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Grassland Variation and Its Driving Factors from 2000 to 2016: A Comparative Assessment between Qinghai-Tibet Plateau and Inner Mongolia Plateau

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Abstract

The grassland of Qinghai-Tibet Plateau (QTP) and Inner Mongolia Plateau (IMP), accounting for 73.9% of the total grassland area in China, is significant to food and ecological safety. Due to climate change and irrational human activities, grasslands on the two plateaus have severely degraded over recent decades. Understanding the dynamic changes of grassland and its driving forces is necessary to make effective measurements to prevent grassland degradation. Here, we selected the net primary productivity (NPP) as an indicator to quantitatively assess the dynamic variation of grassland and the relative roles of climate change and human activities on QTP and IMP from 2000 to 2016. The results found significant spatial variability of grassland on QTP. 28.3% of the grassland experienced degradation and was mainly distributed in the southern QTP, versus 71.7% of the grassland was restored and mainly distributed in the central and northern QTP. In contrast, grassland on IMP didn't show significant spatial variability. Most of the grassland on IMP was restored during the study period. Climate change (*i.e.* increased precipitation) was the dominant factor and could explain 72.8% and 84.4% of the restored grassland in QTP and IMP. Irrational human activities (*i.e.* overgrazing) were the main driving factors and could explain 72.9% and 100.0% of the degraded grassland on the two plateaus during the study period. Ecological restoration projects were favorable for grassland restoration on the two plateaus, and they contributed to 27.2% and 15.6% of the restored grassland in QTP and IMP, respectively. Therefore, climate changes on IMP were more favorable for grassland restoration, and human activities have a greater impact on the grassland variation on QTP.

Keywords

Grassland Degradation, Driving Force, Qinghai-Tibet Plateau, Inner Mongolia Plateau

1. Introduction

Qinghai-Tibet Plateau and Inner Mongolia Plateau are the main distributive regions of grassland in China (accounting for 73.9% of the total grassland area in China) and distributed the largest proportion of alpine and temperate grasslands, respectively. Meanwhile, the two plateaus are sensitive areas to global climate changes [1] (Sha *et al.*, 2015). In recent decades, the two plateaus have been experiencing similarly higher rates of warming than the rest of the world [2] [3] [4], but precipitation in QTP and IMP shows a mixed trend and a decreasing trend, respectively. Also, there is an increasing intensity of human activities in QTP and IMP (China Statistical Yearbook). Due to climate change and human activities, 38.8% and 28.8% of the grassland experienced severe degradation on QTP and IMP, respectively [5] [6]. Grassland degradation could cause serious environmental problems [7] [8] and threaten food and ecological safety [9] [10] [11] [12]. To prevent grassland degradation, the government has been implementing a series of ecological restoration projects on QTP and IMP since 2000. These changes in climate and human activities could profoundly induce the dynamic change of grassland. Therefore, it's necessary to understand the dynamic change of grassland in recent years and its driving factors to help prevent grassland degradation and ensure grassland ecological security.

Many studies discussed grassland degradation and its association with climate change and human activities on QTP and IMP [13]. It is found that the grassland of QTP showed an overall degraded trend before 2000 and a recovery trend after 2000, and climate change is the main driving factor for grassland dynamic change and the role of human activities gradually increases [6] [14] [15] [16]. A similar dynamic change of grassland and its key driving factors are found in IMP [17]. It is emphasized that irrational human activities induced the grassland degradation but ecological projects are favorable to grassland restoration [18] [19] [20] [21] [22]. However, several gaps remain in previous research: 1) most studies focused on several selected fields and hotspots, and large-scale study is few; 2) most of the studies are qualitative but lack quantitative data; 3) there are few studies considering the relative role of human activities as most studies have focused on climatic factors.

Vegetation indexes are effective indicators to monitor grassland degradation and reveal the impacts of human activities and climate change on grassland degradation [14] [23] [24] [25] [26]. Net primary productivity (NPP), the net amount of solar radiation converted to plant organic matter by plants through photosynthesis, can reflect the growth status of vegetation [27] and also is sensitive to both climate variation and human activities [28]. Therefore, many researchers have adopted NPP as an indicator of grassland degradation and to distinguish the impact of climate from that of human activities [29] [30] [31] [32] [33]. Haberl [34] first proposed the human appropriation of NPP as a measure of the environmental impacts of human activities. Zika and Erb introduced this approach for the quantitative assessment of the effect of human activities on degradation [35]. Latest studies improved this approach which introduced actual NPP (ANPP) to monitor the grassland degradation status, the potential NPP (PNPP) and the human-influenced NPP (HNPP, and the difference between PNPP and ANPP) to assess the effect of climate change and human activities on grassland degradation, respectively. These studies confirmed that the NPP is a reliable indicator to monitor grassland degradation and distinguish the impact of climate from that of human activities [6] [14] [23] [24] [25] [26].

The grassland in the two plateaus may respond differently to climate changes and human activities. Regional-scale comparative studies are important in providing an understanding of different regional responses to climate changes and human activities and making progress together to protect grassland [24] [26] [36]. In view of grassland on QTP and IMP playing an important role in the grassland ecosystem of China, this study aims to monitor and evaluate the impact of climate change and human activities on grassland change dynamics on QTP and IMP by using ANPP as the indicator to monitoring the grassland degradation status on QTP and IMP from 2000 to 2016 and combining ANPP with PNPP and HNPP. We hope the results will provide useful information to improve our understanding of the relative contributions of climate changes and human activities to grassland degradation, and therefore contribute to developing reasonable policies to combat grassland degradation in China.

2. Materials and Methods

2.1. Data

In this study, the normalized-difference vegetation index (NDVI), vegetation type data, and meteorological data were necessary to calculate the ANPP in the study area. We downloaded the 16-day synthesized, atmospherically corrected maximum NDVI data (MOD13A1) with the spatial resolution of 1000 m from NASA's archive and distribution System (https://ladsweb.modaps.eosdis.nasa.gov/search/). We used the 16-day NDVI data to synthesize monthly NDVI values using the maximum-value compositing method. Vegetation distribution data was derived from a national vegetation distribution map downloaded from the China's WestDC site (http://westdc.westgis.ac.cn/). The grassland data was obtained from the vegetation distribution map. The vegetation distribution map was created mainly based on field investigation, remote sensing images and other materials in vector format and has the best accuracy in China. The data was resampled to a spatial resolution of 1000 m. The meteorological data was downloaded from China's National Meteorological Information Data (http://data.cma.cn/), which includes monthly average temperature and total precipitation recorded at 204 meteorological stations, and the total solar radiation recorded at 43 meteorological stations in and around the study area. The meteorological data was interpolated using ANUSPLINE version 4.3 software to generate monthly raster images with spatial resolutions of 1000 m. We applied the Albers equal-area conical projection and WGS-84 datum to all spatial data.

Field investigations were conducted to collect the aboveground biomass in 2014, 2015 and 2016 on QTP and 2015 on IMP. There were 80 sites to collect grassland aboveground biomass. At each site, three quadrats of 100 cm multiply by 100 cm were set up, and then the measured NPP was calculated by the aboveground biomass [37].

2.2. Methods

The CASA model, accounting for the light-use efficiency of vegetation, was developed and modified by many researchers [27] [38] [39], and was the most widely used model in recent years [40]. So we used the CASA model to calculate ANPP (g.cm^{-2}.yr^{-1}). ANPP is determined by two variables: the absorbed photosynthetically active radiation (APAR) and light-use efficiency (ε):

$$\text{ANPP} = \text{APAR} \times \varepsilon = \text{FPAR} \times \text{SOL} \times 0.5 \times \varepsilon_{\max} \times T_{\varepsilon} \times W_{\varepsilon} \quad (1)$$

where FPAR is the fraction of the total solar radiation (SOL) accounted for by PAR and can be calculated from NDVI, SOL is the total solar radiation, 0.5 is the proportion of SOL intercepted by the vegetation, $\varepsilon_{\max}$ is the maximum light-use efficiency under ideal conditions, and T_{ε} and W_{ε} is the temperature and moisture stress coefficient, respectively. The detail information of CASA model was discussed by [27].

The validation can be made by comparing the simulation results with observed data [41]. In practice, NPP data converted from biomass is often used as a substitute for observed NPP data as it is usually difficult to obtain the latter [41]. In the present study, the observed NPP data was calculated based on the field-measured biomass data on QTP and IMP. The observed data was used to verify the CASA modeling results on spatial location. Our comparison between the observed ANPP and the CASA simulation results showed good agreement with actual data from field sampling points ($R^2 = 0.829$, $p < 0.01$; **Figure 1**), so the simulation accuracy of the model was satisfactory for the needs of the study.

In this study, we used the Synthetic model to estimate PNPP (g.cm^{-2}.yr^{-1}), which can provided better simulation of PNPP in semiarid and arid areas of China [42]. The model estimated NPP by relating the water-balance and heat-balance equations [42], and was expressed as follows:

$$\text{PNPP} = \text{RDI}^2 \times \frac{r \times \left(1 + \text{RDI} + \text{RDI}^2\right)}{\left(1 + \text{RDI}\right)\left(1 + \text{RDI}^2\right)} \times \exp\left[-\sqrt{9.87 + 6.25\text{RDI}}\right] \times 100 \quad (2)$$

$$\text{RDI} = \left(0.629 + 0.237\text{PER} - 0.00313\text{PER}^2\right)^2 \quad (3)$$

$$\text{PER} = 58.93 \times \text{BT}/r \quad (4)$$

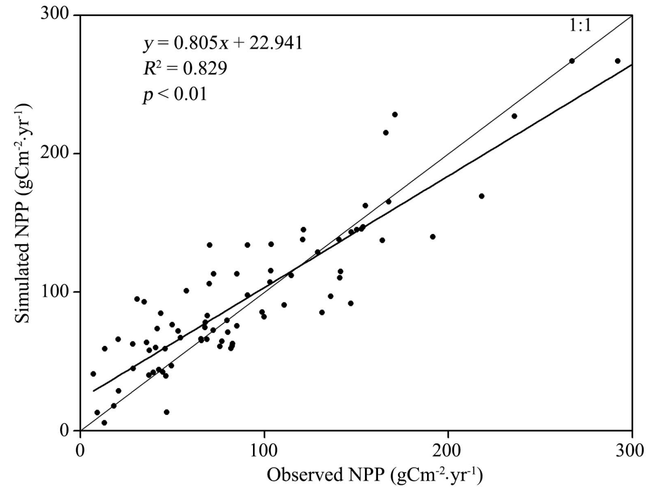

Figure 1. Validation of the CASA model for the grasslands in study area.

where r is the annual total precipitation (mm), BT is annual average biological temperature (˚C), which is defined as the average biological temperature for temperatures ranging between 0˚C and 30˚C, PER is the potential evaporation (mm), RDI is the radiative index of dryness.

HNPP (g.cm^{-2}.yr^{-1}) is the difference between PNPP and ANPP, and represents the loss or increment of NPP induced by human activities:

$$\text{HNPP}(x,t) = \text{PNPP}(x,t) - \text{ANPP}(x,t) \tag{5}$$

Thus, a positive HNPP represents an NPP loss induced by human activities and a negative value represents an NPP increment produced by human activities.

Vegetation dynamics measured by NPP are the most intuitive manifestation of grassland degradation [25]. In this study, the Formula (6) was used to calculate the trends in ANPP, PNPP, and HNPP from 2000 to 2016 in the study area:

$$\text{Slope} = \left[17 \times \sum_{i=1}^{17} i \times \text{NPP}_i - \left(\sum_{i=1}^{17} i \sum_{i=1}^{17} \text{NPP}_i\right)\right] \Big/ \left(17 \times \sum_{i=1}^{17} i^2 - \left(\sum_{i=1}^{17} i\right)^2\right) \tag{6}$$

where $i = 1, 2, \ldots 17$ are the years 2000, 2001, … 2016, respectively, and NPP_i is the NPP value in year i. A positive slope of ANPP (S_{ANPP}) represents grassland reversion, whereas a negative S_{ANPP} represents grassland degradation. The slopes of PNPP (S_{PNPP}) and HNPP (S_{HNPP}) from 2000 to 2016 reveal the impacts of climate change and human activities on grassland degradation, respectively. To determine the change in NPPs during the study period, we calculate the total change of NPP for each pixel using the following formula:

$$\Delta\text{NPP} = (n-1) \times \text{Slope} \tag{7}$$

where n = 17 years, represents the study period from 2000 to 2016. With reference to previous studies of the relative impacts of human activities and climate change on desertification [43] [44], we defined eight scenarios. **Table 1** shows the eight scenarios that induced the grassland dynamics.

Table 1. Methods for assessing the driving factors of grassland restoration or degradation in eight scenarios.

S_{ANPP}	Scenarios	S_{PNPP}	S_{HNPP}	Relative role of climate change (%)	Relative role of human activities (%)
Grassland restoration ($S_{ANPP} > 0$)	Scenarios 1	<0	<0	0	100
	Scenarios 2	>0	>0	100	0
	Scenarios 3	>0	<0	$\frac{\Delta PNPP}{\Delta PNPP + \Delta HNPP} \times 100$	$\frac{\Delta HNPP}{\Delta PNPP + \Delta HNPP} \times 100$
	Scenarios 4	<0	>0	Error	Error
Grassland degradation ($S_{ANPP} < 0$)	Scenarios 5	>0	>0	0	100
	Scenarios 6	<0	<0	100	0
	Scenarios 7	<0	>0	$\frac{\Delta PNPP}{\Delta PNPP + \Delta HNPP} \times 100$	$\frac{\Delta HNPP}{\Delta PNPP + \Delta HNPP} \times 100$
	Scenarios 8	>0	<0	Error	Error

Note: ΔPNPP is the total increase or decrease of PNPP during 2000-2016. ΔHNPP is the total increase or decrease of HNPP. The two indicators were calculated using Equation (7).

3. Results

3.1. Trends in ANPP, PNPP, and HNPP

The simulated results showed the average annual changing rate of grassland ANPP on QTP was 0.9 $g.cm^{-2}{\cdot}a^{-1}$ during the study period, and the rate in most of grassland on QTP was between 0.0 - 2.0 $g.cm^{-2}{\cdot}a^{-1}$. Grassland ANPP on QTP showed obvious spatial variability (**Figure 2(a)**). Grassland that exhibited increasing ANPP ($S_{ANPP} > 0$) was 992,760 km^2, accounted for 71.7% of the total area of grassland. Grassland that exhibited decreasing ANPP ($S_{ANPP} < 0$) was 392 248 km^2, mainly distributed in the south of the QTP, accounted for 28.3% of the total area of grassland (**Figure 2(a)**). Contrary to the grassland on QTP, most of grassland on IMP experienced increasing ANPP, and the annual changing rate in most grassland was above 2.0 $g.cm^{-2}{\cdot}a^{-1}$. The total area with $S_{ANPP} > 0$ was 489 333 km^2, far more than the area with $S_{ANPP} < 0$ (29 901 km^2) on IMP. The grassland with $S_{ANPP} < 0$ only count for 5.8% of the total area of grassland on IMP, which was sporadically distributed (**Figure 2(a)**).

The trend of grassland PNPP on QTP also showed obvious spatial variability. Grassland that exhibited increasing PNPP ($S_{PNPP} > 0$) was 1,084,441 km^2, accounting for 78.3% of the total area of grassland. The remaining 21.7% of this area (300,567 km^2) had $S_{PNPP} < 0$, primarily in the south (**Figure 2(b)**). However, the grassland PNPP exhibited an increasing trend on the whole IMP, and the increasing rate was above 2.0 $g.cm^{-2}{\cdot}a^{-1}$ for most grassland (**Figure 2(b)**). That means climate changes on IMP were more favorable for grassland restoration than that on QTP.

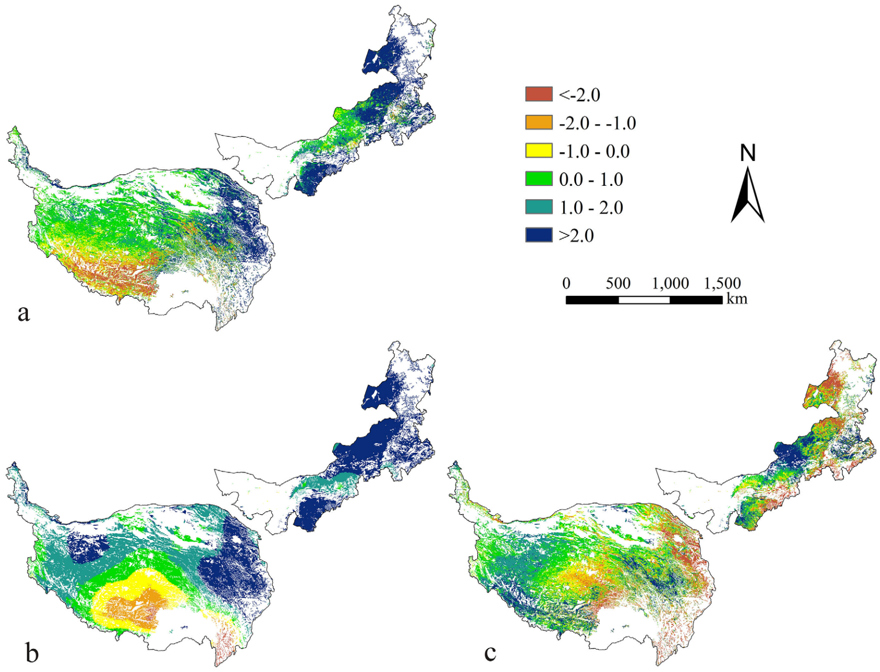

Figure 2. Spatial distributions of trends for (a) ANPP (S_{ANPP}), (b) PNPP (S_{PNPP}) and (c) HNPP (S_{HNPP}) of the QTP and IMP grasslands in the periods 2000-2016.

Compared with PNPP and ANPP, the trend in HNPP from 2000 to 2016 showed a different spatial distribution pattern (**Figure 2(c)**). On QTP, grassland that showed increasing HNPP ($S_{HNPP} > 0$), accounts for 62.6% of the total area and primarily distributes in the west and south. The remaining 37.4% of the total area (518,447 km^2) was in the east and middle region, where human activities had a positive effect on grassland (**Figure 2(c)**). On IMP, the grassland with $S_{HNPP} > 0$, accounts for 57.5% of the total area of grassland (298,605 km^2) and mainly distributed in the west and middle region. The grassland with $S_{HNPP} < 0$ (positive effect of human activities on grassland) accounted for 42.5% of the total area (220,629 km^2), primarily distributed in the north and south region, where the climate was relative warmer and wetter (**Figure 2(c)**).

3.2. Contributions of Climate Change and Human Activities to Grassland Dynamics

By superimposing the data for the trends in PNPP and HNPP in the areas of grassland restoration ($S_{ANPP} > 0$), we obtained the dominant factors responsible for grassland restoration from 2000 to 2016 based on the scenario definitions. The result showed that climate change dominated 72.8% of the grassland restoration on QTP, which mainly distributed in the central and northern region (**Figure 3** & **Table 2**). The remaining 27.2% of grassland restoration was due to human activities. Similarly, climate change was also the main driving factor for grassland restoration on IMP. Climate-dominated restoration accounted for 84.4% of the total grassland restoration area, the remaining 15.6% of grassland restoration was due to human activities (**Figure 2**).

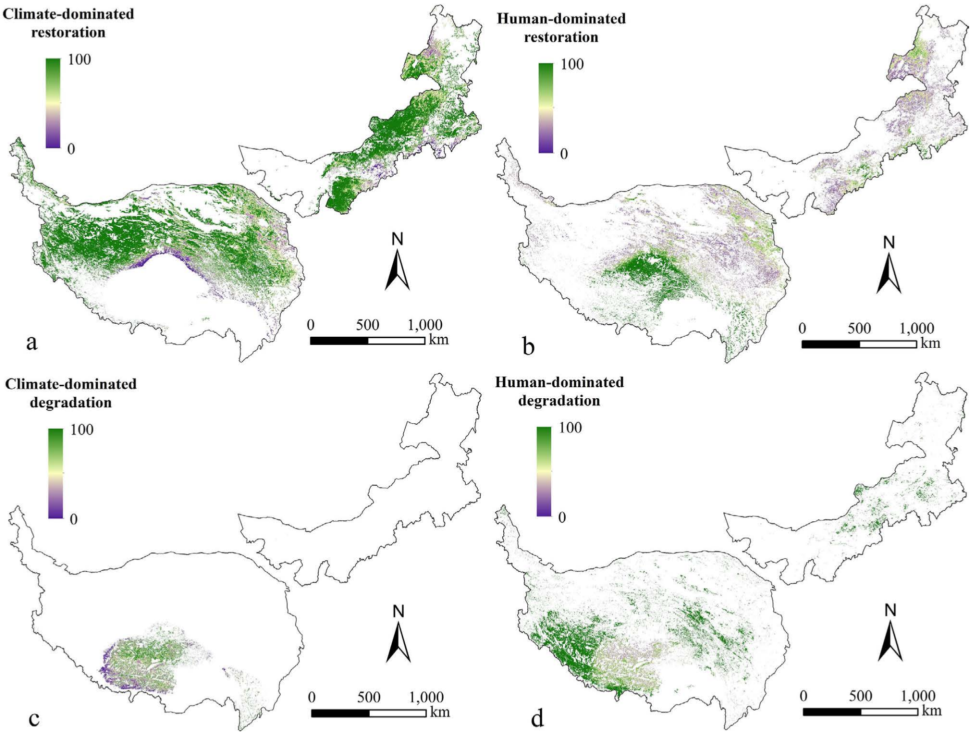

Figure 3. Spatial distribution of the (a) climate-dominated restoration, (b) human- dominated restoration, (c) climate-dominated degradation and (d) human-dominated degradation of the QTP and IMP grasslands.

Table 2. The relative role of climate change and human activities in the dynamic change of grassland.

	QTP		IMP	
	Relative role of climate change (%)	Relative role of human activities (%)	Relative role of climate change (%)	Relative role of human activities (%)
Grassland restoration	72.8	27.2	84.4	15.6
Grassland degradation	27.1	72.9	0.0	100.0

The driving factors of grassland degradation were also analyzed. Spatial variation in the dominant factors responsible for grassland degradation existed on QTP. Climate-dominated degradation accounted for 27.1% of the total degradation area, which mainly distributed in the south region (**Figure 3** & **Table 2**). And 72.9% of the degraded grassland was induced by human activities, which mainly distributed in the southwestern and eastern region. Contrary to QTP, 100% of the degraded grassland on IMP was caused by human activities (**Table 2**).

Spatial distribution of the trends for the average annual temperature and the annual total precipitation of QTP and IMP from 2000 to 2016 were shown in **Figure 4**, while the Time series of grassland PNPP, annual temperature, precipitation, grassland HNPP and livestock number of the two plateaus from 2000 to 2016 were in **Figure 4**.

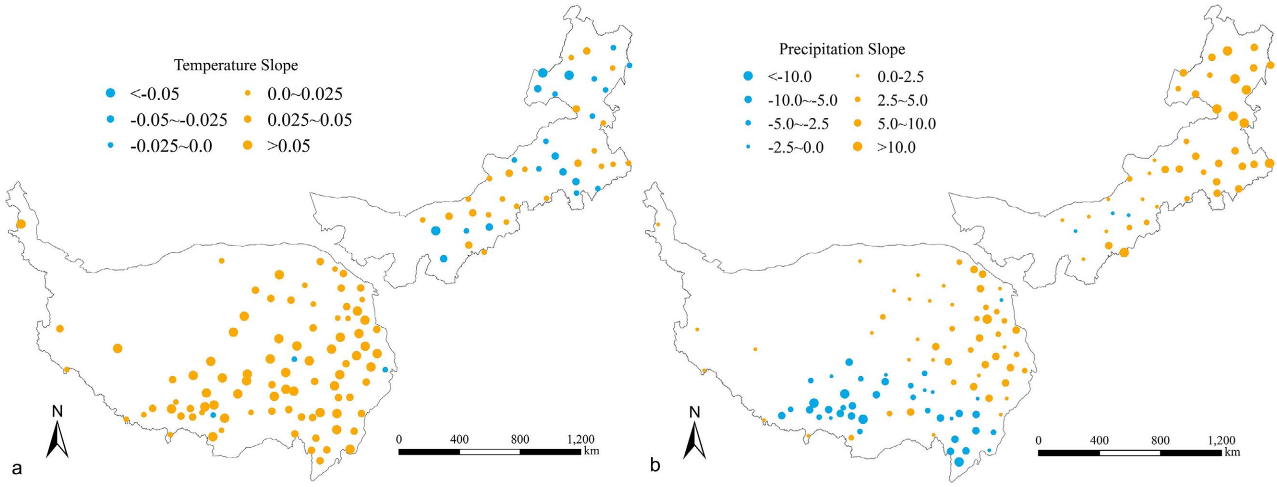

Figure 4. Spatial distribution of the trends for (a) the average annual temperature and (b) the annual total precipitation from 2000 to 2016.

4. Discussion

Climate change is one of the key factors that affect the grassland degradation [45] [46]. In this study, we found that grassland on QTP and IMP showed an overall restoration from 2000 to 2016, and climate changes dominated the grassland restoration. This result was consistent with previous studies of grassland NPP on QTP and IMP [15] [21]. On the QTP and IMP (the most sensitive areas of global climate change), grassland is mainly located in arid, semi-arid and semi-humid zones. The grassland in these regions is particularly susceptible to fluctuations in precipitation [47] [48] [49]. Besides, low temperature was the limiting factor for grassland growth on QTP [50]. On the QTP, there is a consensus that temperature increased in most region in recent 30 to 50 years. But the trend in precipitation varied spatially, with a decrease in southern of QTP, and an increase in central and western of QTP [4] [14] [51]. The trend in precipitation (**Figure 4(b)**) showed a similar spatial distribution to the trends in PNPP and ANPP (**Figure 2**). This suggests that increasing precipitation promoted vegetation growth, and decreasing precipitation restrained vegetation growth. The rising temperature exerts complex effects on vegetation growth [14] [40] [49]. Low temperature was the limiting factor for grassland growth on QTP and rising temperature was favor for the grassland growth. Meanwhile, increased evaporation caused by rising temperature will sharpened the dry condition and limit grassland growth. There was no obvious correspondence between the trend in PNPP and temperature on QTP from 2000 to 2016 (**Figure 5(a)**). Therefore, the variation in precipitation was the dominant climatic driving factor responsible for grassland degradation and restoration on the QTP from 2000 to 2016.

Over the past 30 years, there are an increasing trend in temperature on IMP, and a decreasing trend in precipitation [3] [52]. However, the variation in temperature showed a decreasing trend from 2000 to 2016, the precipitation was in a significantly increasing trend (**Figure 5(b)**). Water is the limiting factor for vegetation growth on the IMP [50]. Increasing precipitation was favor for vegetation

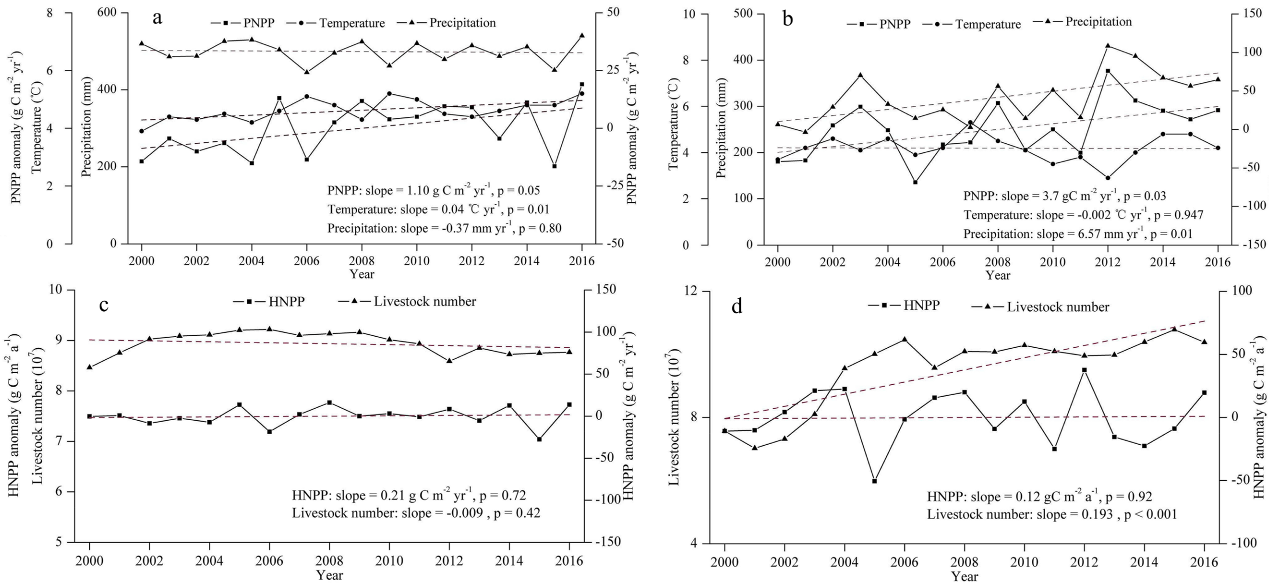

Figure 5. Time series of (a) grassland PNPP, annual temperature, and precipitation of QTP, (b) grassland PNPP, annual temperature, and precipitation of IMP, (c) grassland HNPP, and livestock number of QTP and (d) grassland HNPP, and livestock number of IMP from 2000 to 2016.

growth and grassland restoration. The variation in PNPP has a good agreement with the variation in the integrated precipitation data (**Figure 5(b)**), but there is no obvious correspondence relationship between the trend in PNPP and temperature (**Figure 5(b)**). That means increasing precipitation was the dominant climatic driving factor responsible for grassland restoration on the IMP from 2000 to 2016.

Grazing is one of the important human activities that affected the grassland ecosystem on QTP [7] [14] [53] and IMP [18] [54] [55] [56]. Overgrazing was one of the factors that induced the grassland degradation on QTP [14] [55]. From 2000 to 2016, the total number of livestock in Tibet Autonomous Region and Qinghai Province was in the range of 8.4×10^7 - 9.7×10^7 (standardized sheep units) (**Figure 5(c)**), most of grassland was overloading. However, as the total number of livestock decreased in general versus the trend in HNPP increased (**Figure 5(c)**), it implies that there are other irrational human activities that constraint the grassland growth. For example, in recent decades, the tourism in QTP has been developing and the population also increased rapidly (Qinghai Statistical Yearbook and Tibet Statistical Yearbook), all of such activities have brought tremendous pressure to the vulnerable grassland ecosystem.

The total number of livestock in Inner Mongolia Autonomous Region was in the range of 7.0×10^7 - 10.8×10^7 (standardized sheep units) during this study period, grassland was also overloading. Meanwhile, the total number of livestock significantly increased ($p < 0.001$). And the trend in HNPP also increased from 2000 to 2016 (**Figure 5(d)**). Thus, the overgrazing, increasing livestock number in accordance with the increased HNPP suggest that overgrazing was one of the main factors induced the degradation of grassland. However, the changing trends of the total number of livestock and HNPP on IMP were different. That means besides grazing, there existed other human activities slowed down the increasing trend of HNPP and promoted the grassland reversion in IMP. Compared the impacts of irrational human activities on the grasslands between the two plateaus, the trend in HNPP on QTP grassland was larger than that on IMP grassland, the areas with $S_{ANPP} > 0$ and human-dominated degradation on QTP grassland were also greater than that on IMP grassland. That means the impact of irrational human activities on the grassland on QTP was greater than that on IMP.

Since 2000, a series of ecological restoration projects have implemented on the QTP and IMP, such as the Grazing Withdrawal Program, the Natural Grassland Protection Program and so on. These programs include enclose the degraded grasslands, ecological compensation, blocks rotational grazing, pest control and so on. These measures have been proved to be effective in controlling the grassland degradation [57] [58] [59]. Our results also showed that human activities were an important factor that promoted the grassland reversion (**Figure 3(b)**). However, the contributions of human activities to grassland reversion on the two plateaus were different. 27.2% and 15.6% of restored grassland were induced by human activities on QTP and IMP, respectively. The trends in the total number of livestock from 2000 to 2016 were different for the two plateaus, decreasing on QTP, significantly increasing on IMP (**Figure 5**). Thus, the effect of ecological projects for grassland restoration on QTP was better than those on IMP, which may be related to the differences in ecological protection investment among QTP and IMP.

5. Conclusion

In this study, we analyzed the dynamic variation of grassland and its driving factors on QTP and IMP from 2000 to 2016 by selecting NPP as an indicator. The results showed that the changing trend of grassland on QTP showed obvious spatial variation, 28.3% of grassland area experienced degradation, which was mainly distributed in the southern of QTP. However, grassland NPP exhibited an overall increasing trend on IMP, and 94.2% of grassland experienced restoration. Climate change dominated the grassland restoration on the two plateaus, 84.4% and 72.8% of restored grassland was dominated by climate changes on IMP and QTP, respectively. Precipitation increase was the main climatic factor that induced grassland restoration. Irrational human activities were the dominant factor that leads to grassland degradation on the two plateaus. All of the grassland degradations on IMP were caused by irrational human activities; however, 72.9% and 27.1% of degraded grassland on QTP were due to irrational human activities and drying climate, respectively. The ecological restoration projects implementing promoted the grassland restoration on QTP and IMP, and 15.6% and 27.2% of restored grassland were dominated by human activities on IMP and QTP, respectively. The impact of climate changes on IMP was more favorable for grassland restoration than that on QTP, and the impact of human activities on the QTP grassland was greater than that on the IMP grassland. Thus, the government should continue to implement the ecological programs on the two plateaus and the grassland on QTP deserved more attention.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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