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Comparative assessment of grassland degradation dynamics in response to climate variation and human activities in China, Mongolia, Pakistan and Uzbekistan from 2000 to 2013

Yue Yang [a], Zhaoqi Wang [a], Jianlong Li [a, *], Chencheng Gang [a, b], Yanzhen Zhang [a], Ying Zhang [a], Inakwu Odeh [c], Jiaguo Qi [d]

[a] *Department of Ecology, School of Life Science, Nanjing University, Nanjing, PR China*
[b] *Institute of Soil and Water Conservation, CAS, Yangling, PR China*
[c] *Department of Environmental Sciences, Faculty of Agricultural and Environment, The University of Sydney, Sydney, Australia*
[d] *The Center for Global Change & Earth Observations, Michigan State University, East Lansing, USA*

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ABSTRACT

Quantifying the driving force is significant to understand the impact of climate variation and human activities on grassland degradation. In this study, we selected net primary productivity (NPP) as an indicator to quantitatively assess the relative roles of climate variation and human activities in China, Mongolia, Pakistan and Uzbekistan from 2000 to 2013. The results showed that 1.9% of grassland areas experienced degradation in Uzbekistan. By contrast, 29.6%, 16%, and 32.5% of grassland areas underwent restoration in China, Mongolia and Pakistan, respectively. Furthermore, 83.9%, 85.1%, 6.7% of restored grassland areas were influenced by climate variation and 65%, 79.1%, 11.6% of degraded areas were affected by human activities in Mongolia, Pakistan and Uzbekistan, respectively. The NPP variation also could be calculated to evaluate the impacts of these factors and results were consistent with the findings based on area. Therefore, climate variation dominated grassland restoration, human activities dominated degradation in Mongolia and Pakistan, and Uzbekistan was just the opposite. In China, 38.5% of the grassland restoration areas was caused by climate variations compared with 38% induced by human activities. On the contrary, 37.4% of grassland degradation was caused by climate variation and 30% resulted from human activities. In addition, the results based on NPP variation revealed that 39.2% of restored grassland areas were influenced by human activities and 38.2% of degraded areas were affected by climate variation. Therefore, climate variation dominated grassland degradation and the driving force of restoration was determined by the effectiveness of environmental protection programs.

1. Introduction

The terrestrial ecosystems have undergone dramatic environmental changes, including alterations in climate, atmospheric composition, land use and management (Intergovernmental Panel on Climate Change, 2014). Global warming and increasing human activities have significantly affected the natural ecosystems in the world (Gao et al., 2013; Wang et al., 2012a). Grassland, one of the largest types of vegetation in the world, accounts for nearly 25% of the global land surface. As important natural ecosystems, grasslands play a significant role in maintaining material circulation, and balancing greenhouse gas, particularly in terms of global carbon storage and further carbon sequestration (French, 1979; O'Mara, 2012; Scurlock and Hall, 1998).

Grassland degradation is one of the global ecological environmental problems, and the area of grassland degradation has reached 1401 × 10^4 km^2 in 2010, accounting for nearly 49.3% of the world's grassland areas (Gang et al., 2014). These grassland areas have been degraded to a certain extent because of excessive land use (Harris, 2010), population growth (Nan, 2005), and global warming (Chengqun et al., 2012). Grassland resources in China, Mongolia, Pakistan and Uzbekistan are abundant and most of them

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* Corresponding author.
E-mail address: lijianlongnju@163.com (J. Li).

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have had pastoral use. As the four countries are located in the Silk Road Economic Belt, they form a connected whole. Comparative assessment of these four countries' grassland degradation dynamics is helpful to learn from each other and make progress together to protect grassland. The large grasslands can serve as a significant repository of natural resources and can provide vast lands for farming and grazing. However, many researches on grassland ecosystems in these four countries have focused on local and sub-catchment scales (Peng et al., 2013). In recent years, global climate and overgrazing have caused grassland degradation in Mongolia (Kawamura et al., 2005; Sekiyama et al., 2014) and Pakistan (Scarnecchia et al., 1998). The area of grassland have gradually reduced in Uzbekistan (Fan et al., 2012). China has become one of several countries severely affected by the degradation, approximately 90% of the grassland area in China has been degraded because of climate and human activities (Harris, 2010; Nan, 2005). Therefore, a deeper understanding of the driving factor of degradation is necessary and fundamental to restore degraded grasslands and promote sustainable development of grassland resources. (Han et al., 2008).

According to the previous researches, climate and human activities are the main driving forces of grassland degradation (Esser, 1987; Field, 2001; Haberl, 1997). Many researchers have realized that the grassland degradation is caused by over-grazing and extensive cutting, particularly in the developing countries (Liu and Diamond, 2005; Yang et al., 2005). Similarly, other studies have attributed the degradation to increased global temperature and different precipitation patterns such as drought and winter precipitation (Ravi et al., 2010; Zhou et al., 2005). Nevertheless, it is difficult to distinguish the effects of these two factors (Wessels et al., 2007). It is crucial to use an optimal quantitative assessment method to evaluate the effects of climate and human factors (Verón et al., 2006). Net primary productivity (NPP), the net amount of solar radiation converted to plant organic matter by plants through photosynthesis, is a reliable indicator of ecosystem function and plays a crucial role in regulating carbon balance and maintaining ecosystem health (Yeganeh et al., 2012). NPP can reflect the growth status of vegetation and is sensitive to both climate variation and human activities (Odum, 1971; Schimel, 1995). Therefore, many researchers have adopted NPP as an indicator of degradation and to distinguish the impact of climate from that of human activities (Prince et al., 1998, 2009; Wessels et al., 2008; Zheng et al., 2006). However, the monitoring and assessment of these two factors traditionally depend on field surveys or social statistical data, which is inefficient, particularly in regions where field survey is difficult to perform or statistical data are lacking (Li, 1997; Rojstaczer et al., 2001). To date, few studies have been conducted to quantify the relative roles of climate and human activities in degradation (Gang et al., 2014; Xu et al., 2010; Zhang et al., 2011; Zhou et al., 2014a, 2014b).

In this study, NPP coupled with scenario simulation method was applied to assess the grassland degradation status in the four countries from 2000 to 2013. Six kinds of scenarios were built on the basis of the slope of NPP to evaluate the impacts of climate variation and human activities on degradation or restoration. The primary objectives of this study were as follows: to explore and compare the degradation dynamics in China, Mongolia, Pakistan and Uzbekistan from 2000 to 2013; and to distinguish the relative roles of climate variation and human activities in degradation or restoration. The outcomes of this study not only provide an overall picture of grassland degradation, but also may serve as a firmer basis for policy and decision making in the course of pasture production and grazing management practices.

2. Materials and methods

2.1. Data source and processing

The global grassland map was obtained from the MODIS Terra + Aqua Combined Land Cover product MCD12Q1, which was downloaded from the MODIS Land website (http://modis-land.gsfc.nasa.gov/landcover.html/). The primary land cover scheme identifies 17 classes defined by the International Geosphere-Biosphere Program (IGBP), including 11 natural vegetation classes, three human-altered classes, and three non-vegetated classes. In this study, class number 6–10, with shrubland cover, savanna cover and grassland cover, were selected as a single grassland land cover type.

The global monthly precipitation and temperature data were derived from UDel_AirT_Precip (University of Delaware Air Temperature and Precipitation). The data were downloaded from the Web site at http://www.esrl.noaa.gov/psd/which were provided by NOAA/OAR/ESRL (PSD, Boulder, Colorado, USA). The mean annual temperature and mean annual precipitation were calculated from the downloaded monthly data by using ArcGIS V10.0 (ESRI, California, USA).

Livestock numbers of these four countries in this study were obtained from Food and Agriculture Organization of the United Nations, the annual data were downloaded from the Web site at http://faostat3.fao.org/download/E/EK/E.

All of the related databases were resized to 1-km spatial resolution and the coordinate and projection system used were the World Geodetic System 1984 and the Albers equal area conic projection respectively.

2.2. Estimation of actual NPP

The actual NPP was estimated from the global NPP product MOD17A3 (1 km spatial resolution), which was obtained from the NASA MODIS Land Science team website (http://landval.gsfc.nasa.gov/). The MOD17A3 NPP was calculated based on the BIOME-BGC model, which is expressed as follows:

$$\mathrm{NPP} = \sum_{t}^{365} \mathrm{PSNet} - (R_m + R_g) \tag{1}$$

$$\mathrm{PSNet} = \mathrm{GPP} - R_{lr} \tag{2}$$

where NPP is the annual NPP (gC/m^2/year) and PSNet is the net photosynthesis. R_m and R_g are annual maintenance respiration of live cells in woody tissue and annual growth respiration, respectively. R_{lr} refers to the daily leaf and fine root maintenance respiration.

2.3. Estimation of potential NPP

In this study, we estimate potential NPP using the Thornthwaite memorial model, which is based on the Miami model and modified by Thornthwaite's potential evaporation model (Lieth, 1975; Lieth and Box, 1972). This model mainly consists of annual average evapotranspiration, annual total precipitation and the annual average temperature, which is presented as follows:

$$\mathrm{NPP} = 3000\left[1 - e^{-0.0009695(v-20)}\right] \tag{3}$$

where NPP is the annual total NPP (gC/m^2/year) and v is the annual actual evapotranspiration (mm). The calculated equations are presented as follows:

$$V = \frac{1.05r}{\sqrt{1 + (1 + 1.05r/L)^2}} \tag{4}$$

$$L = 3000 + 25t + 0.05t^3 \tag{5}$$

where r is the annual total precipitation (mm), L is the annual average evapotranspiration (mm), and t is the annual average temperature (°C).

2.4. Grassland dynamic analysis

The vegetation dynamic is a significant ecological process of land degradation. By using NPP as a fundamental indicator of grassland productivity, we can assess the grassland degradation or restoration. The slope was determined by using ordinary least squares regression, which is expressed as follows:

$$\text{Slope} = \frac{n \times \sum_{i=1}^{n} i \times NPP_i - \left(\sum_{i=1}^{n} i\right)\left(\sum_{i=1}^{n} NPP_i\right)}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{6}$$

where i is 1 for year 2000, 2 for year 2001, and so on ($i = 1,2, \ldots 14$); n is 14 in this formula as the study period is from 2000 to 2013. NPP_i is the value of annual NPP in time of i year.

The significance of the variation tendency in our study was analyzed by using the statistic F test, following the formula expressed as:

$$F = U \times (n - 2)/Q \tag{7}$$

$$Q = \sum_{i=1}^{n} \left(y_i - \widehat{y_i}\right) \tag{8}$$

$$U = \sum_{i=1}^{n} \left(\widehat{y_i} - \overline{y}\right)^2 \tag{9}$$

where Q is the sum of the square error, U is a regression sum of the squares. n is the number of years studied, which is 14 in this study. y_i is the observed NPP in the year i, $\widehat{y_i}$ is the regression value, and $\overline{y}$ refers to the mean value of NPP in 14 years. Through the significance test ($P < 0.01$ or $P < 0.05$), the correlation coefficient can indicate whether the trend is “extremely significant” or “significant”.

2.5. Scenario analysis and quantitative assessment method

In order to distinguish the effects of climate variation and human activities on grassland degradation and restoration, we defined three types of NPP. The first type is potential NPP that represents a hypothetical condition of vegetation NPP, which was caused by climate only. The second type is actual NPP that represents a real condition of vegetation productivity, which was determined by climate and human activities. The third type is the human-induced NPP (HNPP) that represents the effect of human activities on vegetation productivity, which is calculated by the difference between potential and actual NPP.

The grassland degradation or restoration can be demonstrated by the slope of actual NPP (S_A) according to Eq. (6). A positive value of S_A represents the grassland restoration. By contrast, a negative S_A indicates the grassland degradation. The effect of climate and human activities on grassland NPP can be represented based on the slope of potential NPP (S_P) and HNPP (S_H). A positive value of S_P indicates that the climate is beneficial to grass growth, while a negative S_P shows that the climate is harmful to grass growth. A negative value of S_H demonstrates that human activities are beneficial to grass growth, whereas a positive S_H means that human activity is the dominant factor of grassland degradation expansion.

Consequently, six scenarios for assessing the relative roles of climate and human activities in degradation can be defined by the slopes of these three types NPP (Table 1). Combining the relative roles of climate variation and human activities, scenario 1 is climate-dominated grassland restoration (CDR), scenario 2 is human activities-dominated grassland restoration (HDR), scenario 3 is both of the two factors dominated grassland restoration (BDR), scenario 4 is climate-dominated grassland degradation (CDD), scenario 5 is human activities-dominated grassland degradation (HDD), scenario 6 is both of the two factors dominated grassland degradation (BDD).

3. Results

3.1. Dynamic analysis of grassland

The spatial distribution of grassland NPP dynamic was represented in the four countries from 2000 to 2013 (Fig. 1). Fig. 2 indicates that the change trend of the grassland did not occur evenly in the four countries. In Uzbekistan, approximately 97% of the grassland area was unchanged during the study period, only 1.9% area underwent degradation, to the extent of 3.4×10^3 km^2, whereas 0.5% of the grassland area experienced restoration. In China, Mongolia and Pakistan, the change trend of grassland NPP was increasing, the restoration areas accounted for 29.6%, 16%, and 32.5% of grassland, respectively. Pakistan had the biggest percentage of grassland restoration area among these four countries. In addition, the grassland NPP variations of these four countries were calculated. The grassland NPP increased 744.7 Gg C year^{-1}, 119 Gg C year^{-1}, 40.3 Gg C year^{-1} in China, Mongolia and Pakistan, respectively. In Uzbekistan, the grassland NPP decreased by 1.1 Gg C year^{-1}. The trend of NPP variation was consistent with the change of grassland area in these four countries. Furthermore, Fig. 1 shows that the spatial trends of grassland NPP at different significance levels are not equal in the four countries. For example, Mongolia had the largest percentage of grassland with significant decrease and extremely significant decrease, which accounted for 1.9% and 2.1% of the grassland. Pakistan had the largest percentage of grassland with significant increase (17.8%) and extremely significant increase (14.7%) in the four countries.

3.2. Relative roles of climate variation and human activities in grassland dynamics based on areas

The spatial distribution of grassland restoration induced by climate variation and human activities in these four countries is shown in Fig. 3. Fig. 4A shows that climate variation exerted the influence on grassland restoration, inducing 38.5%, 83.9%, 85% and 6.7% of restored grassland area in China, Mongolia, Pakistan and Uzbekistan, respectively. Human activities also exerted great influence on driving grassland restoration in China (38.2%), Mongolia (4.6%), Pakistan (11.8%) and Uzbekistan (86.7%). Compared with other three regions, human activities exerted the greatest influence in Uzbekistan. The combined effects of climate variation and human activities resulted in 23.2%, 11.5%, 3.1% and 6.7% of grassland restoration in these four countries.

Grassland degradation caused by climate variation and human activities was also analyzed (Fig. 3). Fig. 4B shows that the degraded areas induced by human activities accounted for 30%, 65%, 79% and 11.6% in China, Mongolia, Pakistan and Uzbekistan, respectively. By

Table 1
The six scenarios for assessing the relative roles of climate and human activities in grassland degradation or restoration.

	Scenario	S_P	S_H	Relative roles of climate and human activities
Grassland restoration ($S_A > 0$)	Scenario 1	>0	>0	Climate-dominated grassland restoration
	Scenario 2	<0	<0	Human activities-dominated grassland restoration
	Scenario 3	>0	<0	Both of the two factors dominated grassland restoration
Grassland degradation ($S_A < 0$)	Scenario 4	<0	<0	Climate-dominated grassland degradation
	Scenario 5	>0	>0	Human activities-dominated grassland degradation
	Scenario 6	<0	>0	Both of the two factors dominated grassland degradation

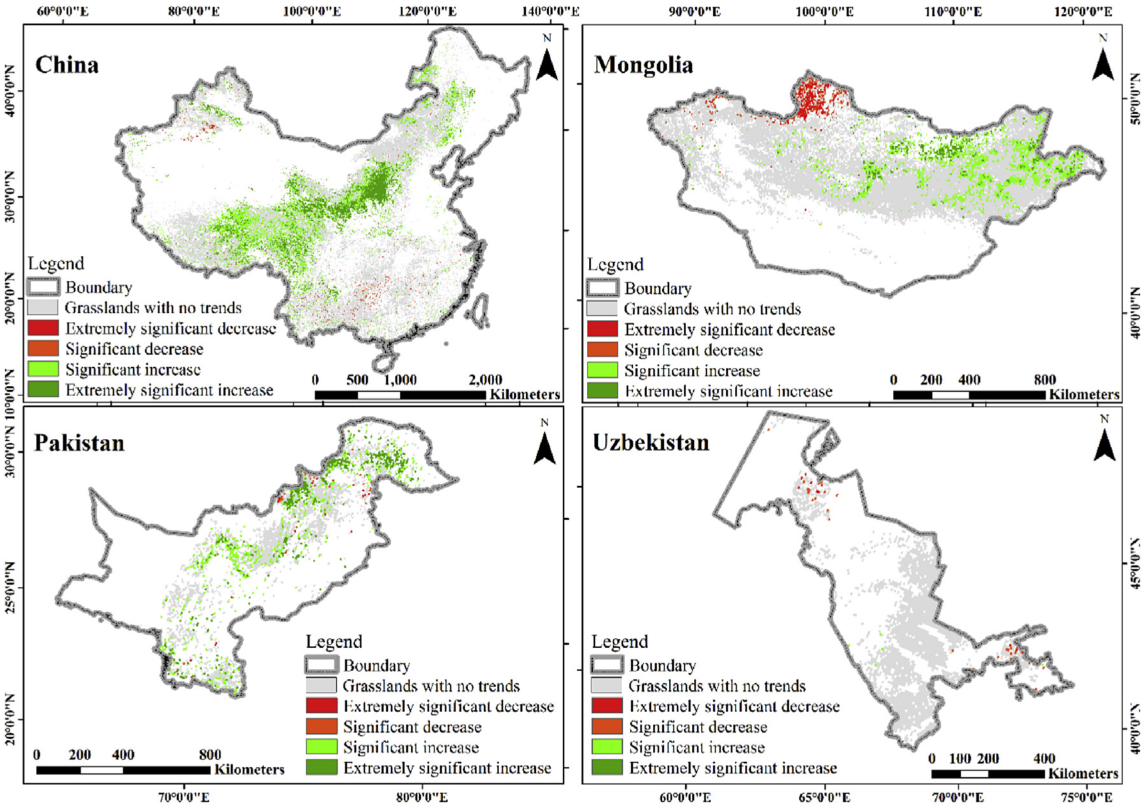

Fig. 1. The spatial trends of grassland NPP at different significance levels in the four countries during 2000–2013.

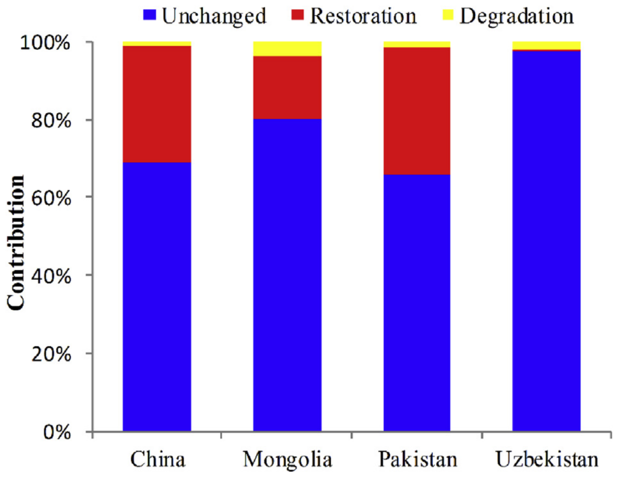

Fig. 2. Area percentages of grassland degradation and restoration in the four countries.

contrast, the combined effects of climate variation and human activities resulted in 32.5%, 30%, 11.9% and 20.9% of degradation, comparing with37.4%, 5.1%, 9% and 67.4% climate-dominated in these four countries.

In summary, grassland restoration was dominated by climate variation in China, Mongolia, Pakistan. Comparing the impacts of climate variation on grassland restoration in these three countries, the most greatly influenced by climate was Pakistan, followed by Mongolia, while the influence on China was minimal. In Uzbekistan, human activities were the driving force of grassland restoration. The dominant factor of grassland degradation was different in these four countries. In Mongolia and Pakistan, human activities were the principal driving force of grassland degradation and caused the greatest influence in Pakistan. However, climate variation played the dominant role of grassland degradation in China and Uzbekistan.

3.3. Relative roles of climate variation and human activities in grassland dynamics based on NPP variation

The relative roles of climate variation and human activities

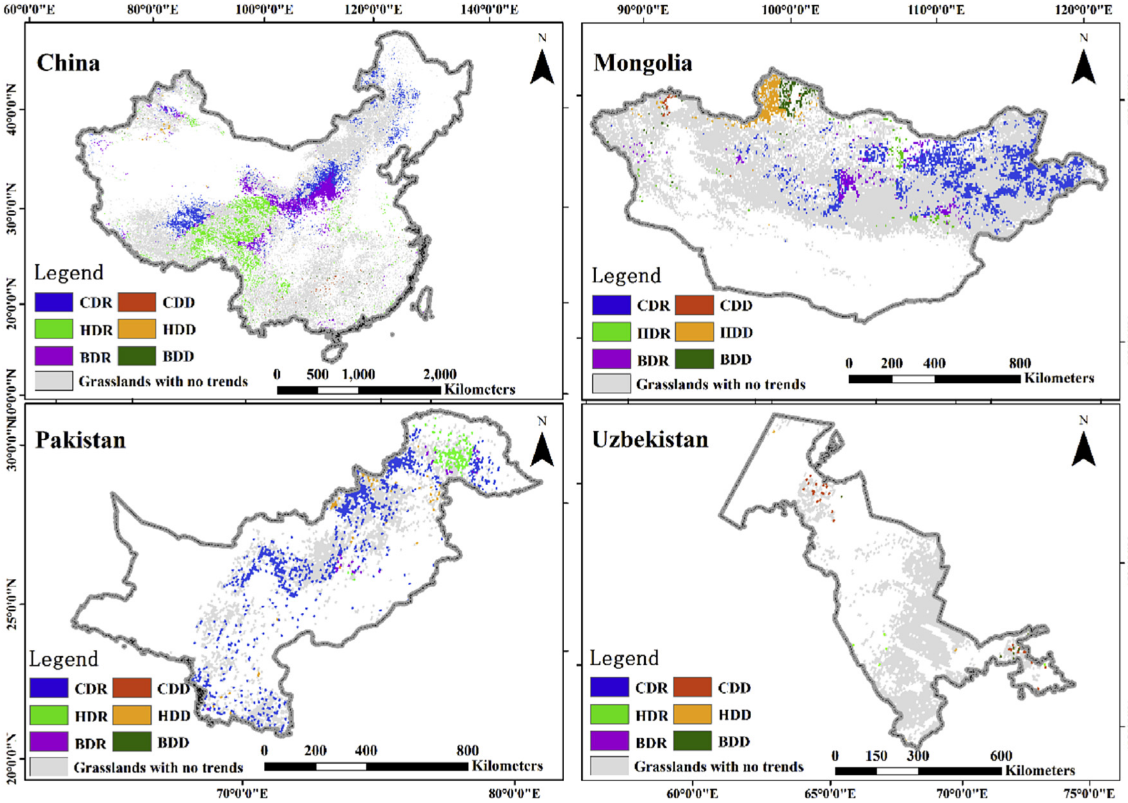

Fig. 3. The spatial distribution of grassland degradation and restoration induced by climate variation, human activities, and the combination of the two factors in the four countries.

based on grassland NPP increase are shown in Fig. 5A. The results revealed that the NPP of restored grassland increased 817 Gg C year^{-1}, 152.7 Gg C year^{-1}, 47.3 Gg C year^{-1}, 0.6 Gg C year^{-1} in China, Mongolia, Pakistan and Uzbekistan, respectively. Furthermore, 25.4%, 83.7%, 82.5%, 6.48% of grassland restoration were caused by climate variation, and 39.2%, 4.4%, 13.1%, 87% were induced by human activities in these four countries. The contribution of the two factors to grassland restoration reached 35.4%, 11.9%, 4.4% and 6.5%.

Due to the grassland degradation, NPP decreased by 72.4 Gg C year^{-1}, 33.8 Gg C year^{-1}, 7 Gg C year^{-1}, 1.7 Gg C year^{-1} in China, Mongolia, Pakistan and Uzbekistan, respectively (Fig. 5B). The results indicated that 38.2%, 2.2%, 8.2%, 58.8% of grassland degradation were caused by climate variation, whereas 16.3%, 71%, 83.4%, 16.8% resulted from human activities in these four countries, respectively.

In summary, the impacts of climate variation and human activities occurred not alike in these four countries. In China and Uzbekistan, human activities played a dominant role of grassland restoration and climate variation was the dominant factor of grassland degradation. However, the condition was different in other two countries. In Mongolia and Pakistan, climate variation was the principal driving force of grassland restoration and caused the greatest influence in Mongolia. By contrast, human activities were the dominant factor in grassland degradation and exerted the greatest impact in Pakistan.

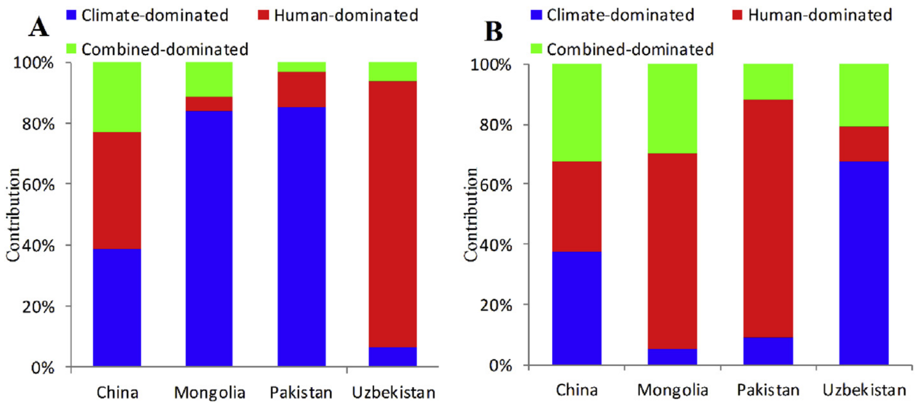

Fig. 4. Contributions of climate variation, human activities, and the combination of these two factors to grassland restoration (A); and grassland degradation (B).

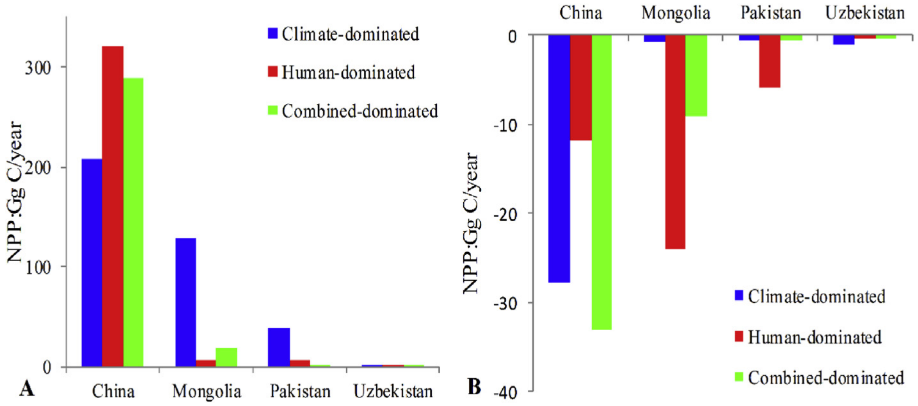

Fig. 5. Changes of grasslands NPP as a result of restoration (A) or degradation (B) induced by climate variation and human activities in the four countries.

4. Discussion

4.1. Methodology

Climate variation and human activities are the two major factors that affect grassland productivity dynamics. Several studies distinguish and assess the relative role of climate variation and human activities in grassland degradation by comparing actual grassland condition with potential one (Wessels et al., 2007; Xu et al., 2009). This method was able to identify the areas, locations and NPP variations affected by climate and human activities. Grassland degradation is reflected by reduced grass density, grass coverage, or increased unpalatable grass species and toxic weeds (Liu and Zha, 2004). NPP has been extensively used as an ecological indicator for monitoring grassland degradation and compare actual grassland condition with potential one to distinguish the degradation-driving factors in the current study (Gang et al., 2014; Ma et al., 2012; Zhou et al., 2014a). Xu et al. (2009) built the methodology to distinguish and assess the relative role of climate variation and human activities in sandy desertification by selecting the slope of NPP and scenarios simulation, Zhou et al. (2015, 2014a) and Gang et al. (2014) have expanded the study region to global and regional scale by using this method. Consequently, NPP coupled scenario simulation methodology has been proved reliable in detecting land degradation. Therefore, we selected this methodology to present the grassland degradation status in these four countries. The results showed that the grassland experienced restoration in China, Mongolia and Pakistan, and the largest proportion of grassland restoration was found in Pakistan. By contrast, the grassland underwent degradation during the study period in Uzbekistan. These results were in agreement with previous studies (Mu et al., 2013b; Sekiyama et al., 2014). According to Gang et al. (2014), the area of grasslands in Asia presented slight increase in NPP. And the areas of grassland decreased from 1991 to 2010 in Uzbekistan (Fan et al., 2012).

Although the potential NPP and HNPP (i.e., the difference between potential NPP and actual NPP) have successfully detected grassland degradation in previous research (Gang et al., 2014; Xu et al., 2010; Zhang et al., 2011; Zhou et al., 2015), this method actually has its drawbacks and limitation. The potential NPP indicates that vegetation productivity is achieved under an ideal situation which is only affected by air temperature and precipitation. Similarly, we assessed the relative roles of climate and human factors in degradation based on the NPP variation and established scenarios which were on the basis of the hypothesis that grassland productivity dynamics is only affected by climate and human activities. However, this situation is somehow influenced by grassland fire, grassland rodent and grassland species, these factors would cause uncertainty to results. Future studies should consider other influential processes.

4.2. Driving factors

Previous studies have indicated that grassland ecosystem changes are the result of climate variation and human activities, by altering regional biogeochemical cycles and ecosystem productivities (Horion et al., 2013; Mu et al., 2013a; Wessels et al., 2007). In this study, climate variation dominated the grassland restoration in Mongolia and Pakistan. This result was consistent with previous studies, which pointed out that climate variation was beneficial to vegetation growth and the contribution of climate variation was greater than that of human activities (Zhang et al., 2011; Zheng et al., 2006; Zhou et al., 2015). Foley and Pollard (2000) found that climate variation influenced terrestrial vegetation mainly through precipitation and temperature changes, which further regulated soil respiration, photosynthesis, and growing status and distribution. In this study, the annual precipitation showed an increase trend during 2000–2013 in China, Mongolia and Pakistan, as shown in Fig. 6. As the rising of rainfall was good for the growth of vegetation, especially in dry land (Herrmann et al., 2005), the grassland NPP increased and caused grassland restoration. Furthermore, the increase trend of Mongolia and Pakistan was larger in China and it made a higher contribution to grassland restoration. In China, the effect of climate change and human activities based on area changes were not consistent with that based on NPP variation. The result showed that climate variation dominated grassland restoration based on restored area, whereas human activities were the principal driving force of grassland restoration based on NPP variation. These findings were connected with the promotion of grassland restoration projects. As widely known, the Chinese government has implemented several effective projects to promote grassland restoration in the main pastoral areas and received significant positive effects, such as the Converting of Farmlands Back to Forests or Grasslands and the Return Grazing to Grass Program (Akiyama and Kawamura, 2007; Han et al., 2008; Yeh, 2005; Yong-Zhong et al., 2005). Although the area affected by environmental protection programs was less than that by climate variation, protection projects caused more increase in grassland NPP. The effect of human activities was larger than that of climate. Therefore, the driving force of restoration was determined by the effectiveness of environmental protection programs.

The dominant factors influencing grassland degradation were different in the four countries. The study showed that climate variation was the dominant factor in Uzbekistan, as the decrease

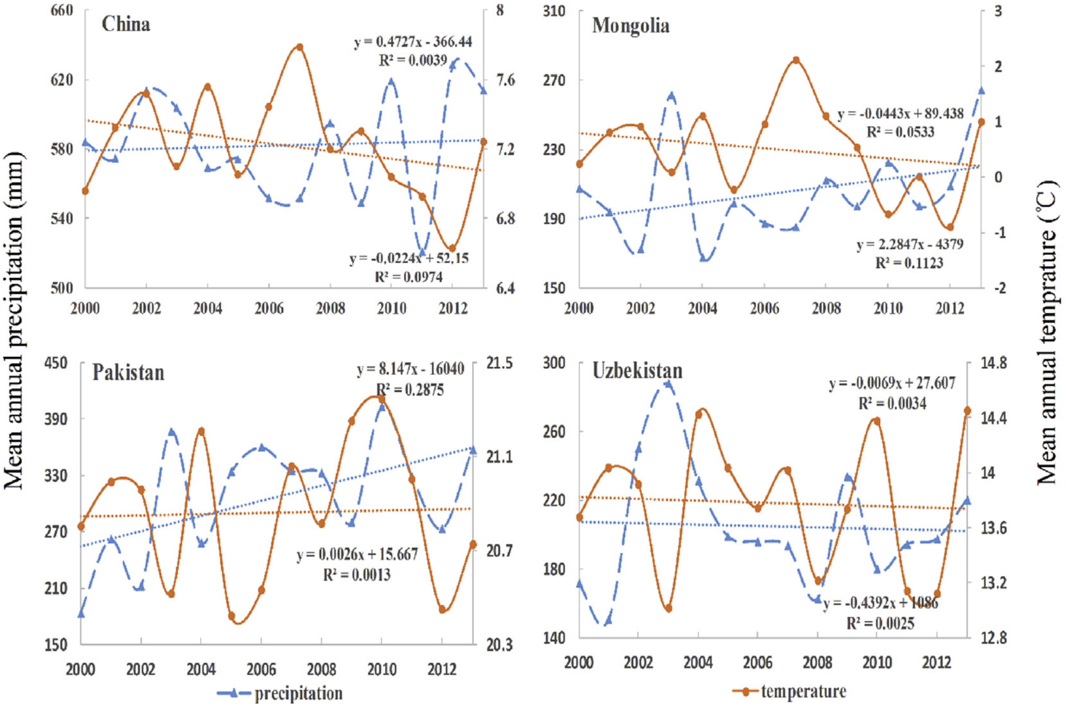

Fig. 6. The changing trends of climate factors in the four countries from 2000 to 2013.

trend of annual precipitation occurred (Fig. 6). In Mongolia and Pakistan, human activity was the dominant factor, and we found that more than half of degradation expansion was caused by human activities. Especially in Pakistan, 83.4% of grassland degradation was induced by human activities. These findings were consistent with these previous studies (Lu et al., 2007; Wang et al., 2012b; Ykhanbai et al., 2015), which concluded that human activities, such as conversion of grassland to cropland and overgrazing, were the dominant factors in land degradation. And grazing was the primary driving force for alpine grassland variations caused by human activities (Chen et al., 2014). According to Xu et al. (2011), the livestock number often served as an indicator of grazing intensity on grassland. Our results showed that the total livestock number increased from 2000 to 2013 and Pakistan had the biggest amount of livestock (Fig. 7). This results indicated that the grazing intensity was growing and caused more grassland degradation by human activities. Furthermore, the biggest amount of livestock in Pakistan was consistent with the previous findings which presented human activities had the biggest influence of grassland degradation in Pakistan.

However, some human activities such as conversion of cropland to grassland and grazing exclusion caused grassland restoration (Wang et al., 2012b), especially in the case of environmental protection programs promoted in China. These results may explain that climate variation dominated the grassland degradation in China. As protection programs taken by the Chinese government, such as the Return Grazing to Grass Program and grazing exclusion on grassland, degradation was avoided. These programs mitigated the

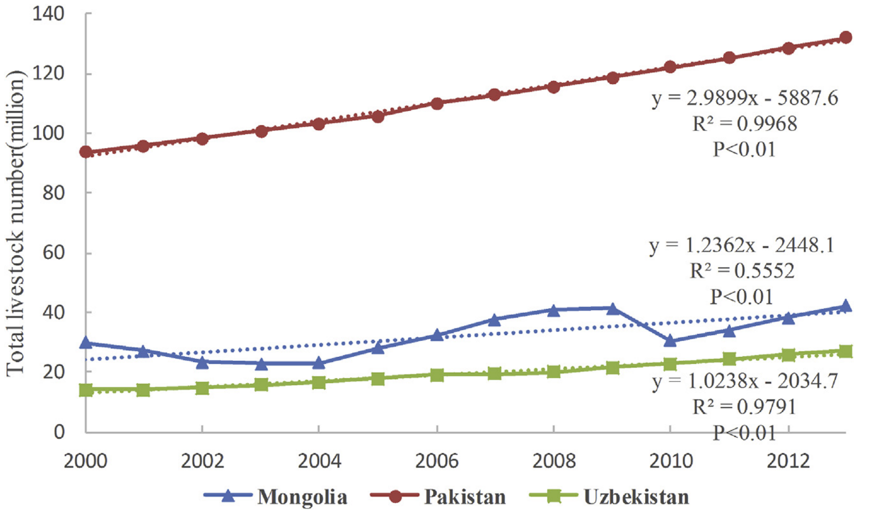

Fig. 7. The inter-annual variation of the livestock number in the study area.

destruction of grassland by human activities, so the influence of climate variation to grassland degradation was relatively increased.

5. Conclusions

This study assessed the relative contributions of climate variation and human activities to grassland dynamics in China, Mongolia, Pakistan and Uzbekistan from 2000 to 2013 by selecting NPP as an indicator. The results showed that grassland in China, Mongolia and Pakistan exhibited an increasing trend during the study period, and the change trend of grassland in Uzbekistan was decreasing. Nearly 29.6%, 16%, and 32.5% of grassland area underwent restoration and grassland NPP increased 744.7 Gg C $year^{-1}$, 119 Gg C $year^{-1}$, 40.3 Gg C $year^{-1}$ in China, Mongolia and Pakistan, respectively. By contrast, nearly 2% of grassland area experienced degradation with a decrease in NPP of 1.1 Gg C $year^{-1}$ in Uzbekistan.

Furthermore, whether the quantitative assessment was based on NPP variation or grassland degradation area, climate variation dominated the grassland restoration and human activities were the principal driving force of grassland degradation in Mongolia and Pakistan. In Uzbekistan, the driving force of grassland degradation and restoration was climate variation and human activities.

In addition, considering the relative roles of climate and human activities varied greatly in China, we derived two propositions to explain the situation. First, human activities were the dominant factor of grassland restoration, whereas climate variation was the principal driving force of grassland degradation. Second, both grassland degradation and restoration were induced by climate variation. Therefore, the driving force of restoration was determined by the effectiveness of environmental protection programs and we should promote protection programs and management measures to control grassland degradation and increase carbon sequestration.

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