

Quantitative assessment of the contributions of climate change and human activities on global grassland degradation

Chengcheng Gang · Wei Zhou · Yizhao Chen ·
Zhaoqi Wang · Zhengguo Sun · Jianlong Li ·
Jianguo Qi · Inakwu Odeh

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Abstract Grassland degradation received considerable concern because of its adverse impact on agronomic productivity and its capacity to provide goods and service. Climate change and human activities are commonly recognized as the two broad underlying drivers that lead to grassland degradation. In this study, a comprehensive method based on net primary productivity (NPP) was introduced to assess quantitatively the relative roles of climate change and human perturbations on worldwide grassland degradation from 2000 to 2010. The results revealed that at a global scale, 49.25 % of grassland ecosystems experienced degradation. Nearly 5 % of these grasslands experienced strong to extreme significant degradation. Climate change was the dominant cause that resulted in 45.51 % of degradation compared with 32.53 % caused by human activities. On the contrary, 39.40 % of grassland restoration

was induced by human interferences, and 30.6 % was driven by climate change. The largest area of degradation and restoration both occurred in Asia. NPP losses ranged between 1.40 Tg C year⁻¹ (in North America) and 13.61 Tg C year⁻¹ (in Oceania) because of grassland degradation. Maximum NPP increase caused by restoration was 17.57 Tg C year⁻¹ (in North America). Minimum NPP was estimated at 1.59 Tg C year⁻¹ (in Europe). The roles of climate change and human activities on degradation and restoration were not consistent at continental level. Grassland ecosystems in the southern hemisphere were more vulnerable and sensitive to climate change. Therefore, climate change issues should be gradually integrated into future policies and plans for domestic grassland management and administration.

Keywords Grassland degradation · Climate change · Human activities · Quantitative assessment · Potential NPP · Actual NPP

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C. Gang · W. Zhou · Y. Chen · Z. Wang · J. Li (✉)
The Global Change Research Institute, College of Life Science,
Nanjing University, Hankou Road 22, Nanjing 210093,
People's Republic of China
e-mail: jianlongli@gmail.com; jlli2008@nju.edu.cn

Z. Sun
College of Prataculture Science, Nanjing Agricultural
University, Nanjing 210095, People's Republic of China

J. Qi
The Center for Global Change and Earth Observations, Michigan
State University, East Lansing, MI 48823, USA

I. Odeh
Faculty of Agricultural and Environment, The University of
Sydney, Sydney, NSW 2006, Australia

Introduction

Grassland is one of the world's largest vegetation types, which accounts for nearly 25 % of the world's land surface and provides a significant contribution to food security by providing a portion of the feed requirements of ruminants used for meat and milk production (Scurlock and Hall 1998; O'Mara 2012). Grassland ecosystem plays a key role in balancing greenhouse gas, particularly in terms of global carbon storage and further carbon sequestration (French 1979). Considerable research on this area reveals that grassland ecosystems are under degradation, which is becoming worse, especially in arid and semi-arid places (UNCCD 1994; Conant et al. 2001; Safriel et al. 2005; Veron et al. 2006). According to the United Nations Convention to

Combat Desertification, grassland degradation may be broadly associated with two underlying drivers, namely, climate change and human activities. Given the sustained growth in population worldwide, numerous signs show that we draw on the grassland ecosystems and degrade them more than ever. The most common instance is domestic overgrazing, particularly in the developing countries (Liu and Diamond 2005; Aguilar et al. 1988; Bai et al. 2002; Shan et al. 1996). Similarly, climate change also exerts great influence on grassland degradation because of increased global temperature and altered precipitation patterns. Increasing chances of fires and drought brought about by climatic events were frequently recorded, which have fundamentally reduced the capacity of grassland ecosystems to provide goods and services (Ravi et al. 2010; Meehl et al. 2000; Zhou et al. 2005). To date, numerous studies have been conducted to analyze grassland degradation worldwide. However, few studies distinguished the relative roles and effects of the two factors. Quantitative assessments of the relative roles of climate and human factors in regional degradation have been reported recently (Xu et al. 2010; Zhang et al. 2011; Zhou et al. 2013a, b, 2014), but limited studies tell us where and to what extent global grassland degradation occurs and the respective contribution of climate change and human activities because of lack of comprehensive and quantitative assessment methods.

The information available today is more comprehensive than the information provided in the past, but it still fails to present a complete picture of the state of the global grassland ecosystem degradation and falls short of management and policy needs. Recent methods that utilize remote sensing and modeling techniques to distinguish between human and climate-induced degradation, such as factor analysis (Li et al. 2007; Ma et al. 2007), principal components analysis (Jiang et al. 2008) and correlation analysis (Chang et al. 2003), were criticized as improper identification methods of the fundamental drivers involved in the degradation process (Wrška et al. 2004). Simultaneously, a residual analysis method, which is conducted by comparing actual with potential vegetation productivity, has begun to gain considerable attention (Zhou et al. 2014; Evans and Geerken 2004; Wessels et al. 2007). Net primary productivity (NPP), which refers to carbon fixed by plants after assimilation through photosynthetic and autotrophic respiration, was selected as the indicator to discriminate the impacts of climate change and human activities on degradation (Zhou et al. 2013a, b, 2014; Xu et al. 2010; Prince et al. 2009). This methodology has been extensively used and successfully detected land degradation. The difference between this method and regression techniques lies in the former's capability of distinguishing and evaluating contributions of climate change and human activities in degradation compared with the individual factor of climate change or human activities.

A critical step in improving the management of grassland ecosystem is to take stock of the status of degradation and to identify the extent induced by various driving factors. To clarify this problem better, the degraded situation of global grassland ecosystems and the relative contribution of climate change and human activities were quantitatively evaluated based on NPP, which was selected as an indicator in the period of 2000–2010. This analysis documented the extent of degradation caused by climate variations or human activities at global and continental scales, and identified corresponding NPP variations induced by climate and human factors over time. The outcomes of this study do not only provide an overall picture of global 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.

Materials and methods

Data source and processing

The global grassland map was derived from the Global Land Cover 2000 (GLC2000), which was generated by an international partnership of 30 research groups coordinated by the European Commission's Joint Research Centre (Bartholomé and Belward 2005). The dataset was based primarily on SPOT (Satellite Pour l'Observation de la Terre) VEGETATION daily 1-km data (Giri et al. 2005), which were obtained from <http://www.bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php>. The GLC2000 global-scale legend documents 22 general land cover types. Class numbers 13–15, with herbaceous cover and sparse herbaceous or shrub cover, were selected as a single grassland land cover type in this study.

Meteorological data, including global monthly temperature and precipitation data used in potential NPP estimation, were obtained from UDel_AirT_Precip (University of Delaware Air Temperature and Precipitation). The data provided by NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, were obtained from their Web site at <http://www.esrl.noaa.gov/psd/>. The annual temperature and precipitation data were incorporated from the monthly data using ArcGIS v9.3 software (ESRI, Redlands, CA, USA). All of the related databases were resized to 1-km resolution and transformed to the Mollweide projection with WGS_1984 spheroid to calculate the area.

Estimation of potential of NPP

The Miami model based on Liebig's "Law of minimum" was the first proposed and widely used NPP estimation model (Lieth 1975). The model is mainly the function of

mean annual temperature (MAT) and mean annual precipitation (MAP). The MAT function is based on the Van't Hoff rule, which states that productivity doubles every 10 °C, between 10 and 20 °C. The MAP function, which indicates that the productivity in arid regions increases by 1.0 g C m² for each millimeter of precipitation, was derived from the Walter ratio (Lieth 1973; Zaks et al. 2007). Simple parameters were involved, but the Miami model reasonably estimates global patterns of productivity, and had been integrated into advanced and currently developed NPP estimation models (Adams et al. 2004).

$$NPP = \min \left\{ \left(\frac{3,000}{1 + \exp(1.315 - 0.119t)} \right), (3,000[1 - \exp(-0.000664r)]) \right\} \quad (1)$$

where *t* is mean annual temperature (°C) and *r* is mean annual precipitation (mm). NPP is calculated in units of g DW m⁻² year⁻¹.

Estimation of the actual NPP

The global NPP product MOD17A3 (~1 km spatial resolution) was used in this study to estimate the actual NPP from 2000 to 2010. The data were obtained from the NASA MODIS Land Science team website (<http://landval.gsfc.nasa.gov>). MOD17A3 NPP was computed using the amount of photosynthetically active radiation (PAR) measured by the MODIS instrument. In the production of MOD17A3, NPP was calculated based on the BIOME-BGC model and presented as follows:

$$PsnNet = GPP - R_{ml} - R_{mr} \\ NPP = \sum_t^{365} PsnNet - (R_{mo} + R_g) \quad (2)$$

where PsnNet is the net photosynthesis and *R_{ml}* and *R_{mr}* are the energy consumed by leaves and roots respiration, respectively. *R_{mo}* and *R_o* refer to the energy consumed by other parts of plant and its growth respiration, respectively. Each pixel of the MODIS NPP product is expressed as grams of g C m⁻² year⁻¹. The NPP images were reprojected and spliced using MRT (MODIS Reprojection Tool) to match other data.

Grassland dynamic assessment

Pearson correlation coefficient was employed to reflect the long-term dynamic of global grassland NPP. The function mainly described the relationship between grassland NPP and its corresponding year followed by the natural sequence of 1, 2, 3, ..., *n* (Piao and Fang 2002; Gao et al. 2009).

$$r_{xi} = \frac{\sum_{i=1}^n (x_i - \bar{x})(i - \bar{i})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (i - \bar{i})^2}} \quad (3)$$

where *n* is the sequential year, which is 11 in this present study, *x_i* refers to the grassland NPP in the year *i*, whereas \bar{x} is the mean value of grassland NPP in 11 years denoted by $t = (n + 1)/2$. A positive value indicates a linear increase of grassland NPP, whereas a negative value predicts a decreasing trend. If the correlation coefficient passes through the significance test ($P < 0.01$ or $P < 0.05$), it indicates an “extremely significant” or “significant” increasing or decreasing trend.

Vegetation dynamics is an important ecological process in land degradation, the productivity of vegetation community is supposed to change simultaneously. As a fundamental indicator of vegetation productivity, NPP is capable of reflecting vegetation dynamics. Grassland NPP variations can presumably cause degradation/restoration brought about by climate and human factors. Therefore, identifying the relationship between NPP dynamic and the degraded situation enables the relative roles of climate change and human activities in this process to be quantified. 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 (Ma and Frank 2006). The formula is expressed as follows:

$$\text{Slope} = \frac{n \times \sum_{i=1}^n i \times NPP_i - (\sum_{i=1}^n i) (\sum_{i=1}^n NPP_i)}{n \times \sum_{i=1}^n i^2 - (\sum_{i=1}^n i)^2} \quad (4)$$

where *i* is 1 for the year 2000, 2 for the year 2001, and so on; *n* is 11 in this paper because the study period is from 2000 to 2010; *NPP_i* is the value of annual NPP in time of *i* year. Compared with the negative value that connotes the occurrence of degradation, the positive value of the slope of actual NPP (*S_A*) indicates a restoration trend.

Establishing the scenarios

Three types of NPP are calculated to distinguish the contribution of climate change and human activities on grassland degradation and restoration. First is potential NPP, which is a hypothetical state of vegetation NPP and determined by climate condition only, excluding human activities. The effect of climate change on grassland NPP can be represented using the slope of potential NPP (*S_P*) according to Eq. 4. A positive value of *S_P* indicates that the climate change during this period is beneficial to grass growth, whereas a negative value demonstrates that climate change is harmful to grass growth.

The second is actual NPP, which is a real state of vegetation productivity determined by climate and human

Table 1 The six scenarios for assessing the relative roles of climate change and human activities on grassland degradation/restoration

	S_P	S_H	Relative roles of climate change and human activities
Degradation ($S_A < 0$)			
Scenario 1	>0	>0	Land degradation is mainly caused by human activities such as overgrazing, over-reclamation, and land abandonment
Scenario 2	<0	<0	Climate plays a dominant role in land degradation
Scenario 3	>0	<0	Climate and human activities are both responsible for land degradation
Restoration ($S_A > 0$)			
Scenario 1	<0	<0	Human activity is the dominant factor responsible for vegetation restoration
Scenario 2	>0	>0	Climate is the dominant factor that controls the vegetation restoration
Scenario 3	<0	>0	Climate and human activities act together to promote vegetation restoration

For scenario 3, in both degradation and restoration, the relative roles of climate change and human activities were calculated as the percentage of absolute value of the change of NPP induced by climate change or human activities, respectively, to the sum of both

S_A the slope value of actual NPP, S_P the slope value of potential NPP, S_H the slope value of human-induced NPP

factors. The MOD17A3 dataset is employed in this study to represent the actual NPP. A positive changing trend of actual NPP means that restoration occurs in grassland. By contrast, a negatively changing trend of the actual NPP represents degradation expansion. The third type is the human-induced NPP (HNPP), which is estimated by the difference between potential and actual NPP. The effect of human activities on grass growth can be assessed based on the slope of HNPP (S_H). Negative S_H indicates that human activities during this period are beneficial to vegetation growth, which implies that human interventions promote grassland restoration. Conversely, a positive S_H indicates decline in vegetation and the occurrence of human-dominated degradation (the correlation coefficient between potential and human-induced NPP at different scales is supplied as an online supplementary table).

Accordingly, six possible scenarios are defined by the slopes of the actual NPP, potential NPP, and HNPP (Table 1). These scenarios are mainly based on the changing directions of three NPPs. Established scenarios have been reported to distinguish the role of climate and human factors in the Shiyanghe (Zhang et al. 2011; Zhou et al. 2013a) and Heihe Basin (Zhou et al. 2013b). However, an error scenario may occur under a condition when $S_A < 0$, $S_P < 0$ and $S_H > 0$, or $S_A > 0$, $S_P > 0$ and $S_H < 0$. The former indicates that land degradation occurs, but the climate change and human activities promote grass growth. The latter describes an opposite

scenario, which indicates that restoration occurred but climate and human factors lead to degradation expansion. According to Xu et al. (2010) and Zhou et al. (2014), these situations may take place when transferring scales between different dataset, or in some regions where NPP is decreasing as a result of land use and cover change but experience degradation revision.

Results

Dynamic analysis of grassland

The spatial distribution of global grassland NPP dynamic over time was calculated using Eq. 3 (Fig. 1). Nearly half of the global grassland ecosystems had undergone degradation during the study period, to the extent of $1,401.01 \times 10^4 \text{ km}^2$ (49.25 %). Regions with the largest distribution presented a slight increase in NPP, which account for 40.42 % of total grassland ecosystems, compared with the areas with slight NPP decrease of 36.94 %. Grasslands that experienced extremely significant decrease in NPP amounted to 4.99 % of total grasslands. Figure 1 shows that the changing trends of grassland NPP did not occur evenly at continental level. For example, the area of grasslands in Asia and North America that presented slight increase in NPP accounted for up to 41.31 and 59.27 % of total grassland covers, respectively. By contrast, the regions which showed slight decrease in NPP dominated the grassland ecosystems in other continents, which include Africa (41.54 %), Oceania (45.09 %), South America (41.31 %), and Europe (47.74 %). The largest area that demonstrated an extremely significant decrease of NPP was in South America, which accounts for 11.36 % of grasslands in this continent. The total area of degraded grassland ($290.95 \times 10^4 \text{ km}^2$) in Oceania amounted to more than twice of the restored grassland ($121.39 \times 10^4 \text{ km}^2$), which was mainly localized in Western Australia. The least grassland degradation was estimated ($73.05 \times 10^4 \text{ km}^2$) in Europe, but overall degradation trend was still observed.

Relative roles of climate change and human activities in grassland degradation

Grassland degradation contributed by climate change and human activities was assessed (Fig. 2). Our findings show that alarming grassland degradation has reached a truly global scale. In addition, climate change exerted the greatest influence, inducing 45.51 % of grassland degradation worldwide. Human-dominated and the combined effects resulted in 32.53 and 21.96 % degradation, respectively. Figure 3a shows that grassland ecosystems in Oceania, especially in West Australia, were mostly

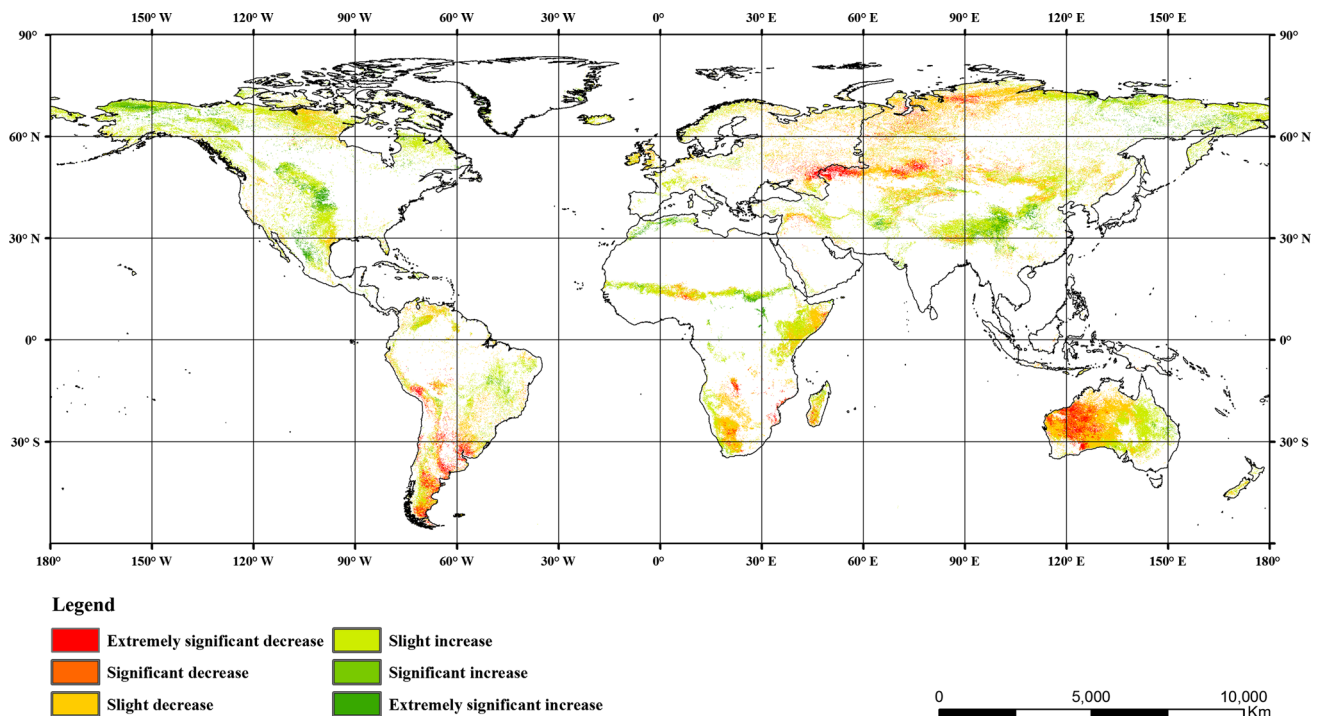


Fig. 1 The spatial trends of global grassland NPP at different significance levels during 2000–2010. The grassland NPP dynamic was calculated using Eq. 3. If r_{Nt} is positive, it means that grassland NPP increased in this period, while a negative value of r_{Nt} indicates a

linear decreasing trend of grassland NPP. If the correlation coefficient passes through the significance test ($P < 0.01$ or $P < 0.05$), it represents an “extremely significant” or “significant” increasing or decreasing trend

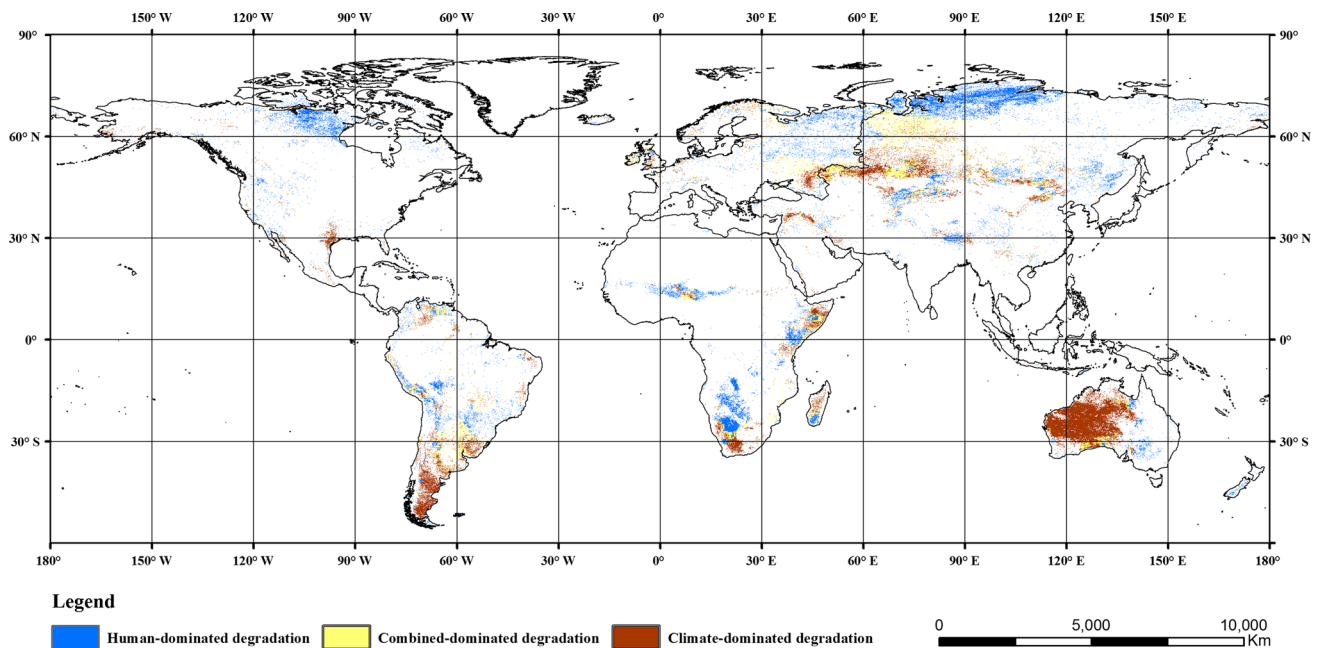


Fig. 2 The spatial distribution of global grassland degradation induced by climate change, human activities, and the combination of the two factors

influenced by climate change, which accounts for up to 85.66 % of total degraded grassland. Climate change also caused the largest area of degradation (43.92 %) in South

America, compared with 27.40 % human-dominated and 28.68 % combined effects. Human activities played a dominant role in driving degradation in other continents. In

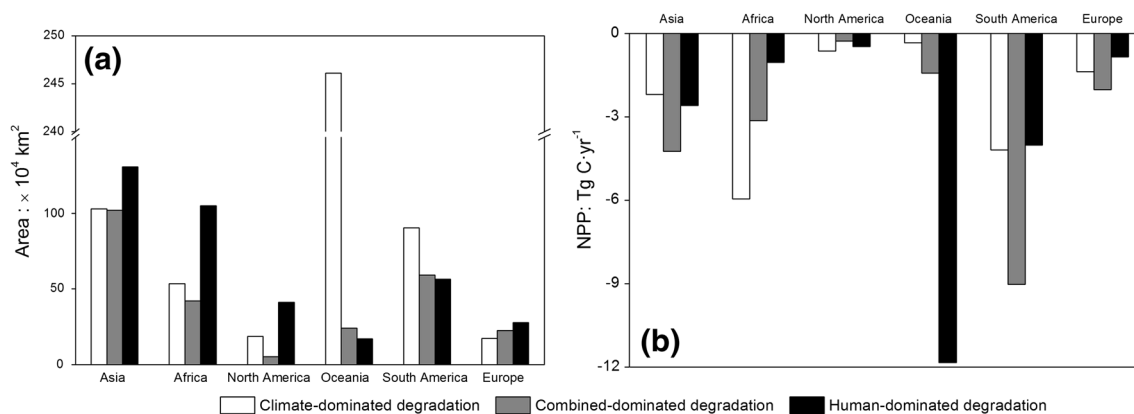


Fig. 3 Changes of grasslands area (a) and NPP (b) as a result of degradation induced by climate and human factors at continental level

Africa for example, grassland degradation induced by human intervention amounted to more than half of all degraded areas (52.37 %), whereas climate change and joint effects contributed to 26.68 and 20.95 %, respectively. In North America and Asia, human activities induced 63.11 and 38.94 % of grassland degradation, respectively. Apart from the dominated role of human activities in Asia, the contribution of climate change and combined effects were quite similar at 30.67 and 30.38 %, respectively.

Figure 3b shows that NPP losses occur because of grassland degradation caused by the climate and human factors. Global grassland NPP decreased by 58.84 Tg C year⁻¹ during the study period. The roles of climate and human factors on area changes were not consistent with NPP dynamics. For example, the largest degradation occurred in Asia, but the maximum NPP losses were estimated in South America at 17.23 Tg C year⁻¹, wherein combined effects played a dominant role. Combined effects also predominated NPP losses in Asia (49.94 %) and Europe (47.5 %), whereas climate change controlled NPP losses in Africa (58.7 %) and North America (46.0 %), respectively. NPP decrease was also observed in Oceania. Human interference, which is the main driving force, had led to 11.84 Tg C year⁻¹ losses, whereas climate change that induced NPP decrease seemed negligible (0.34 Tg C year⁻¹).

Relative roles of climate change and human activities in grassland restoration

Grassland restoration caused by either singular or combined effects of climate change and human activities were also analyzed (Fig. 4). Our results show that the area of grassland that presented restoration was slightly larger than the area that showed degradation ($1443.90 \times 10^4 \text{ km}^2$). Human activities contributed mostly to the restoration

(39.4 %), whereas climate change and combined effects resulted in 30.6 and 30.0 % of restoration, respectively. Figure 5a shows that the maximum estimation of grassland restoration was in Asia ($335.55 \times 10^4 \text{ km}^2$, 32.2 %). Oceania was the only continent where climate change predominated grassland restoration ($60.07 \times 10^4 \text{ km}^2$, 50.2 %). In Asia, restoration induced by human activities amounted to 36.12 % of all restored grassland, whereas combined effects and climate change contributed to 35.12 and 28.76 %, respectively. A similar pattern was found in North America, South America, and Europe. However, besides human-dominated restoration, climate change outweighed the joint effects in Africa, with 36.47 % restoration compared with 22.08 % caused by joint effects.

NPP increased by 56.66 Tg C year⁻¹ globally because of grassland restoration. Combined effect was the primary driving force (43.18 %), and the human and climate-dominated restoration contributed to 39.55 and 17.27 %, respectively. Figure 5b shows that the largest NPP increase was found in North America (31.0 %), where the impacts of combined effects were marked with 45.9 %. The joint effects also dominated grassland NPP increase in Asia (53.1 %). Human interference played a key role in the NPP increase in Africa, South America, and Europe, which contributed to 48.0, 51.7, and 51.8 %, respectively. In Oceania, climate change induced the maximum NPP increase (50.8 %), whereas combined effects and human activities contributed to 38.8 and 10.3 %, respectively.

Discussion

Grassland ecosystem has long been modified by climate change and human activities, which fundamentally altered regional biogeochemical cycles and ecosystem productivities (Horion et al. 2013; Mu et al. 2013; Trnka et al. 2011). This paper presents a general picture of the status of global

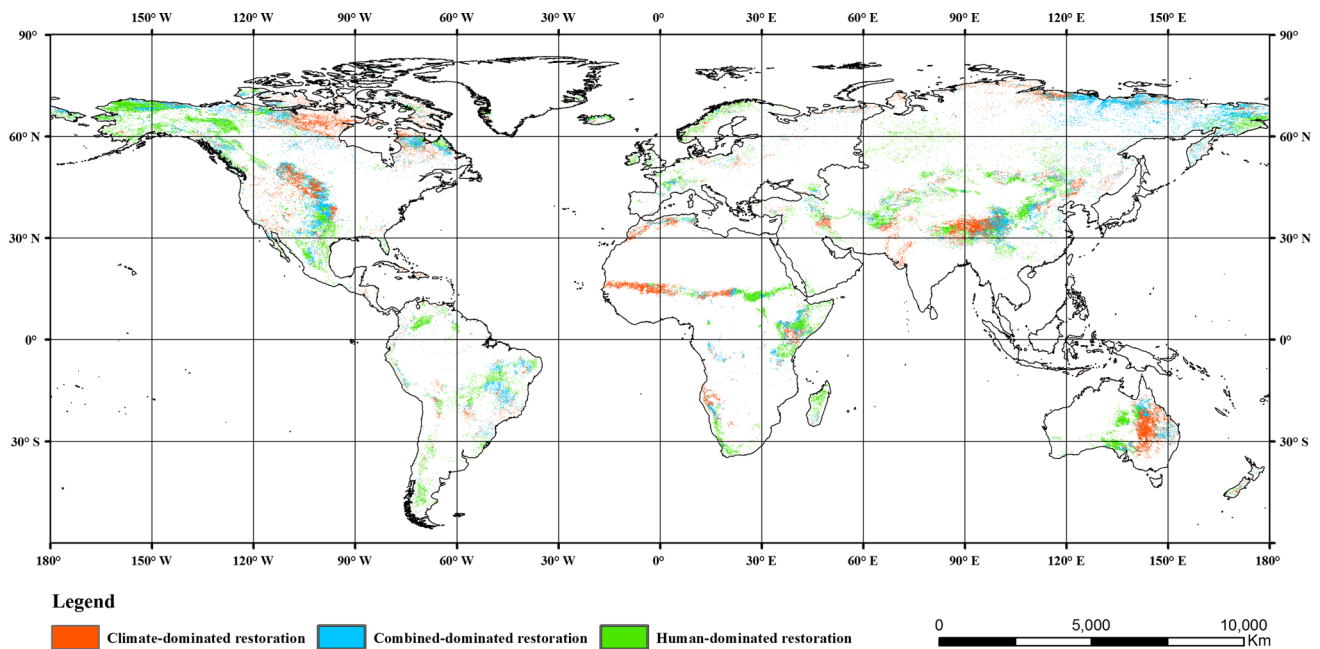


Fig. 4 The spatial distribution of global grassland restoration induced by climate change, human activities, and the combination of the two factors

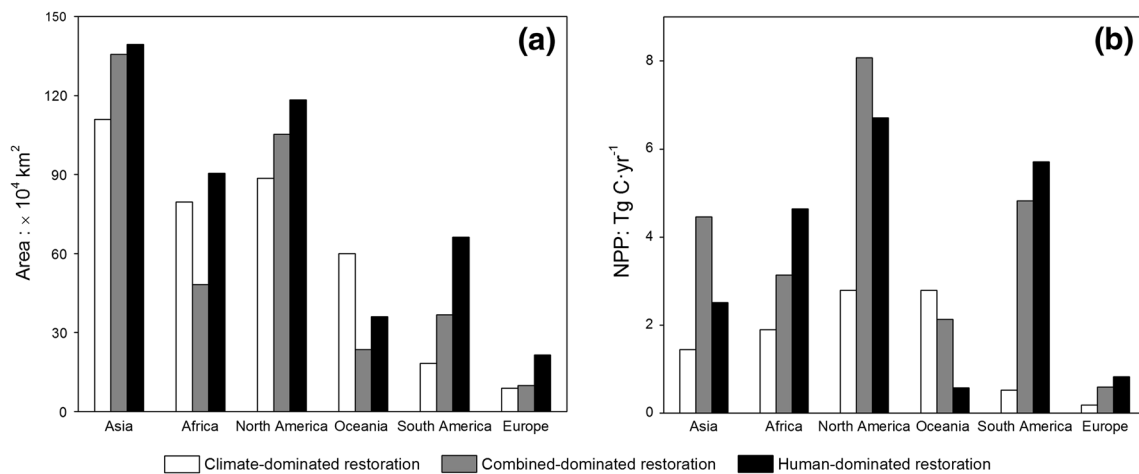


Fig. 5 Changes of grasslands area (a) and NPP (b) as a result of restoration induced by climate and human factors at continental level

grassland degradation through readily accessible global datasets, and quantitatively assessed the respective contribution of climate change and human activities.

NPP has been extensively used as an ecological indicator for monitoring climate change and anthropogenic alteration of terrestrial ecosystem (Ma et al. 2012; Erb et al. 2009; Wessels et al. 2004). Our results show that nearly half (49.25 %) of global grassland experienced degradation, and climate change was the intrinsic controlling driving force that led to 45.51 %. Human activities and joint effects contributed to 32.53 and 21.96 %, respectively. Climate change affected terrestrial vegetation

mainly through temperature and precipitation changes, which further regulated photosynthesis, soil respiration, and growing status and distribution (Foley et al. 2000). The most significant grassland degradation induced by climate change occurred in Western Australia. The climate extreme El Niño-Southern Oscillation (ENSO), which brought warmer and drier conditions, was frequently recorded in eastern and southwestern Australia (Power et al. 1998; Nicholls and Collins 2006). In South America, climate-dominated degradation was mainly distributed in Patagonia Plateau, which was in agreement with previous studies on rangeland degradation in Patagonia, Argentina caused by

altered precipitation pattern and a general warming trend (Bertiller et al. 2002; Santibáñez and Santibáñez 2007; Ares et al. 1990). By contrast, climate change was relegated to secondary status, which only worsened the degradation in other continents. For example, human activities had induced 52.37 % of grassland degradation in Africa. Land degradation was believed to be one of the most severe and widespread environmental problems in Africa, and human interventions were an undeniable leading cause (Wessels et al. 2004, 2007). Addressing rural poverty and sustaining the demands of population increases were accorded with primary importance in most African regions. Thus, agricultural land expanded at the expense of grasslands and forests, and the most important biogeochemical cycles on grassland ecosystems, namely, water, carbon, and nitrogen cycles, had been adversely altered by human activities (Jordan 1986; Barbier 2000; Symeonakis and Drake 2004).

The global grassland that presented restoration amounted to 50.75 % of total grassland ecosystems. Human activities topped the driving factors. The maximum restored grassland was found in Asia ($139.39 \times 10^4 \text{ km}^2$). The effects of human modification in Qinghai–Tibet Plateau and Inner Mongolia in China were highlighted. Several effective projects had been implemented by the Chinese government since the beginning of the century to reverse the degradation situation of grassland in the main pastoral areas. These projects include, “Converting of Farmlands Back to Forests or Grasslands” and “Converting farmland to grassplot,” which received significant positive effects (Su et al. 2005; Akiyama and Kawamura 2007; Han et al. 2008; Yeh 2005). A similar pattern was also observed in North America, South America, and Europe. Climate change also contributed to grassland restoration in Africa. Restored grassland was mainly distributed in sub-Sahara regions and the Ethiopian Highland. These areas reported grassland restoration under rising temperature and redistributed rainfall pattern (Batjes 2004; Asefa et al. 2003; Gashaw et al. 2002). The largest area of grassland restoration induced by climate change in Oceania was mainly distributed in the eastern Australia, whereas human-dominated restoration was localized in central Australia (Cole and Lunt 2005; Ruiz Jaen and Mitchell Aide 2005).

However, vegetation succession, which presented an increase or insignificant change in NPP, may have experienced degradation, which may cause errors (Verdoodt and Van Ranst 2006). Hueneke et al. (2002) reported the occurrence of server degradation in the Chihuahuan Desert in the US, where grasslands were replaced by desert scrub. This change only led to small decreases in the average aboveground biomass. Errors may exist in the assessment at the local or regional scale, but the methodology

introduced in this study provides a novel method of quantitatively evaluating the spatial distribution of the relative roles of climate change and human activities at a global scale.

Conclusions

The relative roles of climate change and human activities on grassland degradation and restoration from 2000 to 2010 were evaluated in this paper. Nearly half (49.25 %) of the grassland ecosystems experienced degradation at a global scale. Climate change was the principal influence, which resulted in 45.51 % of degradation. About 39.40 % of grassland restoration was induced by human interference, and 30.6 % was caused by climate change. The largest area of degraded and restored grassland was found in Asia. Grassland ecosystems in the southern hemisphere were more sensitive to climate change, especially in Australia. The overall restoration trend is dominated by far, but the capacity for grassland ecosystems to continue providing goods and services is declining. Simultaneously, human activities positively contributed to NPP increases, however, intensive management regimes and infrastructure development also contributed to grassland degradation.

Global-scale analysis of grassland degradation is further complicated by our limited ability to conduct a timely and precise quantitative assessment of the roles of climate and human factors on grassland degradation. We detected a general loss of plant productivity through a combination of satellite data and meteorology data, but the degraded situation may have become irreversible. This analysis provides basis for establishing indicators that can be used to detect grassland degradations to implement effective measurements before degradation becomes irreversible. Climate change issues should be gradually mainstreamed into policies, plans, and strategies for grassland development and management.

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References

- Adams B, White A, Lenton TM (2004) An analysis of some diverse approaches to modelling terrestrial net primary productivity. *Ecol Model* 177:353–391
- Aguilar R, Kelly EF, Heil RD (1988) Effects of cultivation on soils in northern Great Plains rangeland. *Soil Sci Soc Am J* 52:1081–1085
- Akiyama T, Kawamura K (2007) Grassland degradation in China: methods of monitoring, management and restoration. *Grassl Sci* 53:1–17
- Ares J, Beeskow AM, Bertiller M, Rostagno M, Irisarri M, Anchorena J, Defossé G, Merino C (1990) Structural and dynamic characteristics of overgrazed lands of northern Patagonia, Argentina. *Ecosyst World* 17:149–175
- Asefa DT, Oba G, Weladji RB, Colman JE (2003) An assessment of restoration of biodiversity in degraded high mountain grazing lands in northern Ethiopia. *Land Degrad Dev* 14:25–38
- Bai WQ, Zhang YL, Xie GD, Shen ZX (2002) Analysis of formation causes of grassland degradation in Maduo County in the source region of Yellow River. *J Appl Ecol* 13:823
- Barbier EB (2000) The economic linkages between rural poverty and land degradation: some evidence from Africa. *Agric Ecosyst Environ* 82:355–370
- Bartholomé E, Belward AS (2005) GLC2000: a new approach to global land cover mapping from Earth observation data. *Int J Remote Sens* 26:1959–1977
- Batjes NH (2004) Estimation of soil carbon gains upon improved management within croplands and grasslands of Africa. *Environ Dev Sustain* 6:133–143
- Bertiller MB, Ares JO, Bisigato AJ (2002) Multiscale indicators of land degradation in the Patagonian Monte, Argentina. *Environ Manage* 30:704–715
- Chang XL, Lu CX, Gao YB (2003) Impacts of human economic activities on wind and sand environment in Kerqin sandy land. *Res Sci* 5:11
- Cole BI, Lunt ID (2005) Restoring Kangaroo Grass (*Themeda triandra*) to grassland and woodland understoreys: a review of establishment requirements and restoration exercises in south-east Australia. *Ecol Manag Restor* 6:28–33
- Conant RT, Paustian K, Elliott ET (2001) Grassland management and conversion into grassland: effects on soil carbon. *Ecol Appl* 11:343–355
- Erb K, Krausmann F, Gaube V, Gingrich S, Bondeau A, Fischer-Kowalski M, Haberl H (2009) Analyzing the global human appropriation of net primary production—processes, trajectories, implications. An introduction. *Ecol Econ* 69:250–259
- Evans J, Geerken R (2004) Discrimination between climate and human-induced dryland degradation. *J Arid Environ* 57:535–554
- Foley JA, Levis S, Costa MH, Cramer W, Pollard D (2000) Incorporating dynamic vegetation cover within global climate models. *Ecol Appl* 10:1620–1632
- French NR (1979) *Perspectives in grassland ecology*. Springer-Verlag, New York
- Gao QZ, Li Y, Wan YF, Qin XB, Jiangcun WZ, Liu YH (2009) Dynamics of alpine grassland NPP and its response to climate change in Northern Tibet. *Clim Change* 97:515–528
- Gashaw M, Michelsen A, Jensen M, Friis I (2002) Soil seed bank dynamics of fire-prone wooded grassland, woodland and dry forest ecosystems in Ethiopia. *Nord J Bot* 22:5–17
- Giri C, Zhu Z, Reed B (2005) A comparative analysis of the Global Land Cover 2000 and MODIS land cover data sets. *Remote Sens Environ* 94:123–132
- Han JG, Zhang YJ, Wang CJ, Bai WM, Wang YR, Han GD, Li LH (2008) Rangeland degradation and restoration management in China. *Rangel J* 30:233–239
- Horion S, Cornet Y, Erpicum M, Tychon B (2013) Studying interactions between climate variability and vegetation dynamic using a phenology based approach. *Int J Appl Earth Obs Geoinf* 20:20–32
- Huenneke LF, Anderson JP, Remmenga M, Schlesinger WH (2002) Desertification alters patterns of aboveground net primary production in Chihuahuan ecosystems. *Glob Change Biol* 8:247–264
- Jiang ZR, An L, Chai CW (2008) Quantitative study on influencing factors of desertification in Minqin County, Gansu province. *J Desert Res* 28:35–41
- Jordan AM (1986) *Trypanosomiasis control and African rural development*. Longman, New York
- Li S, Zheng Y, Luo P, Wang X, Li H, Lin P (2007) Desertification in western Hainan Island, China (1959–2003). *Land Degrad Dev* 18:473–485
- Lieth H (1973) Primary production: terrestrial ecosystems. *Hum Ecol* 1:303–332
- Lieth H (1975) Modeling the primary production of the world. In: Lieth H, Whittaker RH (eds) *Primary productivity of the Biosphere*. Springer, Berlin, pp 237–283
- Liu J, Diamond J (2005) China’s environment in a globalizing world. *Nature* 435:1179–1186
- Ma MG, Frank V (2006) Interannual variability of vegetation cover in the Chinese Heihe River Basin and its relation to meteorological parameters. *Int J Remote Sens* 27:3473–3486
- Ma YH, Fan SY, Zhou LH, Dong ZY, Zhang KC, Feng JM (2007) The temporal change of driving factors during the course of land desertification in arid region of North China: the case of Minqin County. *Environ Geol* 51:999–1008
- Ma T, Zhou CH, Pei T (2012) Simulating and estimating tempo-spatial patterns in global human appropriation of net primary production (HANPP): a consumption-based approach. *Ecol Ind* 23:660–667
- Meehl GA, Zwiers F, Evans J, Knutson T, Mearns L, Whetton P (2000) Trends in extreme weather and climate events: issues related to modeling extremes in projections of future climate change. *B Am Meteorol Soc* 81:427–436
- Mu SJ, Yang HF, Li JL, Chen YZ, Gang CC, Zhou W, Ju WM (2013) Spatio-temporal dynamics of vegetation coverage and its relationship with climate factors in Inner Mongolia, China. *J Geogr Sci* 23:231–246
- Nicholls N, Collins D (2006) Observed climate change in Australia over the past century. *Ener Environ* 17:1–12
- O’Mara FP (2012) The role of grasslands in food security and climate change. *Ann Bot* 110:1263–1270
- Piao SL, Fang JY (2002) Terrestrial net primary production and its spatio-temporal patterns in Qinghai-Xizang Plateau, China during 1982–1999. *J Nat Res* 17:373
- Power S, Tseitkin F, Torok S, Lavery B, Dahni R, McAvaney B (1998) Australian temperature, Australian rainfall and the Southern Oscillation, 1910–1992: coherent variability and recent changes. *Aust Meteorol Mag* 47:85–101
- Prince SD, Becker-Reshef I, Rishmawi K (2009) Detection and mapping of long-term land degradation using local net production scaling: application to Zimbabwe. *Remote Sens Environ* 113:1046–1057
- Ravi S, Breshears DD, Huxman TE, D’Odorico P (2010) Land degradation in drylands: interactions among hydrologic–aeolian erosion and vegetation dynamics. *Geomorphology* 116:236–245
- Ruiz Jaen MC, Mitchell Aide T (2005) Restoration success: how is it being measured? *Restor Ecol* 13:569–577
- Safriel U, Adeel Z, Niemeijer D, Puigdefabregas J, White R, Lal R, Winslow M, Ziedler J, Prince S, Archer E, King C, Shapiro B, Wessels K, Nielsen T, Portnov B, Reshef I, Thonell J, Lachman

- E, McNab D (2005) Dryland systems. In: Hassan R, Scholes R, Ash N (eds) The millennium ecosystem assessment, ecosystems and human well-being: current state and trends. Island Press, Washington DC, pp 623–662
- Santibáñez F, Santibáñez P (2007) Trends in land degradation in Latin America and the Caribbean, the role of climate change. In: Sivakumar MK, Ndiang Ui (eds) Climate and land degradation, Springer, Berlin Heidelberg, p 65–81
- Scurlock JMO, Hall DO (1998) The global carbon sink: a grassland perspective. *Glob Change Biol* 4:229–233
- Shan C, Humphrey C, Sneath D (1996) Inner Asian grassland degradation and plant transformation. *Culture and environment in Inner Asia. Pastoral Econ Environ* 1:111–123
- Su YZ, Li YL, Cui JY, Zhao WJ (2005) Influences of continuous grazing and livestock exclusion on soil properties in a degraded sandy grassland, Inner Mongolia, northern China. *Catena* 59:267–278
- Symeonakis E, Drake N (2004) Monitoring desertification and land degradation over sub-Saharan Africa. *Int J Remote Sens* 25:573–592
- Trnka M, Bartošová L, Schaumberger A, Ruget F, Eitzinger J, Formayer H, Seguin B, Olesen JE, Pötsch EM, Krautzer B (2011) Climate change and impact on European grasslands. In: *Proceedings of the 16th Symposium of the European Grassland Federation, Gumpenstein, Austria, Agricultural Research and Education Center (AREC) Raumberg-Gumpenstein* pp 39–51
- UNCCD (1994) United Nations convention to combat desertification in countries experiencing serious drought and/or desertification, particularly in Africa. *A/AC.241/27*, Paris
- Verdoodt A, Van Ranst E (2006) Environmental assessment tools for multi-scale land resources information systems: a case study of Rwanda. *Agric Ecosyst Environ* 114:170–184
- Veron SR, Paruelo JM, Oesterheld M (2006) Assessing desertification. *J Arid Environ* 66:751–763
- Wessels KJ, Prince SD, Frost PE, Van Zyl D (2004) Assessing the effects of human-induced land degradation in the former homelands of northern South Africa with a 1 km AVHRR NDVI time-series. *Remote Sens Environ* 91:47–67
- Wessels KJ, Prince SD, Malherbe J, Small J, Frost PE, VanZyl D (2007) Can human-induced land degradation be distinguished from the effects of rainfall variability? A case study in South Africa. *J Arid Environ* 68:271–297
- Wrbka T, Erb K, Schulz NB, Peterseil J, Hahn C, Haberl H (2004) Linking pattern and process in cultural landscapes. An empirical study based on spatially explicit indicators. *Land Use Policy* 21:289–306
- Xu DY, Kang XW, Zhuang DF, Pan JJ (2010) Multi-scale quantitative assessment of the relative roles of climate change and human activities in desertification: a case study of the Ordos Plateau, China. *J Arid Environ* 74:498–507
- Yeh ET (2005) Green governmentality and pastoralism in western China: ‘converting pastures to grasslands’. *Nomadic People* 9:1–2
- Zaks DP, Ramankutty N, Barford CC, Foley JA (2007) From Miami to Madison: investigating the relationship between climate and terrestrial net primary production. *Glob Biogeochem* 21:B3004
- Zhang CX, Wang XM, Li JC, Hua T (2011) Roles of climate changes and human interventions in land degradation: a case study by net primary productivity analysis in China’s Shiyanghe Basin. *Environ Earth Sci* 64:2183–2193
- Zhou HK, Zhao XQ, Tang YH, Gu S, Zhou L (2005) Alpine grassland degradation and its control in the source region of the Yangtze and Yellow Rivers, China. *Grassl Sci* 51:191–203
- Zhou W, Li JL, Mu SJ, Gang CC, Sun ZG (2013a) Effects of ecological restoration-induced land-use change and improved management on grassland net primary productivity in the Shiyanghe River Basin, north-west China. *Grass Forage Sci* 10:1111
- Zhou W, Sun ZG, Li JL, Gang CC, Zhang CB (2013b) Desertification dynamic and the relative roles of climate change and human activities in desertification in the Heihe River Basin based on NPP. *J Arid Land* 5:465–479
- Zhou W, Gang CC, Zhou L, Chen YZ, Li JL, Ju WM, Odeh I (2014) Dynamic of grassland vegetation degradation and its quantitative assessment in the northwest China. *Acta Oecologica* 55:86–96