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Quantitative assessment of the relative roles of climate change and human activities in desertification processes on the Qinghai-Tibet Plateau based on net primary productivity

Qing Li, Chunlai Zhang *, Yaping Shen, Wenru Jia, Jiao Li

State Key Laboratory of Earth Surface Processes and Resource Ecology, MOE Engineering Research Center of Desertification and Blown-sand Control, Beijing Normal University, Xinjiekouwai Street 19, Beijing 100875, China

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ABSTRACT

Accurately identifying the contributions of climate change and human activities to desertification will support effective strategies for combating desertification. In this study, we employed the changes in net primary productivity (NPP) in areas of aeolian desertification on the Qinghai-Tibet Plateau from 2000 to 2014 to determine the dynamics of desertification. Changes in the potential NPP (PNPP) and the difference between PNPP and actual NPP (ANPP) revealed the relative contributions of climate change and human activities to desertification. We found overall mitigation of desertification during the study period. However, desertification varied both spatially and temporally. Areas with mitigation accounted for 80.1% of the total desertified land; other areas experienced exacerbation. In 67.3% of the area of mitigation, the improvement was attributed to climate change, and especially to increased precipitation. Climate change also accounted for the exacerbation of desertification in 38.0% of the total area in which desertification worsened, largely due to reduced precipitation. Therefore, climate change was the dominant factor for mitigation of desertification, and human activities were the dominant factor for exacerbation of desertification. The dominant factors for mitigation and exacerbation varied spatially. In the central and northeastern Qinghai-Tibet Plateau, climate change was the primary factor for mitigation of desertification and human activities dominated the exacerbation of desertification. In the southern and western Qinghai-Tibet Plateau, the reverse was the case. The ecological protection projects that have been implemented since 2000 in most of the Qinghai-Tibet Plateau have not yet become a dominant factor in controlling desertification processes.

1. Introduction

Desertification is a major type of land degradation occurring around the world, and has become one of the most serious environmental issues (Dregne et al., 1991; UNCED, 1992; Adger et al., 2000; Reynolds and Stafford Smith, 2002; MEA, 2005; Reynolds et al., 2007). Since the 1990s, the environmental and social problems caused by desertification have become one of the key factors preventing sustainable development in the world's arid, semi-arid and sub-humid zones, which account for 41% of the global land area (UNEP, 1991; Williams and Balling, 1996; Reynolds and Stafford Smith, 2002). Climate change and human activities are the driving factors for desertification (UNEP, 1994; Evans and Geerken, 2004; Wessels et al., 2004, 2007; Olsson et al., 2005), but their relative contributions to desertification remain poorly understood (Wang et al., 2006; Xu et al., 2014).

Previous researchers have used correlation analysis (Sun and Li, 2002; Zhang et al., 2003) and principal-components analysis (Dong, 1989; Zhang, 2000) to estimate the contribution of each driving factor. However, these methods suffered from obvious subjectivity in terms of the selection of variables. Recently, some studies have selected vegetation dynamic as an indicator to reveal the impacts of human activities and climate change on desertification (Evans and Geerken, 2004; Wessels et al., 2004, 2007, 2008). Net primary productivity (NPP) provides an objective measure of vegetation cover and plant health, and its variation reveals changes in vegetation growing conditions (Piao et al., 2001). Haberl (1997) 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 effects of human activities on desertification (Xu et al., 2010). Later studies confirmed that the dynamics of NPP in areas undergoing desertification is a reliable indicator of the exacerbation and mitigation of desertification (Xu et al., 2010, 2014; Zhang et al., 2011; Zhou et al., 2013, 2015). In the present study, we select NPP as the desertification assessment indicator.

Desertification is a serious problem on China's Qinghai-Tibet Plateau. This region is strongly affected by atmospheric circulation patterns and its high altitude, and most areas of the plateau suffer from a cold and dry

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* Corresponding author.
E-mail address: clzhang@bnu.edu.cn (C. Zhang).

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climate, resulting in a fragile ecology that creates favorable conditions for desertification (Li et al., 2001). The monitoring result of aeolian desertified land revealed the area of desertified land accounted for above 10% of the total land area (Li et al., 2001). Serious desertification has therefore hampered socioeconomic development of the Qinghai-Tibet Plateau (Li et al., 2010; Zhang et al., 2009). Due to the fragile ecological environment, the desertification on the plateau was prone to be influenced by the human activities. Overgrazing, excessive cultivation and wood-cutting have caused damage of the natural vegetation, leading to exacerbation of desertification; On the other hand, forbidding grazing, conversion of cropland to grassland and controlling the number of livestock are advantageous for the recovery of the natural vegetation, leading to mitigation of desertification (Li et al., 2010; Lv and Yu, 2011).

In addition, the Qinghai-Tibet Plateau plays a prominent role in the evolution of the Asian monsoon system and acts as a primary water resource for East Asia's major rivers, so desertification on the plateau has greatly affected the ecological environment of China and East Asia (Li et al., 2001). To support the development of strategies to mitigate desertification on the plateau, it is necessary to improve our understanding of the relative contributions of climatic change and human activities to desertification. In the present study, our goal was to provide data on these contributions. To accomplish this goal, we used changes in the actual NPP (ANPP) in desertified land as a quantitative indicator of changes in the desertification status from 2000 to 2014. We also determined the potential NPP (PNPP) based on climate conditions in each part of the study area, and calculated the human-influenced NPP (HNPP) as the difference between PNPP and ANPP. The PNPP and HNPP data were then used to quantify the relative impacts of climatic and anthropogenic factors on desertification on the plateau. Regional differences in the roles of climate change and human activities in desertification, and their changes over time, were also revealed. Through quantifying the roles of climate change and human activities to aeolian desertification on the Qinghai-Tibet plateau, the present study aims to provide useful information to improve our understanding of the key causes of aeolian desertification so that helps the central and local government to figure out effective environmental management measures to combat aeolian desertification.

2. Data and methods

2.1. Study area

The Qinghai-Tibet Plateau is located in southwestern China, where it covers an area of 2,603,431 km^2. The elevation is generally >4000 m (Qiu, 2008). The administrative regions include the Tibet Autonomous Region, Qinghai Province, and parts of the Xinjiang Uygur Autonomous Region and of Gansu, Sichuan, and Yunnan provinces. The plateau is surrounded by great mountain ranges interlaced with valleys and basins. Because of the diverse topography, the climate is very complex. It is generally warm and wet in the southeast and cold and dry in the northwest. Across the region, the annual average temperature ranges from −5.6 °C to 17.6 °C, and the daily temperature difference ranges from 14 °C to 17 °C. The precipitation distribution is uneven. Annual precipitation in the Motuo area, in the southeast, and the Lenghu area, in the northwest, is above 4000 mm and 17.6 mm, respectively. Under the influence of the westerly circulation and the plateau's terrain, annual average wind speed is >3.0 m s^{-1}, with gales (i.e., a wind speed higher than 17 m s^{-1}) occurring >50 days annually (Li et al., 2001).

The Plateau's population density is low, and is mainly concentrated in cities, towns, and river valleys with good natural conditions for crop farming. The average regional population density is 5.0 persons per km^2, but in some areas, it is <1.0 person per km^{-2}. Because of the low temperatures and distribution of precipitation, only about 12,453 km^2 (0.5% of the total area) is suitable for crop farming, mostly in the valleys of the Yarlung Zangbo River, Lancang River, Nujiang River, and Yangtze River in the southeastern plateau and the Yellow River and Huangshui River in the northeast. Animal husbandry is the only agricultural activity in 57 of the total 188 counties, with a total area of grazing land of 1,421,473 km^2 (Zhang et al., 2012; Lv and Yu, 2011), accounting for 40.3% of the total area excessive animal grazing is the major human activity that has exacerbated desertification on the plateau.

2.2. Data sources and processing

Our study period was from 2000 to 2014. Calculation of NPP using the Carnegie-Ames-Stanford Approach (CASA) model (Potter et al., 1993; Field et al., 1995) requires data on the normalized-difference vegetation index (NDVI), land cover data, and meteorological data for the study area. We downloaded the 16-day synthesized, atmospherically corrected maximum NDVI data (MOD13A1) with the spatial resolution of 500 m from NASA's archive and distribution System (https://ladsweb.nascom.nasa.gov/data/). We used the 16-day NDVI data to synthesize monthly NDVI values using the maximum-value compositing method. Land-cover data was derived from a national land-use data downloaded from the China's WestDC site (http://westdc.westgis.ac.cn/). The land-cover data was created mainly based on visual interpretation of Landsat Thematic Mapper images in vector format with a scale of 1:100 thousand and the average interpretation accuracy was 92.9% (Liu et al., 2003). The data was resampled to a spatial resolution of 500 m. The meteorological data were derived from China's Meteorological Data Sharing Service System (http://cdc.nmic.cn/home.do), which includes monthly average temperature and total precipitation recorded at 122 meteorological stations on the plateau, and the total solar radiation recorded at 26 meteorological stations in and around the study area. The spline function interpolation method used polynomial fitting to generate a smooth interpolation curve. It was suitable for the interpolation of meteorological data (Li et al., 2006). So we applied the spline function interpolation method to interpolate the meteorological data to generate monthly raster images with a spatial resolution of 500 m. We applied the Albers equal-area conical projection and WGS-84 datum to all spatial data.

We used visual interpretation of 30-m-resolution Landsat image data from 2000 to obtain the distribution of aeolian desertified land. The interpretation accuracy was better than 95% according to the field verification results with the Kappa coefficient of 94.3%. The data was resampled to a spatial resolution of 500 m and transformed to the same coordinate system as for all spatial data. The results showed that aeolian desertified land on the plateau covered 401,632 km^2 in 2000, accounting for 15.4% of the total area. The area of aeolian desertified land in Tibet autonomous region and Qinghai Province was 205,956 km^2 and 129,434 km^2, respectively. The results were very close to the data derived from Landsat TM images by China's State Forestry Administration in 1999 that was 201,895 km^2 and 119,645 km^2 in Tibet autonomous region and Qinghai Province, respectively (SFAC, 2000). The aeolian desertification was widespread (Fig. 1). Except for the large and concentrated distribution of desertified land in the northern Plateau, most of the desertification was scattered throughout the plateau, but concentrated mostly in the western half. The area of the patches of desertification increased from southeast to northwest on the plateau.

2.3. Calculation of ANPP, PNPP, and HNPP

CASA model was established based on the vegetation mechanism. Although with some weaknesses on the parameter determination and the model calculation (Zhang et al., 2011), it was the most widely used model in recent years since it fully considered the environment conditions and the characteristics of vegetation (Gao et al., 2009). So present study used the CASA model to calculate ANPP (g C m^{-2} yr^{-1}). CASA accounts for the light-use efficiency of vegetation using a model derived from a combination of remote sensing, meteorological data, vegetation types, and soil data (Potter et al., 1993; Field et al., 1995). ANPP is determined based on the absorbed photosynthetically active

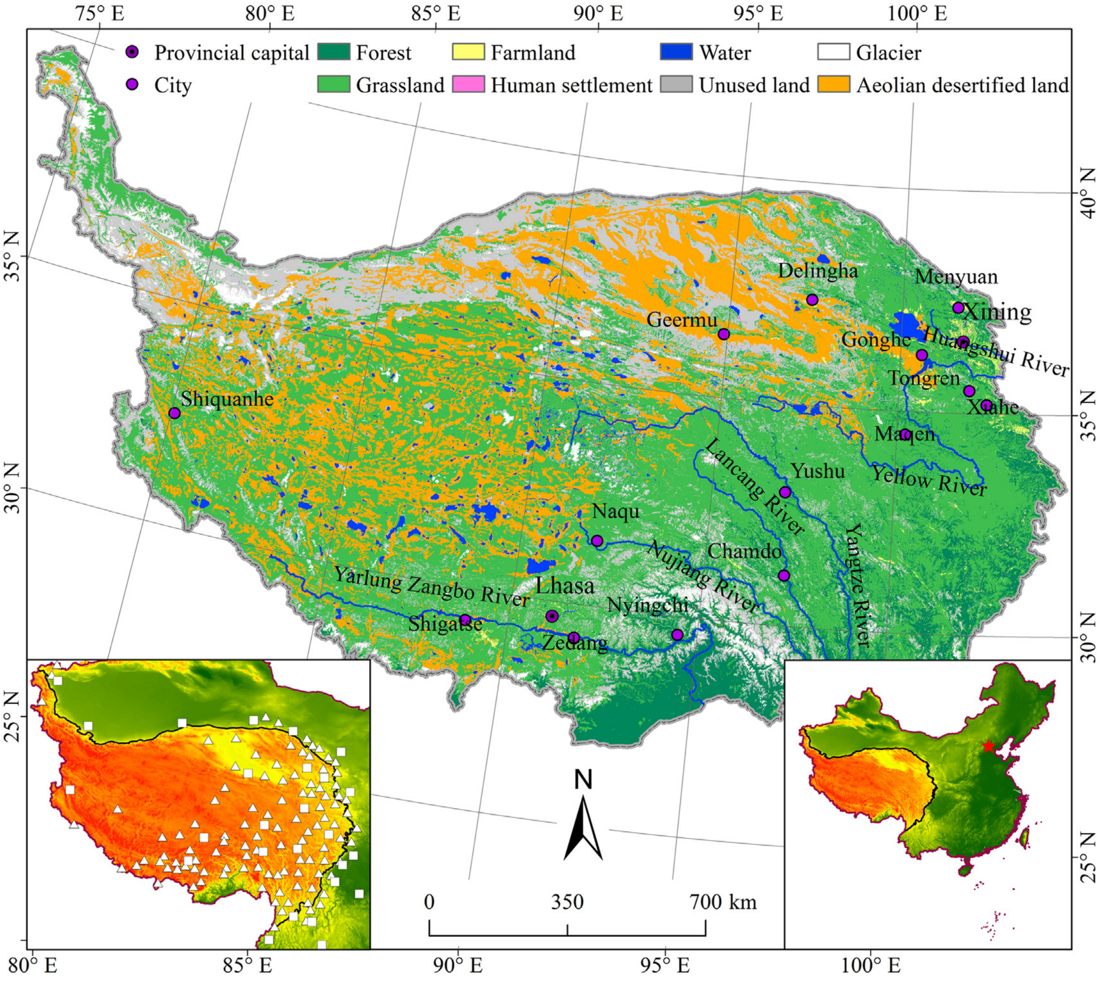

Fig. 1. Location of the study area, land cover patterns, the distribution of aeolian desertified land in 2000, and the locations of meteorological stations used in the present study.

radiation (APAR) and light-use efficiency (ε):

$$\mathrm{ANPP}(x,t) = \mathrm{APAR}(x,t) \times \varepsilon(x,t) \tag{1}$$

where x is the spatial location and t is the time. APAR is the incident photosynthetically active radiation (PAR, MJ m^{-2}) absorbed by the vegetation per unit time and ε is the actual light-use efficiency (g C MJ^{-1}). APAR is calculated from the fraction of the total solar radiation (SOL) accounted for by PAR (FPAR):

$$\mathrm{APAR}(x,t) = \mathrm{SOL}(x,t) \times \mathrm{FPAR}(x,t) \times 0.5 \tag{2}$$

where FPAR can be calculated from NDVI and 0.5 is the proportion of SOL intercepted by the vegetation. Under ideal conditions, the vegetation can achieve its maximum light-use efficiency (ε_{max}), but in reality, this efficiency is constrained by both the temperature and the soil moisture (Piao et al., 2001). These constraints are accounted for as follows:

$$\varepsilon(x,t) = T_{\varepsilon 1}(x,t) \times T_{\varepsilon 2}(x,t) \times W_{\varepsilon}(x,t) \times \varepsilon_{max} \tag{3}$$

where $T_{\varepsilon 1}$ and $T_{\varepsilon 2}$ are the temperature stress coefficients for light-use efficiency, W_{ε} is the moisture stress coefficient, and ε_{max} is the maximum light-use efficiency under ideal conditions.

The validation can be made by comparing the simulation results with observed data (Zhu et al., 2005). 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 (Zhu et al., 2005). In the present study, the observed NPP data was calculated from the field-measured biomass data in Qinghai-Tibet Plateau in August 2013 and 2014, which 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 ($R^2 = 0.750$, $p < 0.01$; Fig. 2), so the simulation accuracy of the model was satisfactory for the needs of the study.

The Miami model is the first widely accepted NPP estimation model that was derived based on least-squares regressions between field-measured NPP data and temperature and precipitation data for a study area (Lieth, 1975). The Thornthwaite Memorial model was established based on the data used in the Miami model, but was

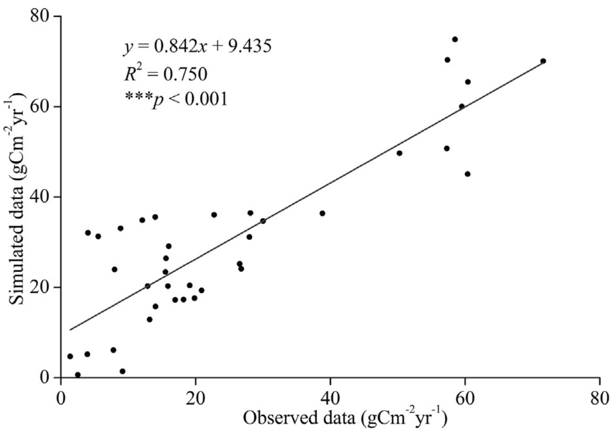

Fig. 2. Validation of the CASA model for the Qinghai-Tibet Plateau.

modified to include Thornthwaite's potential evaporation model (Lieth and Box, 1972). We used the Thornthwaite Memorial model to estimate PNPP ($\mathrm{g\,C\,m^{-2}\,yr^{-1}}$):

$$\mathrm{PNPP}(x,t)=3000\left[1-exp^{-0.0009695(v(x,t)-20)}\right] \tag{4}$$

$$v(x,t)=1.05r(x,t)\left\{1+[1+1.05r(x,t)/L(x,t)]^2\right\}^{-1/2} \tag{5}$$

$$L(x,t)=3000+25T(x,t)+0.05T(x,t)^3 \tag{6}$$

where x is the spatial location, t is the time, v is the annual average of the actual evaporation volume (mm), L is the annual average evaporation volume (mm), r is the annual total precipitation volume (mm), and T is the average annual temperature (°C).

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

$$\mathrm{HNPP}(x,t)=\mathrm{PNPP}(x,t)-\mathrm{ANPP}(x,t) \tag{7}$$

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

2.4. Assessment of the relative roles of climate change and human activities in desertification

Vegetation dynamics measured by NPP are the most intuitive manifestation of desertification (Zhou et al., 2015). Therefore, the trends in ANPP represent the dynamic changes in desertification during a period. The relative contributions of climate change and human activities can be assessed by comparing the trends in PNPP and HNPP during the same period. In the present study, we calculated the trends in ANPP, PNPP, and HNPP from 2000 to 2014 in the study area based on the rates of change in the three variables as a function of time during this period:

$$\mathrm{Slope}=\left[15\times\textstyle\sum_{i=1}^{15} i\times \mathrm{NPP}_i-\left(\sum_{i=1}^{15} i\sum_{i=1}^{15}\mathrm{NPP}_i\right)\right]\Big/\left(15\times\textstyle\sum_{i=1}^{15} i^2-\sum_{i=1}^{15} i\right) \tag{8}$$

where $i=1,2,\ldots 15$ are the years 2000, 2001, … 2014, respectively, and NPP_i is the NPP value in year i.

A positive slope for ANPP (S_{ANPP}) from 2000 to 2014 represents increased vegetation cover and mitigation of desertification, whereas a negative S_{ANPP} represents vegetation degradation and exacerbation of desertification. The slopes of PNPP (S_{PNPP}) and HNPP (S_{HNPP}) from 2000 to 2014 reveal the impacts of climate change and human activities, respectively, on desertification. A positive S_{PNPP} or a negative S_{HNPP} represents climate change or human activities (respectively) that improved vegetation cover and mitigated desertification. Negative S_{PNPP} or positive S_{HNPP} represent climate change or human activities that led to vegetation degradation and exacerbated desertification. With reference to previous studies of the relative impacts of human activities and climate change on desertification (Wessels et al., 2008; Xu et al., 2010, 2014; Zhou et al., 2013, 2015), we defined six scenarios:

In the case of desertification mitigation, S_{ANPP} is positive, and there are three possible scenarios:

a. $S_{\mathrm{PNPP}} < 0$, $S_{\mathrm{HNPP}} < 0$. Human activities are benefit for the desertification mitigation, and climate change is benefit for the desertification exacerbation. In this scenario, desertification mitigation is caused by human activities.
b. $S_{\mathrm{PNPP}} > 0$, $S_{\mathrm{HNPP}} > 0$. Human activities are benefit for the desertification exacerbation, and climate change is benefit for the desertification mitigation. In this scenario, desertification mitigation is caused by climate change;
c. $S_{\mathrm{PNPP}} > 0$, $S_{\mathrm{HNPP}} < 0$. Human activities and climate change are benefit for the desertification mitigation. In this scenario, human activities and climate change are both responsible for the mitigation of desertification.

In the case of desertification exacerbation, S_{ANPP} is negative, and there are also three possible scenarios:

a. $S_{\mathrm{PNPP}} < 0$, $S_{\mathrm{HNPP}} < 0$. Human activities are conducive to the desertification mitigation, and climate change is conducive to the desertification exacerbation. In this scenario, desertification exacerbation is caused by climate change;
b. $S_{\mathrm{PNPP}} > 0$, $S_{\mathrm{HNPP}} > 0$. Human activities are conducive to the desertification exacerbation, and climate change is conducive to the desertification mitigation. In this scenario, desertification exacerbation is caused by human activities;
c. $S_{\mathrm{PNPP}} < 0$, $S_{\mathrm{HNPP}} > 0$. Human activities and climate change are conducive to the desertification exacerbation. In this scenario, human activities and climate change are both responsible for the exacerbation of desertification.

Because the objective of this study was to analyze the impacts of climate change and human activities on aeolian desertification in the Qinghai-Tibet Plateau, we have focused on the areas that were identified as desertified in 2000 (Fig. 1), and have ignored the areas that were free of desertification.

3. Results

3.1. ANPP and PNPP of desertified land

For the 401,632 $\mathrm{km^2}$ of desertified land on the Qinghai-Tibet Plateau, the annual average ANPP from 2000 to 2014 totaled 1.53×10^{13} $\mathrm{g\,C\,yr^{-1}}$, which is equivalent to 38.1 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$, and this is close to the results (44 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ and 41.4 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$) of Piao et al. (2006) and Zhang et al. (2013). The ANPP of the desertified land decreased from the southeast toward the northwest. This spatial distribution was consistent with the spatial variations in temperature and precipitation on the plateau.

The ANPP value of desertified land was smallest in the north and northwest, at a mean value for the study period of <25 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ in most parts of these areas (Fig. 3A). In the central area it was around 25 to 50 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$. Better temperature and moisture conditions in the source regions of rivers in the southeast and of the Yarlung Zangbo River in the south produced an ANPP larger than 50 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$.

From 2000 to 2014, the mean PNPP of the aeolian desertified land in the study area totaled 1.15×10^{14} $\mathrm{g\,C\,yr^{-1}}$, which is equivalent to 285.7 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$. PNPP decreased from the southeast toward the northwest (Fig. 3B). It was smallest in the north and the northwest, with mean values <150 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ in most cases. The largest PNPP occurred in the south, with mean values larger than 450 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$.

3.2. Trends in ANPP, PNPP, and HNPP

Except for decreased ANPP in some areas ($S_{\mathrm{ANPP}} < 0$), the overall trend for ANPP in the plateau was an increase ($S_{\mathrm{ANPP}} > 0$) from 2000 to 2014 (Fig. 4A). The total area with $S_{\mathrm{ANPP}} > 0$ was 321,752 $\mathrm{km^2}$, which represents 80.1% of the total area of desertified land in the north and the east. This means that desertification in 80.1% of the total area of desertified land was mitigated. The total area with $S_{\mathrm{ANPP}} < 0$ was 79,880 $\mathrm{km^2}$, which accounted for 19.9% of the total area of desertified land, primarily in the middle.

The trends in PNPP indicated an overall favorable trend for vegetation response to climate change in most areas (Fig. 4B). The total area with $S_{\mathrm{PNPP}} > 0$ was 279,046 $\mathrm{km^2}$, accounting for 69.5% of the total area

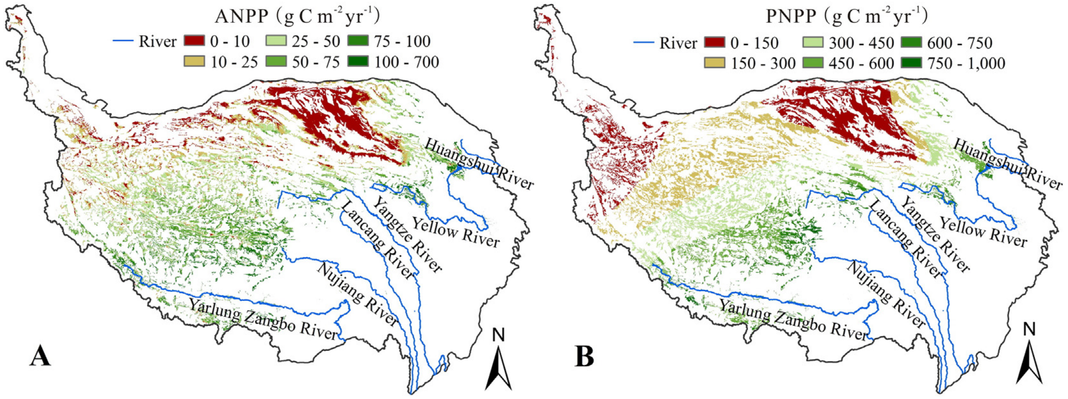

Fig. 3. Spatial distribution of the mean annual (A) ANPP and (B) PNPP from 2000 to 2014.

of desertified lands on the Qinghai-Tibet Plateau, whereas the remaining 30.5% of this area (122,586 km^2) had $S_{PNPP} < 0$, primarily in the west and the south, where increasing temperatures and decreasing precipitation exacerbated the vegetation degradation.

The trend for S_{HNPP} indicated that NPP loss due to human activities increased from 2000 to 2014 in most areas (Fig. 4C). The total area with $S_{HNPP} > 0$ (i.e., negative effects of human activities on vegetation) was 266,215 km^2, accounting for 66.3% of the total area of desertified lands, primarily in the north and northeast. The remaining 33.7% of the total (135,417 km^2) was concentrated in the west and the south, where human activities had a net positive effect on vegetation.

3.3. Contributions of climate change and human activities to desertification

By superimposing the maps for the trends in PNPP (Fig. 4B) and HNPP (Fig. 4C) in the areas of desertification mitigation ($S_{ANPP} > 0$), we confirmed that climate change was the major factor contributing to the mitigation of desertification from 2000 to 2014 based on the scenario definitions. Climate change accounted for 67.4% of the total area where mitigation occurred; the mitigation in the other 27.8% of the area was due to human activities; the remaining 4.8% of the area was affected roughly equally by human activities and climate change (Fig. 5A). The spatial variation in the dominant factors responsible for the mitigation of desertification resulted from remarkable differences in climate change and human activities across large areas. Climate change was the dominant factor for desertification mitigation in the north and the east, whereas human activities dominated desertification mitigation in the west and the south. The area where climate change and human activities played roughly equivalent roles in mitigating desertification was relatively small.

Similarly, the map of the areas where desertification was exacerbated ($S_{ANPP} < 0$) showed that climate change was responsible for exacerbation of desertification in 30,343 km^2 (38.0% of the total area where exacerbation occurred; Fig. 5B). Human activities dominated the

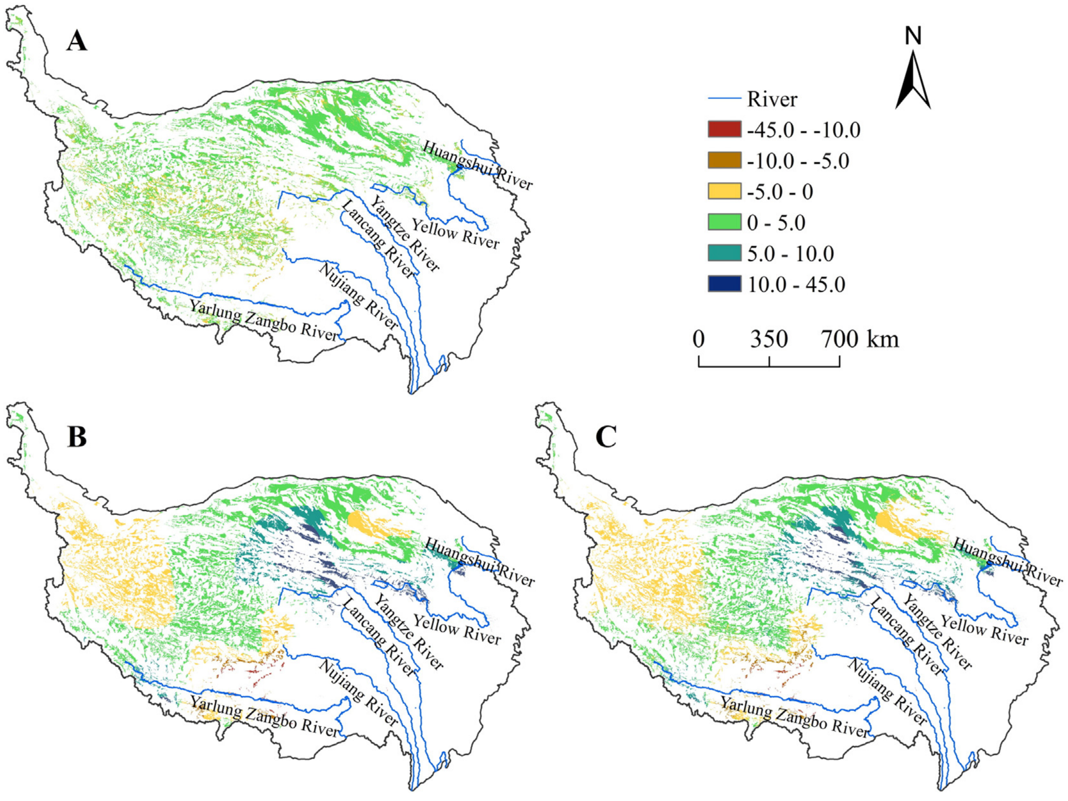

Fig. 4. Spatial distribution of the trends (slopes) for (A) ANPP (S_{ANPP}), (B) PNPP (S_{PNPP}), and (C) HNPP (S_{HNPP}).

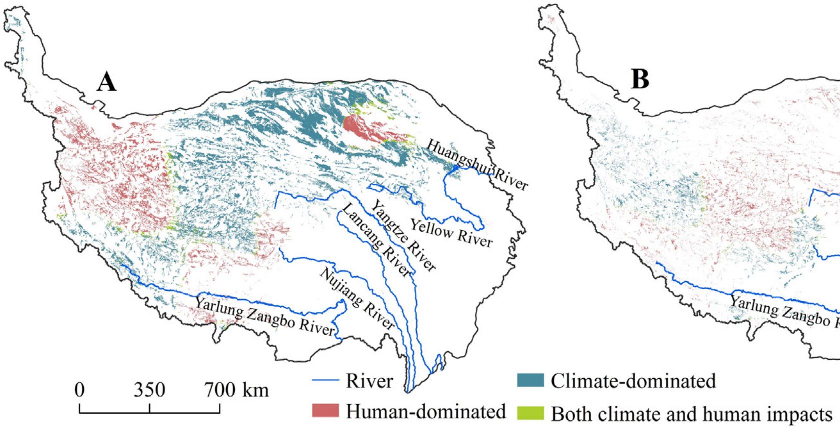

Fig. 5. Spatial distribution of the relative roles of climate change, human activities, and the combination of these two factors on (A) the mitigation and (B) the exacerbation of desertification.

exacerbation of desertification in 46,802 km^2 (58.6% of the total area where exacerbation occurred). In the remaining 2735 km^2 (3.4% of the total), desertification was exacerbated to roughly equal extents by climate change and human activities. Spatial variation in the dominant factors responsible for the exacerbation of desertification also existed, with climate change being the dominant factor in the south and the west and human activities dominating in the northern and central areas.

4. Discussion

Climate change is one of the main factors affecting desertification in Africa (Prince et al., 1998). On the Qinghai-Tibet Plateau, aeolian desertified land is located in arid, semi-arid, and subhumid areas, where the vegetation is particularly susceptible to fluctuations in precipitation and temperature (Fensholt et al., 2015). Although the understanding of climate change on the plateau varies among researchers, there is a general consensus that temperatures rose in the most recent 30 to 50 years, but that the trend for precipitation varied spatially; that is, parts of the region's climate became warmer and wetter whereas the rest became warmer and drier (Han et al., 2011; Zhang et al., 2012; Chen et al., 2014; Shen et al., 2015). In the study area, precipitation in most areas increased from 2000 to 2014, except in parts of the west and the south (Fig. 6A). The trends for PNPP and ANPP showed a similar spatial distribution to that of precipitation, since precipitation is the main factor that controls NPP and its variation in dry regions (Piao et al., 2012; Chen et al., 2014). This pattern suggests that rising temperature and increasing precipitation promoted vegetation cover improvement and desertification mitigation, whereas rising temperature and decreasing precipitation promoted the degradation of vegetation and exacerbation of desertification. Therefore, the variation in precipitation was the dominant climatic driving factor responsible for both exacerbation and mitigation of desertification on the plateau from 2000 to 2014, but the rising temperature intensified the magnitude of the mitigation or exacerbation.

Since the 1960s, the economy of the Qinghai-Tibet Plateau has developed rapidly, and the population continues to increase (Fig. 7). To meet the demand for food and other resources created by the increasing population, the number of livestock and the area of cultivated land have also increased (Fig. 7), imposing much pressure on the region's fragile ecological environment. The increased number of livestock has exceeded the carrying capacity of the grazing land in many areas, and the areas where cultivation has expanded are distributed mostly in areas of shrubby grassland that are unsuitable for agriculture (Zhang et al., 2009; Li et al., 2010). In addition, the growing population has led to extensive harvesting of natural shrubs as a crucial source of domestic fuel in large parts of the plateau (Li et al., 2010). Such irrational human activities as overgrazing and excessive cultivation and woodcutting have caused severe damage to the natural vegetation and have increased the area of exposed topsoil, which is vulnerable to erosion by the region's strong winds, leading to exacerbation of desertification (Lv and Yu, 2011). The intensity of these human activities also varied spatially on the Qinghai-Tibet Plateau, so their impact on desertification varied spatially. Case studies by Li et al. (2010) and Zhang et al. (2009) suggested that human activities were the secondary driving factors responsible for desertification in the southern and southwestern parts of the plateau from 1990 to 2005, but have been the dominant factor in the northeast since the 1980s. The present results suggest that human

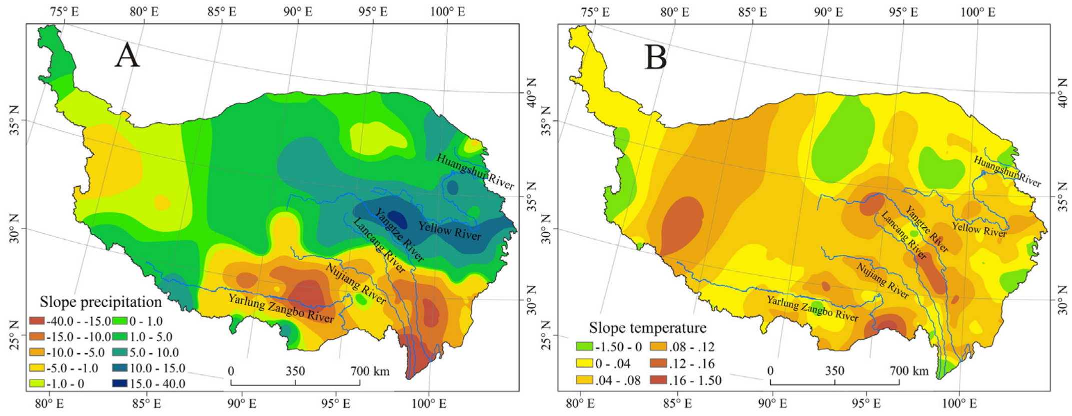

Fig. 6. Spatial distribution of the trends for (A) the annual total precipitation and (B) the average annual temperature from 2000 to 2014.

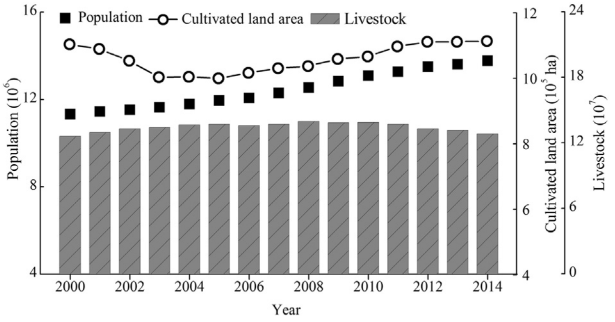

Fig. 7. Changes in the population, the area of cultivated land, and the number of livestock on the Qinghai-Tibet Plateau.

activities led to exacerbation of desertification in about 35.9% of the area in the south and southwest; in the northeast, this increased to 92.8%.

Environmental protection programs, including forbidding grazing in vulnerable or degraded areas, conversion of cropland to grassland or to forest or shrub communities, and controlling the number of livestock have been implemented throughout the plateau since 2000 to combat desertification. However, unreasonable human activities remained the dominant factor that exacerbated desertification in most of the north and northeast (Fig. 5B). In the southeast, especially in the Yarlung Zangbo River valley, these programs were implemented much earlier (in 1993) with great effort, resulting in a better effect and making this one of the areas where human activities played the major role in the mitigation of desertification. Implementation of these programs in parts of the western plateau also played a major role in the mitigation of desertification, although the human population density was <2 persons per km^2 and has dropped in recent years, thereby lowering the pressure on the environment. For the whole plateau, however, most of the grassland has been overgrazed by 39.2% above the carrying capacity (Zhang et al., 2012) due to continuously increasing human and livestock populations (Fig. 7). Thus, overgrazing remains the most important and widespread unreasonable human activity that is continuing to induce and exacerbate desertification on the plateau, despite the measures that were adopted to control this problem.

5. Conclusions

Aeolian desertified land on the Qinghai-Tibet Plateau totaled 401,632 km^2 in 2000, accounting for 15.4% of the total land area. We selected NPP as a quantitative indicator of desertification to monitor the changes in desertification from 2000 to 2014 and assess the relative roles of climate change and human activities. The ANPP results showed overall mitigation of desertification since 2000. Mitigation occurred in 80.1% of the total area of desertified land, primarily in the north and the east. The area where desertification was exacerbated accounted for 19.9% of the total area, primarily in the south.

The PNPP and HNPP results indicated that climate change was the dominant factor responsible for desertification: 67.4% of the mitigation was attributed to climate change, 27.8% was attributed to human activities (primarily programs to protect the ecological environment), and the remaining 4.8% of the area was affected equally by these two factors. In areas were desertification was exacerbated, the contributions of climate change and human activities were 38.0% and 58.6%, respectively, with the remaining 3.4% contributed equally by the two factors.

Changes in precipitation were the primary climatic factor that affected the desertification process; however, increasing temperatures changed the magnitude of the processes. The contributions of climate change and human activities to desertification varied spatially throughout the plateau. In the central and northeastern regions, climate change drove the mitigation and human activities exacerbated desertification. In the southern and northwestern regions, the opposite occurred. Ecological protection programs that have been implemented throughout the plateau have therefore not yet controlled desertification, except in limited areas of the southern plateau.

To support site-level mitigation programs, it will be necessary to obtain data with finer spatial resolution. In addition, it will be necessary to continue this monitoring in the future to identify areas where ecological restoration programs remain ineffective so that alternative measures can be implemented.

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