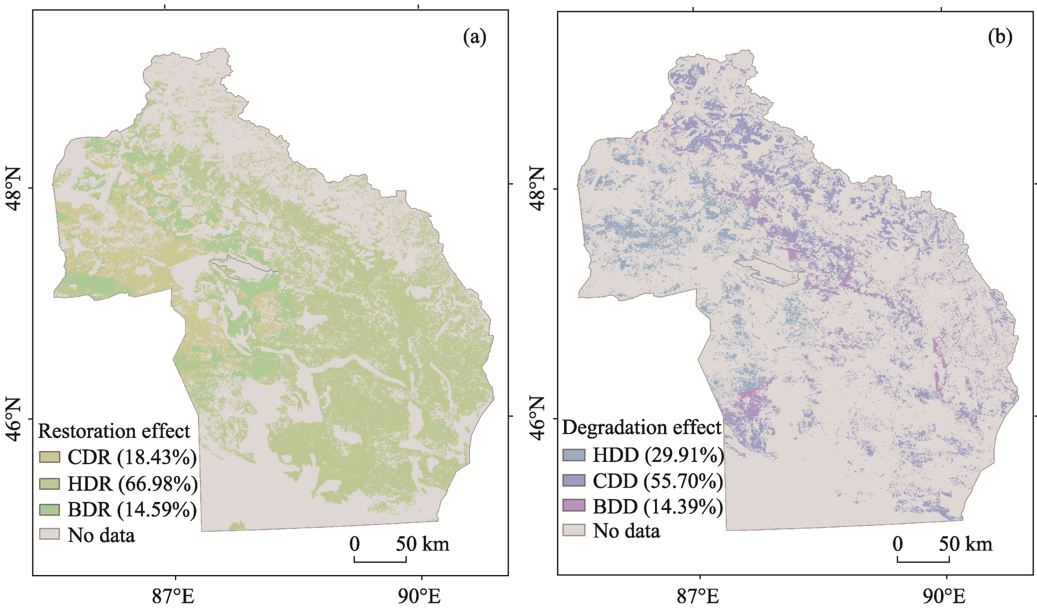

Fig. 5 Relative contributions of climate and human factors to grassland changes in Altay Prefecture from 2000 to 2019
Note: (a) Restoration effect. CDR, HDR, and BDR denote grassland restoration that is dominated by climate change, human activities, and the combination of the two factors, respectively; (b) Degradation effect. HDD, CDD, and BDD denote grassland degradation that is dominated by human activities, climate change, and the combination of the two factors, respectively.

uted to degradation presented a sporadic distribution in the study area.

The restored and degraded areas of different grassland types in Altay Prefecture were statistically analyzed (Fig. 6). Overall, these grassland types primarily experienced restoration over the study period, while the contributions of their driving factors also presented significant differences. Specifically, the temperate steppe (TS) had the largest area of restored grassland, which accounted for 77.29% of the temperate steppe, and the human activities contribution to the restored area was 75.78% in the temperate steppe. Additionally, the restored areas of temperate desert (TD) and mountain meadow (MM) both exceeded 70% of the areas themselves, and the former was mainly induced by human activities (63.37%), whereas climate change and human activities were both responsible for the latter (59.20%). Compared to the above grassland types, only 55.49% of grassland restoration occurred in alpine steppe (AS), where human activities resulted in 79.00% of the grassland restoration. Meanwhile, the area of restoration was close to that of degradation in alpine meadow (AM), which accounted for 50.27% and 49.73% of the total area, respectively. Moreover, human activities played a dominant role in grassland restoration (92.59%) and climate change was the dominant factor responsible for grassland degradation (92.73%) in alpine meadow.

4 Discussion

4.1 Validation of NPP simulated by the CASA model

In the present study, we discovered that the simulated NPP_A value was larger than the values in the MOD17A3 dataset overall. This phenomenon was consistent with some previ-

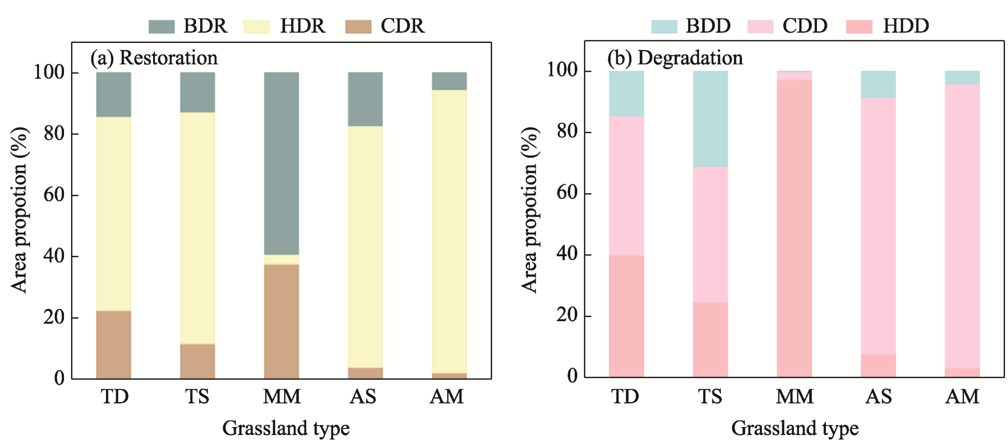

Fig. 6 The relative contributions of climate change and human activities for either restoration or degradation in the different types of grassland

ous studies, which indicated the NPP products offered by MODIS were frequently underestimated in Northwestern China (Li, 2004; Pan and Li, 2015). The primary objective in developing the MODIS NPP products was to satisfy the related research needs at the global scale (Running et al., 2004; Li and Pan, 2018), which may lead to its inability to precisely show the actual NPP variation to some extent at the regional scale. Furthermore, numerous studies have obtained good results by using the CASA model to simulate the actual NPP to investigate vegetation productivity dynamics and analyze the driving factors in Northwestern China (Mu et al., 2013; Liu et al., 2019a; Li et al., 2021). Therefore, we concluded that the CASA model could reproduce the actual NPP dynamics in the study area reasonably well.

To further validate the simulated NPP in this paper, the results of other studies were compared with ours (Table 4). Owing to the temperate desert being the largest grassland type that occupied most of the study area (65.8%), we applied the results of other studies that involved temperate desert NPP around the study area for validating the feasibility of the experiment. For instance, Zhang et al. found that during 2001–2014, the simulated value of temperate desert in Xinjiang was equal to 65.37 g C m^{-2} yr^{-1}, which was highly consistent with our results (Zhang et al., 2020). Additionally, another study (Ren et al., 2017) showed the mean NPP value of Xinjiang temperate desert was 54.66 g C m^{-2} yr^{-1} in August from 2000 to 2014. This is very close to the result of (Yang et al., 2014) which found that the mean NPP value of temperate desert in Xinjiang from 2000 to 2010 was 57.68 g C m^{-2} yr^{-1}, which was slightly less than our results. Overall, the NPP simulated by the CASA model presented high correspondence with the other previously reported results around the study area. These studies further demonstrate the reliability of our results when taking the differences in model parameters, applied methods, and the spatial-temporal variations into consideration.

Table 4 Comparisons of the values simulated in this study with those of other studies

Study area	Study period	Mean annual NPP (g C m^{-2} yr^{-1})	Reference
Altay Prefecture	2000–2020	64.25 (Temperate desert)	This study
Xinjiang	2001–2014	65.73 (Temperate desert)	Zhang et al., 2020
Xinjiang	2000–2010	57.68 (Temperate steppe)	Yang et al., 2014
Xinjiang	2000–2014	54.66 (Temperate desert)	Ren et al., 2017

4.2 The intrinsic connection between NPP_A and meteorological factors

Based on the CASA and Thornthwaite Memorial model, this paper used the resulting simulated NPP to evaluate the relative effects of climate change and human activities in Altay Prefecture grassland. The results indicated that only 12.9% of the grassland restoration was induced by climate change, whereas the grassland degradation caused by climate change accounted for 14.6%, which was nearly twice that of human activities. Furthermore, the previous studies showed that climate change influenced grassland productivity primarily through temperature and precipitation changes, which further regulated photosynthesis as well as growing status and distribution (Wang et al., 2016; Liu et al., 2019a; Liu et al., 2019b). Therefore, correlation analysis was applied to NPP_A and precipitation as well as temperature. In total, these results showed the NPP_A had a slight positive correlation with precipitation and temperature (Fig. 7a and 7b), which was consistent with the previous studies (Zhu et al., 2019; Qin et al., 2020).

However, the NPP_A presented conflicting correlations with the precipitation and temperature locally in the study area. In particular, the NPP_A showed a negative correlation with precipitation in the south temperate desert and presented a strong positive correlation with the temperature in the north Altay Mountains regions. In terms of grassland NPP in temperate desert, previous studies (Jiao et al., 2017; Jia et al., 2019; Tong et al., 2020) concluded that the vegetation NPP increase in northwest China was mainly induced by precipitation. However, the study area is characterized by an arid and semi-arid continental climate, so the variation of grassland productivity should have a strong relationship with the soil moisture, soil microbes, and soil physical and chemical properties (Niu et al., 2008). Meanwhile, the temperate desert in Altay Prefecture adjacent to the Xinjiang Gurbantunggut Desert has suffered severe salinization, as well as serious surface evaporation and wind erosion (Li et al., 2005). These factors have led to the increasingly fragile ecosystem of the grasslands in the study area, with significantly reduced soil fertility and soil moisture retention capacity (Patrick et al., 2007). Simultaneously, the higher precipitation will increase the soil erosion to some extent, which will further inhibit the grassland growth (Lin et al., 2020). Hence, the precipitation presented a negative correlation with NPP in the partial desert. This phenomenon that the grassland NPP in the Altay Mountains regions showed a significantly positive correlation with temperature can be attributed to several factors. Firstly, the higher altitude and lower year-round temperature in the northern Altay Mountains enable vegetation litter to decompose slowly in the soil. With the temperature gradually increasing, the process of

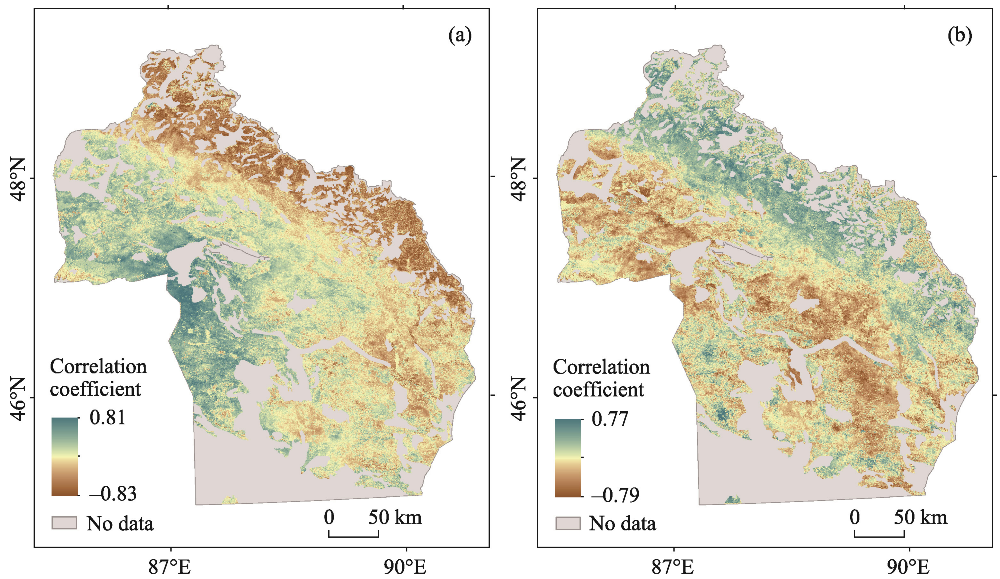

Fig. 7 Spatial distribution of correlation coefficients between NPP_A and influencing factors

Note: (a) Annual total precipitation; (b) Annual mean temperature.

organic matter decomposition is accelerated, which can offer a better material basis for the growth of grassland (Li et al., 2005). Secondly, the higher temperature may enhance the activity of microorganisms in the cold zone, which would contribute to soil organic matter accumulation, and promote carbon assimilation and biomass production (Liang, 2014). Thirdly, a higher temperature will cause earlier spring phenology, a longer vegetation growing season, and a faster photosynthetic rate (Sun et al., 2021).

According to the statistical results of the correlations between meteorological factors with various grassland types in Altay Prefecture, the precipitation has a significant stimulative influence on temperate desert and mountain meadow (Fig. 8a and 8c). Altay Prefecture is a typical arid and semi-arid region, where most of the grassland lacks the necessary moisture and organic matter. These conditions result in precipitation playing a crucial role in the growth of most of the grassland. In contrast, the temperature has an obvious inhibitory effect on temperate steppe, alpine meadow, and alpine steppe (Fig. 8b and 8d and 8e). These grasslands are mainly distributed in the Altay Mountains and Sawuer Mountains, where they are provided with adequate water to maintain vegetation development. However, these regions have a lower temperature along with the altitude increases, so a higher temperature is needed to offer a better development environment for seed germination, thus temperature becomes the determinant of vegetation growth among these grassland types.

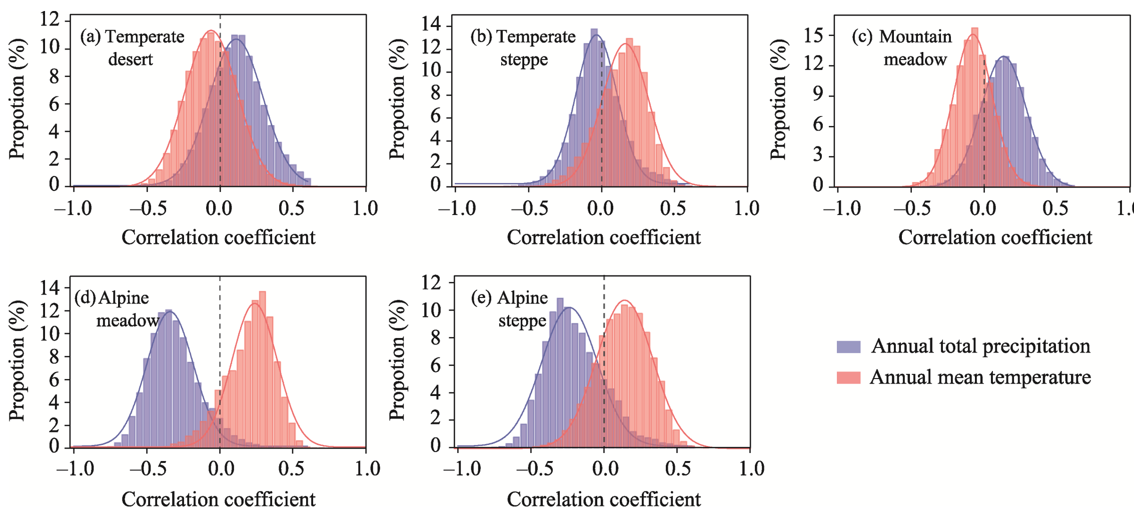

Fig. 8 Correlations between meteorological factors (annual total precipitation and annual mean temperature) and NPP_A in different grassland types

4.3 Impacts of climate change and human activities

The influences of climate variation on the grassland ecosystem mainly depend on the changes in temperature and precipitation, which could regulate the plant growth and, thus, the overall ecosystem productivity (Liu et al., 2019b). Previous studies (Zhou et al., 2014) pointed out that precipitation is the dominant factor regulating the vegetation NPP in arid and semi-arid areas. With the precipitation gradually increasing from 2000 to 2019, the restored area and vegetation cover in Altay Prefecture grassland should be improved. However, the positive effect of precipitation on the NPP increase is not obvious in most regions, except in the western and southern areas of Ulungur Lake. Meanwhile, climate variation was found to be an essential controlling factor that dominated the grassland degradation in this study. These phenomena may be relative to the extreme climatic events in the study area. In arid and semi-arid regions, where the fragile ecosystems are extremely sensitive to climate change, the effects of extreme climatic events may be further amplified in decreasing vegetation productivity, affecting the ecosystem balance and even inducing ecosystem degradation (Chen et al., 2019; Ye et al., 2020). In recent decades, the study area has experienced many natural hazards. For instance, the extreme drought in 2008 was the second most severe drought in Xinjiang since meteorological records began, which influenced a grassland area up to 65.82×10^4 ha. Moreover, Altay Prefecture suffered extraordinary snowstorms in 2009 and severe snowmelt flooding induced by the rapidly increasing temperature in 2010. Additionally, a catastrophic flood in 2016, the biggest one in the past 16 years, devastated the northern part of Xinjiang and had a drastic influence on vegetation growth. These extreme climatic events have further destroyed the fragile ecosystem, which was sensitive to climate change on the Altay Prefecture and was easily destroyed by the extreme climate (Ye et al., 2020). In such environments, seed germination and regular growth have suffered inhibition to varying extents, even though the grassland has sufficient precipitation (Sun et al., 2021), and the positive effects of climate change on grassland restoration were not distinctive overall. To conclude, precipitation played a crucial role in regulating grassland productivity, but climate change did not make a clear contribution to grassland restoration in this study, which may be attributed to the extreme climatic events that occurred over the recent periods.

This study showed that human activities have obviously promoted grassland restoration in the study area, contributing up to 47% of the total area, whereas the area of grassland degradation induced by human activities only represented 7.8%. These results may be closely linked with the effective implementation of various integrated environmental protection strategies. For example, to achieve sustainable development, the Return Grazing to Grass Program has been implemented by the government since 2002. Moreover, Zhang et al. found that the fenced area in Xinjiang rapidly increased to 1082.67×10^4 ha from 2003 to 2010, which can effectively prevent overgrazing and protect the natural grassland resources (Zhang et al., 2016). Furthermore, the Grassland Ecological Compensation Policy has been fully implemented since 2011, which focuses on grass-livestock balance and sustainable development of grassland. According to previous studies (Zhang, 2013; Hu, 2016), the vegetation coverage and grass production increased by 22.43% and 13.54%, respectively. These phenomena show that various protection measures have achieved productive results in promoting grassland restoration and adjusting the grass-livestock balance. Additionally, as shown in Fig. 9, the volume of livestock had a significant decrease from 2000 to 2019, whereas the non-agricultural population experienced a slight increase in the study area. These conditions indicated that the human disturbance from grazing and reclamation had decreased under ecological protection programs, which had an intrinsic interaction with the variation of NPP_H during the same period. In general, the grassland restoration was closely related with ecological engineering efforts implemented over the research period, which further confirmed that positive human activities can increase grassland productivity and promote the restoration in arid and semi-arid regions (Li et al., 2018).

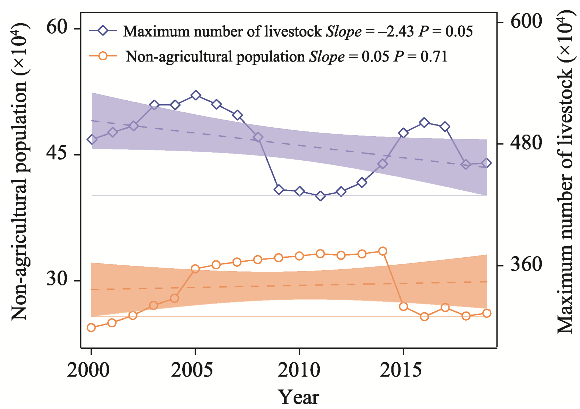

Fig. 9 The trends of the non-agricultural population and livestock over the study period from 2000 to 2019

4.4 Limitations and next steps

The methodology employed in this study also has some drawbacks. On the one hand, since the study area is located in the northwest border area and has complex climatic conditions, it is difficult to implement large-scale grassland investigations, so we used the MODIS NPP product and the results of other studies to validate the simulated NPP. However, using field investigation to validate the simulated values would improve the verification precision to some extent. Therefore, we suggest that field investigations should be considered to validate the simulated results in future studies.

On the other hand, there have been other factors controlling grassland NPP variation, like grassland fires, grassland species and disease outbreaks, and the concurrent and lagged effects of extreme climatic events, which have not been quantified in this study owing to the limitations of our methodology (Liu et al., 2019a). Meanwhile, as mentioned above, some positive human activities have significantly improved the ecological conditions in the study area, but it would be difficult to distinguish the spatial patterns of the contributions of these engineering projects to the grassland restoration because of the difficulty in data acquisition and quantification methodology. Furthermore, this paper only presents a qualitative analysis of the effects of soil physicochemical properties on the grassland productivity, while its quantitative assessment in fragile ecosystems deserves further study, especially in the arid and semi-arid regions. These factors probably effect the grassland NPP variation in either a straightforward or indirect way. Separating the conflicting impacts of these specific factors on climate variation and human activities and quantitatively assessing of their relative contributions to the grassland NPP variation should receive more attention in future research.

5 Conclusions

In this study, NPP was selected as the indicator and its slope was used as the basis for scenario simulation in evaluating the relative contributions of climate change and human activities to grassland dynamics in the Altay Prefecture from 2000 to 2019. The grassland in Altay Prefecture presented a slight increasing trend over the study period. The NPP_A with a significant continuous increase occurred locally in the research regions, especially in Ulungur River, Irtysh River, and Sawuer Mountains, which have good irrigation conditions or abundant precipitation. Additionally, the evolving direction of NPP_A in some study area is continuously unchanged, but most of area is changing in an uncertain direction. This study showed that it was human activities, and not climate change, which was the primary trigger of the grassland NPP increase. Meanwhile, in various grassland types, the dominant factor that affected grassland restoration was also human activities, whereas climate change played a dominant role in grassland degradation. The potential explanation for these results is that grassland restoration has mainly benefited from the great contribution caused by ecosystem protection projects in recent years. In this study, we found that the NPP_A presented an inverse correlation with the precipitation and temperature locally in the study area, especially in the south temperate desert and north Altay Mountains. This phenomenon was closely related to the joint action of the ecological environment and the physicochemical properties of the soil in the study area. Therefore, different scenarios are required according to the local situations, and they are crucial for mitigating grassland desertification and realizing sustainable development.

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定量评估气候变化和人类活动对阿勒泰地区草地净初级生产力的影响

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摘 要：阿勒泰地区的草地退化严重阻碍了当地经济的可持续发展和畜牧业的稳定运行，如今受到了广泛的关注。而气候变化和人类活动被认为是草原退化的主要诱因，定量评估气候变化和人类活动对草地变化的相对作用，对于探究草地退化机制和控制草地退化具有重要意义。本文采用 Carnegie-Ames-Stanford Approach 和 Thornthwaite memorial 模型，模拟了 2000–2019 年阿勒泰地区的实际(NPP_A)和潜在净初级生产力(NPP_P)，并采用两者之差来反映人类活动对草地净初级生产力的相对作用(NPP_H)。在此基础上，我们利用皮尔逊相关系数验证了模拟 NPP 的可行性，探究阿勒泰地区草地净初级生产力的时空变化，并构建综合情景以定量评估气候变化和人类活动对草地变化的相对作用。结果表明：（1）本文模拟的 NPP_A 与 MOD17A3 数据集在空间分布上具有高度一致性；（2）NPP_A 增加的地区占总面积的 70.53%，而 NPP_A 减少的地区则为总面积的 29.47%。研究期间，NPP_A 呈现出轻微的增加趋势(0.83 g C m^{-2} yr^{-1})，而 NPP_P 和 NPP_H 则呈现出下降趋势(–1.31 和–2.15 g C m^{-2} yr^{-1})；（3）人类活动在草地恢复过程中起到了关键作用，人类活动促进了 66.98%的区域发生恢复。气候变化则是导致草原退化的主要原因，导致 55.70%的草地退化。这些结果可以揭示气候变化和人类活动所引起的草地变化机制，并进一步应用于制定阿勒泰地区防治荒漠化的有效措施。

关键词：草地退化；植被净初级生产力；气候变化；人类活动；阿勒泰地区