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ORIGINAL ARTICLE

Controls on desertification during the early twenty-first century in the Water Tower region of China

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Abstract China's water source includes the headwaters of the Yangtze, Yellow, and Lantsang (the Mekong outside China) rivers and is located in the heart of the Tibet Plateau, which has an average altitude of 4,200 m. Due to the importance of the Water Tower to the ecological security and economic development of China and South Asia, desertification issues in this region have attracted the attention of the public, scholars, government officials, and international organizations. Combined satellite-derived vegetation indices, field surveys, and surface meteorological data to evaluate the effects of climate change, our analyzed results show that during the early part of the twenty-first century, no desertification occurred in these source areas. However, between 2000 and 2010, human activities may have had a negative effect on about 50 % of the region, although vegetation rehabilitation still occurred during this period. Although the Ecological Protection and Restoration Program was launched in China in 2005, the negative impacts of human activities such as agriculture have still increased in the water source. Vegetation rehabilitation in these source areas appears to be driven mainly by the effect of climate change, and it is possible that human activities do not play an important role in regional ecological and environmental evolution. Although at present we cannot determine whether it was rising temperatures or increasing precipitation that enhanced vegetation growth in the region, our results show that the dominant factors controlling vegetation rehabilitation in China's Water Tower are related to climate.

Keywords Desertification · Water source region · Human activity · Climate change · Tibet Plateau · South Asia

Introduction

The Yangtze and Yellow river basins are considered to be the cradles of Chinese civilization, and together with the Lantsang river (known as the Mekong outside China), originate in the center of the Tibet Plateau. The plateau covers an area of 312,930 km^2, has an average altitude of 4,200 m, and provides 25, 49, and 15 % of the water for the Yangtze, Yellow, and Lantsang rivers, respectively (Qin et al. 2008; Zhao 2011; Fig. 1 and S1). Due to its importance to water resources in China and South Asia, this region is known as China's or Asia's Water Tower. The ecological and environmental evolution of this area can be related to global climate change (Arnell 1999) and to the environmental security of South Asia and western China (Gautam 2010; Qian et al. 2010), and consequently, has attracted the attention of the public, in addition to researchers, government officials, and international organizations (Shen and Tan 2012). In addition, this region has the largest wetland of China, and with its high altitude and great biodiversity, these fragile ecosystems are highly

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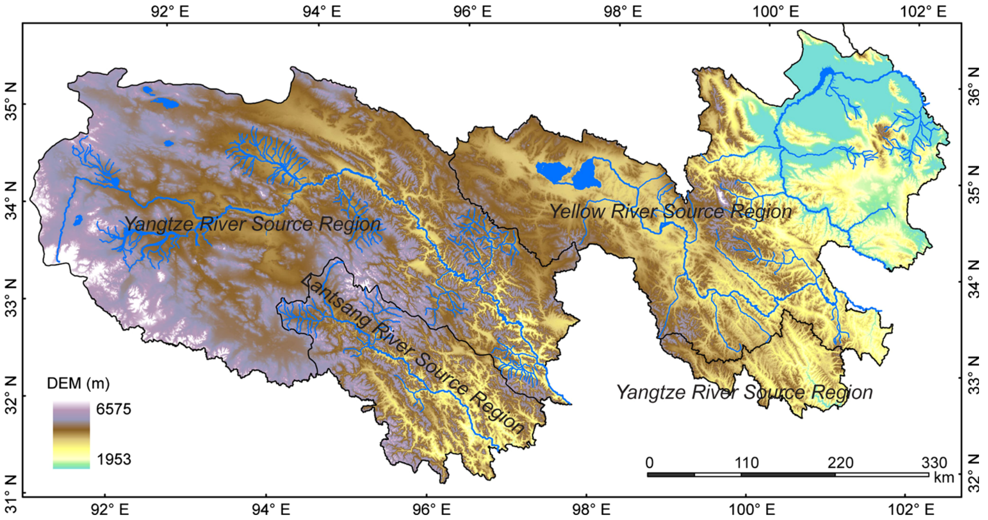


Fig. 1 Location *map* showing the source areas of the Yellow, Yangtze, and Lantsang rivers, and the locations of meteorological stations (*black circles*). Their locations in China are shown in Fig. S1 of the supplemental material

sensitive to climate change (Tang et al. 2006; Fan et al. 2010; Li et al. 2011, 2012) and human activities (Chen 2005; Zhao and Zhou 2005).

Over recent decades, desertification has become an important issue in this region with its effects including grassland degradation (Li 1997; Wang et al. 2001; Wang and Cheng 2001; Yan et al. 2003; Liu 2007), decreased biodiversity (Wen et al. 2011), wetland degradation (Zheng et al. 2012), and sandy desertification (Fang et al. 1998; Han et al. 2004; Feng et al. 2005; Li et al. 2006) occurring in different periods. For instance, Liu et al. (2008) suggested that from the late 1970s to the early 2000s, severe grassland degradation occurred in this region. In addition, between the 1980s and the late 1990s, severe sandy desertification occurred in the region (Zou et al. 2002), and between 1975 and 2005, the areas of sandy desertification in the Yangtze river basin increased continuously (Dong et al. 2012), and from the mid-1970s to the early 2000s the supply of water from rivers in the region showed a continuous decline (Li et al. 2010).

In 2005, with the aim of combating desertification and land degradation, the Chinese government initiated a large-scale ecological migration program in the source regions of the Yellow, Yangtze, and Lantsang rivers; i.e., the Ecological Protection and Restoration Program (EPRP) (Qinghai Provincial Government 2005; Chen et al. 2007; Wang et al. 2010). The key measures of this program included reform of the traditional agricultural and animal husbandry practices, limiting the scale of herding in the region, removal of the bulk of the population from regions with fragile ecological environments, and to propose legislation for procuring regional environments (Qinghai Provincial Government 2007a, b). However, the effects of this program and the impact of climate change on ecological restoration in this region remain poorly understood. Therefore, in this study, we combine satellite-derived vegetation indices, field surveys, and surface meteorological data to evaluate the effects of the EPRP and the influence of climate change on desertification in this region. The main aims of this paper are to determine whether desertification has occurred over the past decade and to assess the roles of climate change and human activities on desertification processes in this region.

Methods

Satellite and meteorological data

Moderate-resolution imaging spectroradiometer (MODIS) surface reflectance daily L2G global 250 m data (MOD09GQ, Collection 5), the Landsat TM/ETM+ data, and meteorological data (provided by China National Meteorological Administration) from 2000 to 2012 were used in this study. The MODIS data (h26v05, h25v05) covering the study area were obtained from NASA (National Aeronautics and Space Administration) and can be accessed at http://reverb.echo.nasa.gov/reverb. MODIS images with cloud cover and pixels with values outside the valid range specified by the MOD09GQ.005 quality control descriptions were excluded from the analysis. The MODIS Reprojection Tool (MRT) was used to mosaic every two scenes and convert the sinusoidal projection into a WGS 1984 Albers projection. Subsets covering only the study area were then extracted from each image, and values were scaled between −1.0 and 1.0 by ENVI 4.7 to acquire daily normalized difference vegetation index (NDVI) data. Lastly, the maximum value composites (MVC) were processed by month to obtain the monthly NDVI.

The Landsat TM data with a spatial resolution of 30 m were obtained from the US Geological Survey (USGS) and can be accessed at http://earthexplorer.usgs.gov/. Landsat TM/ETM+ scenes obtained in 2000, 2005, and 2010 were selected for further analysis of the variations in trends in mobile sandy areas using time series obtained from May to September (MJJAS) images when vegetation cover reaches its maximum each year. More details of our analysis of the trends in the mobile sandy lands are provided in section S2 of the supplemental material. Due to the heavy cloud cover on the Tibetan Plateau, it was necessary to replace several images with an image from the same month of the previous or following year, but this had no significant effect on the interpretation of the trends in the mobile sandy lands because here we only compare trends in mobile sandy lands from 2000, 2005, and 2010. Radiometric calibration and atmospheric corrections were performed using ENVI4.7. Histogram normalization was applied to yield normalized radiometric data and so remove or normalize the reflectance variation between images acquired at different times. Scenes were mosaicked to obtain intact images. For comparative analysis among the images, image-to-image registration was used, and images were geo-referenced to the WGS 1984 Albers Equal-Area Conic coordinate system.

The meteorological data, which include monthly precipitation, temperature, and mean wind speed, were obtained from the China Meteorological Administration. Due to the harsh environments and arduous work conditions, there are only a few meteorological stations scattered across this region, and they provide insufficient data for high-resolution spatial analysis. Therefore, in each source area (Yellow, Yangtze, and Lantsang rivers), we integrated the meteorological data from all stations to assess the extent of regional climate change between 2000 and 2012.

Data processing

NDVI data processing

Variations in NDVI values usually represent changes in the vigor and photosynthetic capacity (or greenness) of the

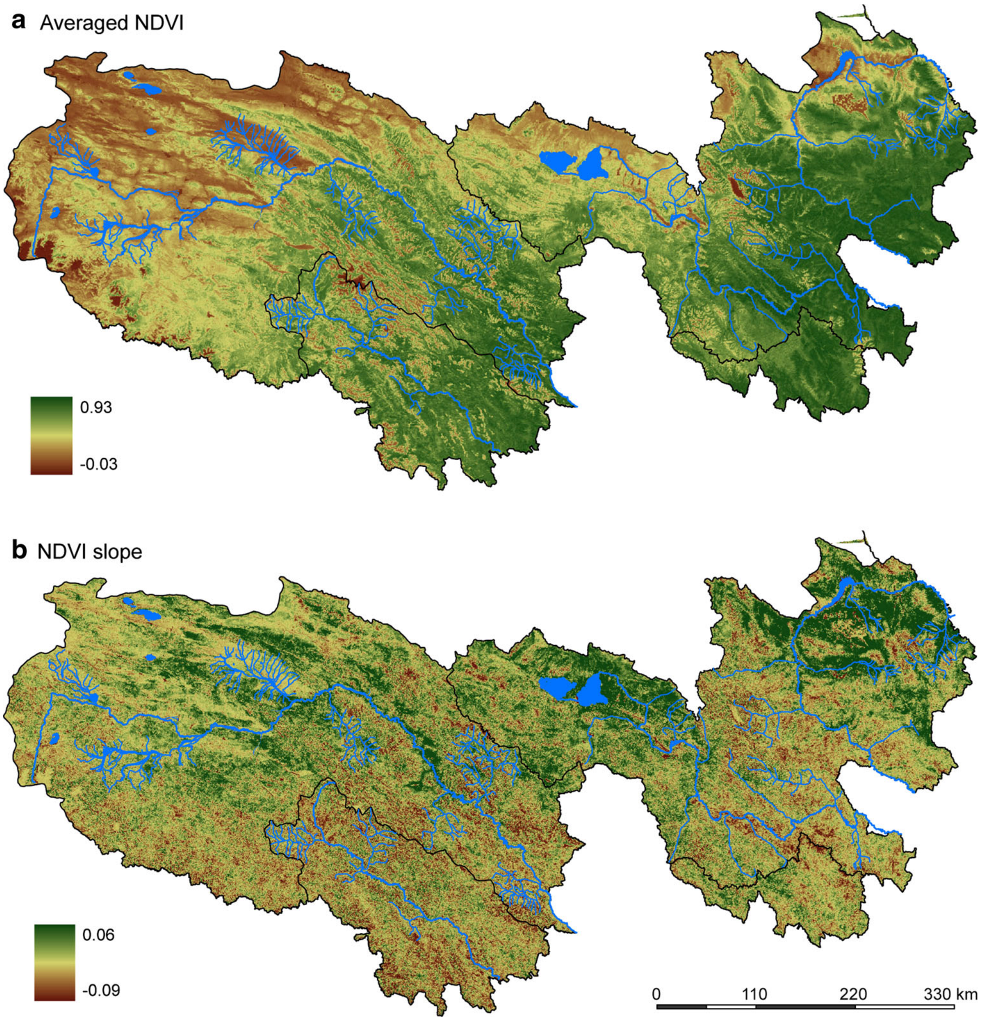


Fig. 2 Spatial trends in NDVI (**a**) and NDVI slope (**b**) between 2000 and 2010 in the source areas

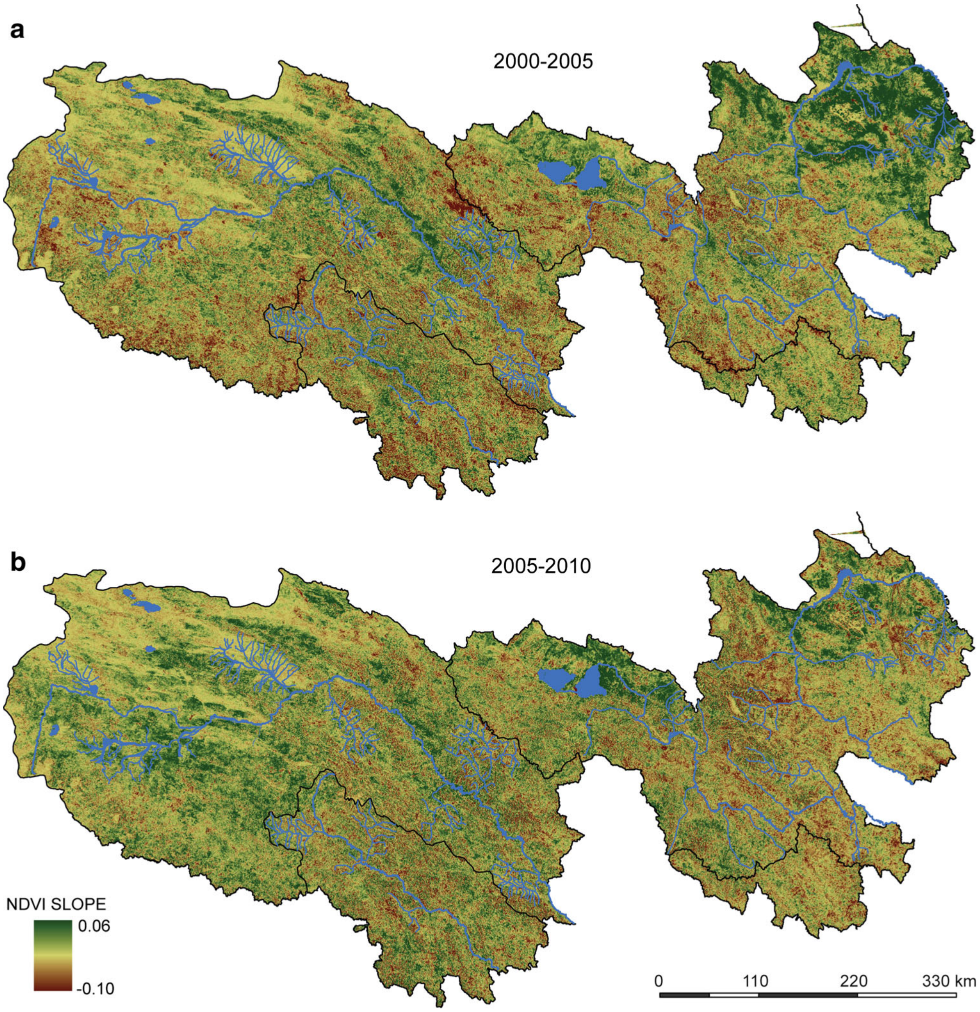


Fig. 3 Comparisons of spatial trends in NDVI slope in the periods 2000–2005 (**a**) and 2005–2010 (**b**)

vegetation canopy (Chen and Brutsaert 1998), whose values are positively correlated with vegetation coverage with the desertification status of the region (e.g., Wang et al. 2003; Piao et al. 2005). Here, the maximum NDVI of the growing season (MJJAS) was defined as the annual NDVI values (e.g., Pettorelli et al. 2005; Verbyla 2008) and was employed in further analysis.

NDVI time series were evaluated using a linear regression model to obtain the temporal trend of every pixel. This method fits a linear equation to the NDVI as a function of the variable YEAR, to acquire the slope of the images. For every pixel, the linear relationship between NDVI and YEAR was determined using the ordinary least squares (OLS) method:

$$\mathrm{NDVI} = \mathrm{SLOPE} \times \mathrm{YEAR} + b \tag{1}$$

$$\mathrm{SLOPE} = \frac{n \times \sum_{i=1}^{n} i \times \mathrm{NDVI}_i - \left(\sum_{i=1}^{n} i\right)\left(\sum_{i=1}^{n} \mathrm{NDVI}_i\right)}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \tag{2}$$

Table 1 NDVI slope variations from 2000 to 2010 (km^2)

Source region		Yellow river	Yangtze river	Lantsang river	Total source region
2000–2005	<0	37,787	58,889	15,882	112,558
	>0	78,916	100,075	21,378	200,369
	% of >0	67.62	62.95	57.38	64.03
2005–2010	<0	44,222	40,497	13,140	97,858
	>0	72,481	118,467	24,120	215,069
	% of >0	62.11	74.52	64.73	68.73
2000–2010	<0	28,787	41,880	17,095	87,762
	>0	87,916	117,084	20,165	225,165
	% of >0	75.33	73.65	54.12	71.95

here, SLOPE represents the NDVI trend, with values greater than zero indicating an increasing NDVI and high vegetation productivity (e.g., Fang et al. 2004); conversely,

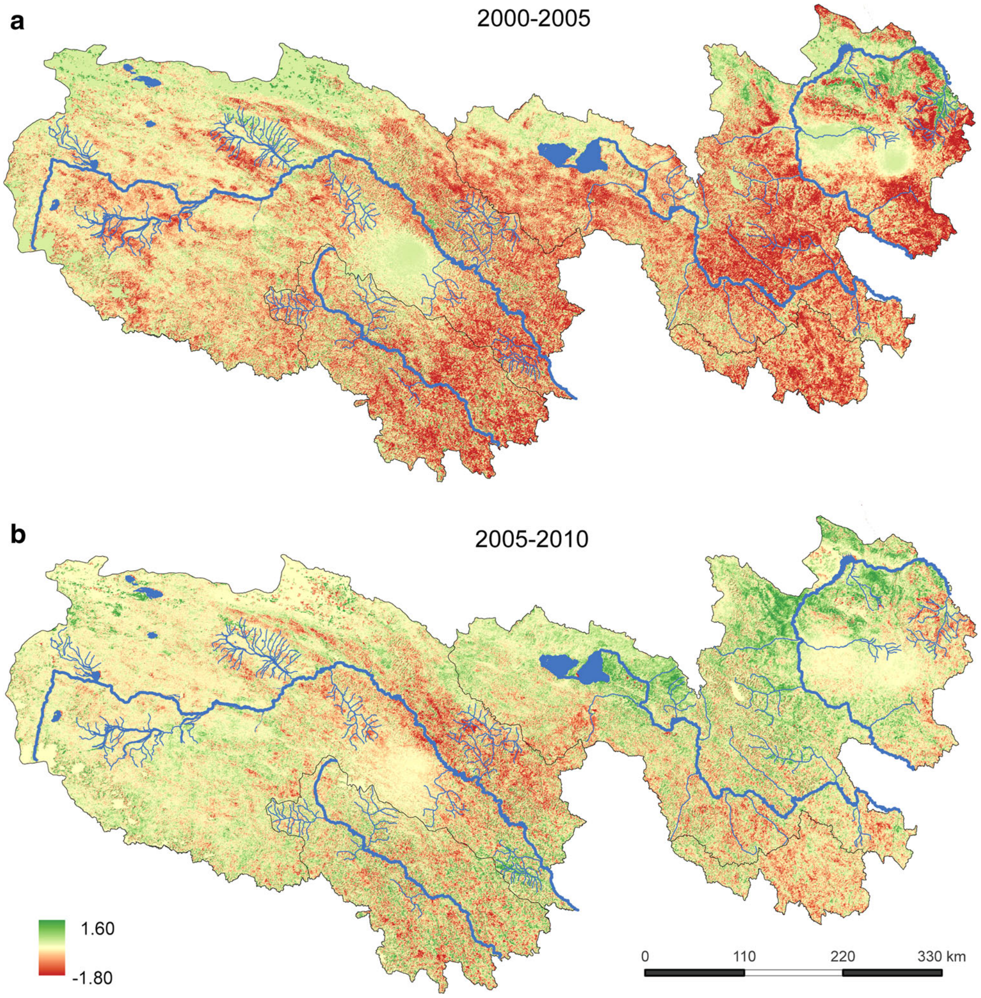


Fig. 4 Comparisons of spatial trends in potential NPP slope in the periods 2000–2005 (**a**) and 2005–2010 (**b**)

values less than zero suggest a decreasing NDVI trend and low vegetation productivity in the region (see section S3 of the supplemental materials).

Actual and potential net primary productivity data processing

Net primary productivity (NPP) estimations have been used previously to investigate the magnitude and geographical distribution of primary productivity (Field et al. 1998; Cramer et al. 1999; Grosso et al. 2008) and have been successfully used to assess land degradation at various spatial and temporal scales (Wessels et al. 2003; Prince et al. 2009). More recently, NPP models have been widely used to quantitatively assess the relative roles of climatic and human activities in desertification or land degradation (Evans and Geerken 2004; Potter 2004; Wessels et al. 2004; Tao et al. 2005).

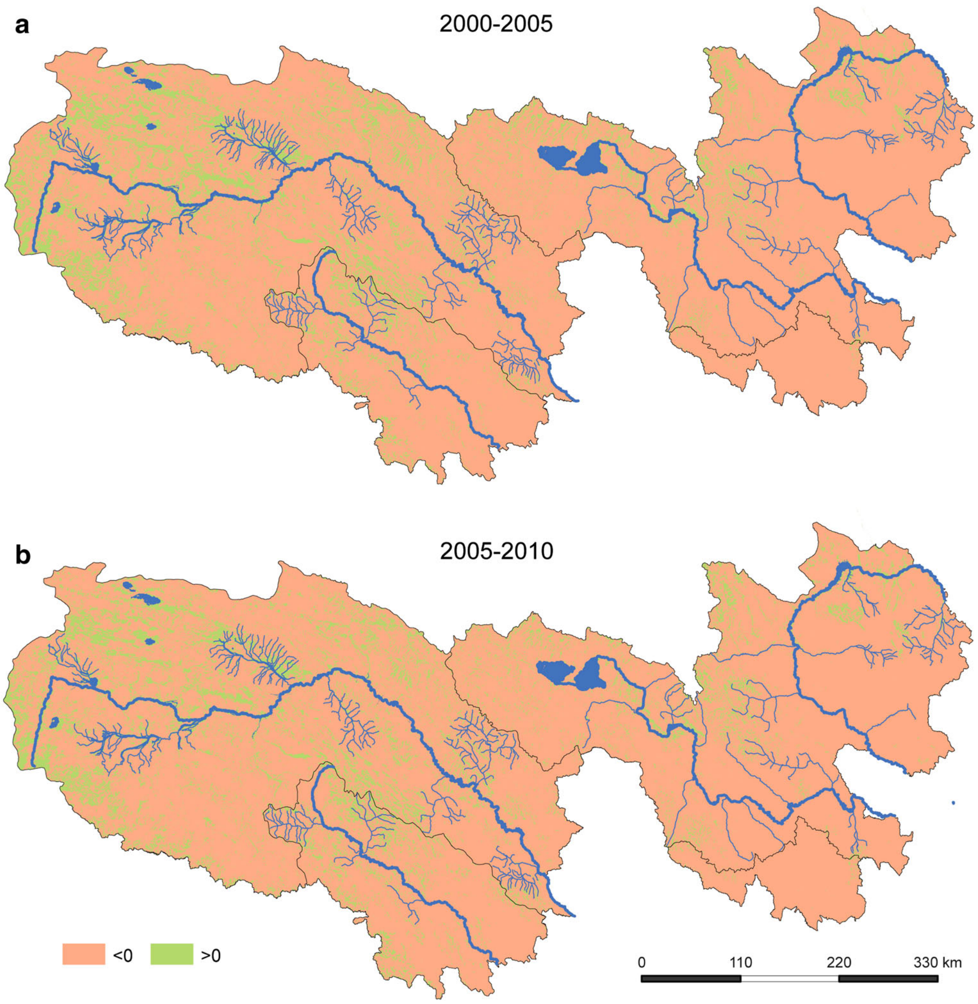
Table 2 Potential NPP slope variations from 2000 to 2010 (km^2)

Source region		Yellow river	Yangtze river	Lantsang river	Total source region
2000–2005	<0	100,945	136,988	31,723	269,657
	>0	15,758	21,976	5,537	43,270
	% of >0	13.50	13.82	14.86	13.83
2005–2010	<0	40,367	78,096	17,731	136,194
	>0	76,336	80,868	19,529	176,733
	% of >0	65.41	50.87	52.41	56.48
2000–2010	<0	68,023	97,125	23,156	188,304
	>0	48,680	61,839	14,105	124,623
	% of >0	41.71	38.90	37.85	39.83

Here, we employ the Carnegie–Ames–Stanford Approach (CASA) model to evaluate the actual NPP variations in the region. In the CASA model, the NPP is determined mainly from the product of the absorbed photosynthetically active radiation (APAR) and light use efficiency (ε):

$$\mathrm{NPP}(x,t) = \mathrm{APAR}(x,t) \times \varepsilon(x,t) \tag{3}$$

Fig. 5 Comparisons of the residuals between the potential and actual NPPs in the periods 2000–2005 (**a**) and 2005–2010 (**b**)



The data processing related to NPP outputs includes mean monthly temperature, evapotranspiration, sunshine duration, vegetation index, vegetation type, and soil type, about which additional information is provided in section S4 of the supplemental materials.

We also employ a similar method to the CASA model to assess the regional potential NPP, and more details of these methods are provided in the supplemental materials. Similarly to the NDVI slope, the temporal trends of the potential NPP slope can be taken to be representative of the role of climate change in desertification in the region, with values greater than zero indicating an increasing potential NPP trend and self-restoration of vegetation. We also employ the differences between the potential and actual NPPs (i.e., the residuals) to evaluate the impacts of human activities on the regional ecology and environment. Following previous studies (Evans and Geerken 2004), residuals with values of >0 and <0 were used to indicate whether human activities had negative or positive effects, respectively, on primary productivity. To further analyze the contribution of human activities to desertification in the region, the temporal trends in the residuals were considered. Negative trends indicate that human activities during a particular period had a positive influence on vegetation rehabilitation (Wessels et al. 2004), and vice versa. More details of these methods can be found in section S5 of the supplemental materials.

Table 3 Residual variations from 2000 to 2010 (km^2)

Source region		Yellow river	Yangtze river	Lantsang river	Total source region
2000–2005	<0	108,092	133,051	33,639	274,782
	>0	8,611	25,913	3,621	38,145
	% of >0	7.38	16.30	9.72	12.19
2005–2010	<0	107,971	133,578	32,957	274,506
	>0	8,732	25,386	4,304	38,421
	% of >0	7.48	15.97	11.55	12.28

Results

NDVI trends over the past decade

The averaged NDVI spatial and slope trends (per year) between 2000 and 2010 in these source regions (Fig. 2a) show that there was relatively high vegetation coverage in the northeast source regions of the Yellow and Yangtze rivers, and along the Lantsang river. Regions with relatively low vegetation cover only appeared in the northeast source regions of the Yellow and Yangtze rivers. In addition, spatial trends in NDVI slope (Fig. 2b) show that the increases in vegetation productivity between 2000 and 2010 mainly occurred in the northern areas of these source regions, and the average NDVI slope (per year) acquired employing Arcgis zonal statistics functions for the Yellow, Yangtze, and Lantsang rivers was 0.00353, 0.00239, and 0.00026, respectively.

In most of these source areas, there were no significant variations in NDVI from before and after 2005, when the EPRP was initiated (Fig. 3). For instance, during the period 2000–2005, the proportion of the total area in which vegetation productivity increased (areas with NDVI slope >0) for the Yellow, Yangtze, and Lantsang rivers was 67.62, 62.95, and 57.38 %, while from 2005 to 2010, it was 62.11, 74.52, and 64.74 %, respectively. For the total source regions, it was 64.03 and 68.73 % for the two periods, respectively (Table 1). The NDVI slope from 2000 to 2005 in the three source regions was 0.00473, 0.00244, and 0.00184, and from 2005 to 2010 was 0.00313, 0.00493, and 0.00357, respectively.

Potential NPP trends

If we exclude the impacts of human activity on vegetation productivity, we observe some variations in potential NPP values in these regions before and after 2005. For instance, between 2000 and 2005, the potential NPP decreased in most of the source areas of the Yellow and Lantsang rivers, while from 2005 to 2010, the potential NPP increased in most of these areas, and across most of the source areas of the Yangtze river, these values decreased significantly (Fig. 4). These results indicate that in the period 2005–2010, climate change promoted an increase in vegetation cover in the source areas of the Yellow, Yangtze, and Lantsang rivers. It is also apparent that in the period 2005–2010, climate change played a more important role in vegetation rehabilitation in the region compared with the period 2000–2005. For instance, from 2000 to 2005, the proportion of the source areas of the Yellow, Yangtze, and Lantsang rivers where the slope of the potential NPP was greater than zero was 13.50, 13.82, and 14.86 %, respectively, while from 2005 to 2010, it was 65.41, 50.87, and 52.41 %, respectively (Table 2). For the total source areas, these values were 13.83 % before 2005 and 56.48 % after 2005. These results show that over the past decade, the impact of climate change on vegetation rehabilitation in the region has varied.

The residuals between the potential and actual NPP values also show that before and after the start of the EPRP, human activities had no appreciable impact across most of the Water Tower (Fig. 5). For instance, in the headwaters of the Yellow, Yangtze, and the Lantsang rivers from 2000 to 2005, the area with residuals of potential and actual NPPs >0 covered 7.38, 16.30, and 9.72 % of the total area, respectively, and from 2005 to 2010 covered 7.48, 15.97, and 11.55 %, respectively. For the whole source regions, these proportions were 12.19 % before 2005 and 12.28 % after 2005 (Table 3). In addition, the statistics show that after the EPRP was launched in the region, the negative effects of human activities continued to increase: in the source areas of the Yellow, Yangtze, and

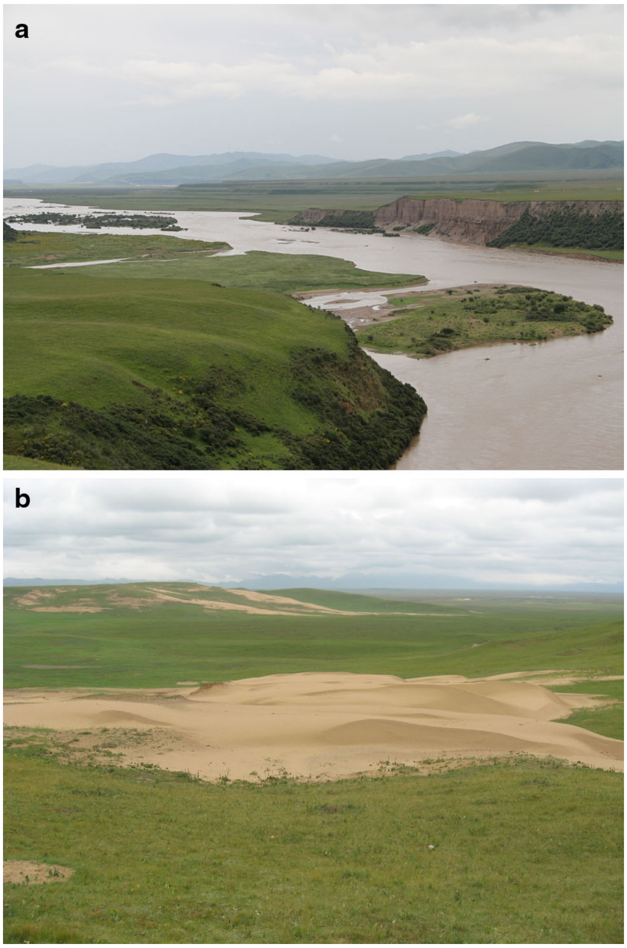


Fig. 6 Rivers developed within the grasslands (**a**) and one of the forms of sandy desertification (**b**) in the source regions. The exact locations of the photographs are unknown

Lantsang rivers from 2000 to 2005, the areas with residual slope >0 covered 38.63, 45.68, and 46.97 % of the total area, while from 2005 to 2010, the proportions were 52.66, 56.43, and 58.52 %, respectively. For the total source areas, the area covered was 43.20 % before 2005 and 55.27 % after 2005. These results show that over the past decade, human activities had a negative effect on about 50 % of the source areas, and even after the EPRP began, there were still some slight increases.

Discussion

At present, the United Nations Environment Programme (UNEP) defines desertification as "land degradation in arid, semi-arid, and dry sub-humid areas resulting from various factors including climatic variations and human activities" (UNEP 1992; United Nations 1992; Wessels et al. 2008). In particular, sandy desertification is characterized by high wind activity in regions with sandy surface sediments and is accompanied by signs of strengthening wind activity coincident with the onset of land degradation (Zhu and Chen 1994; Wang et al. 2008). The main processes of sandy desertification include dune reactivation, surface coarsening, grassland degradation, and other related processes (Wu 2009). Over recent decades, several studies have suggested that severe land degradation/desertification has occurred in the source areas of the three rivers (Wang et al. 2002; Li et al. 2010), and the major forms of desertification during this period included grassland degradation (Liu et al. 2006; Yang et al. 2006; Zhang et al. 2006) and sandy desertification (Dong and Chen 2002; Feng et al. 2004). Due to the appearance of severe sandy desertification issues (Dong et al. 2012), this region has attracted the attention of scholars, governments, and international organizations (Foggin 2011).

In their source regions, the tributaries of the Yellow, Yangtze, and Lantsang rivers flow through grasslands underlain by sandy sediments (Fig. 6a), and the area covered by mobile sandy lands is 43,635 km^2, which accounts for 13.94 % of the total area of the source regions. In addition, although there are no large areas of mobile sandy

Fig. 7 Comparisons of spatial trends in mobile sandy lands in the periods 2000–2005 (**a**) and 2005–2010 (**b**)

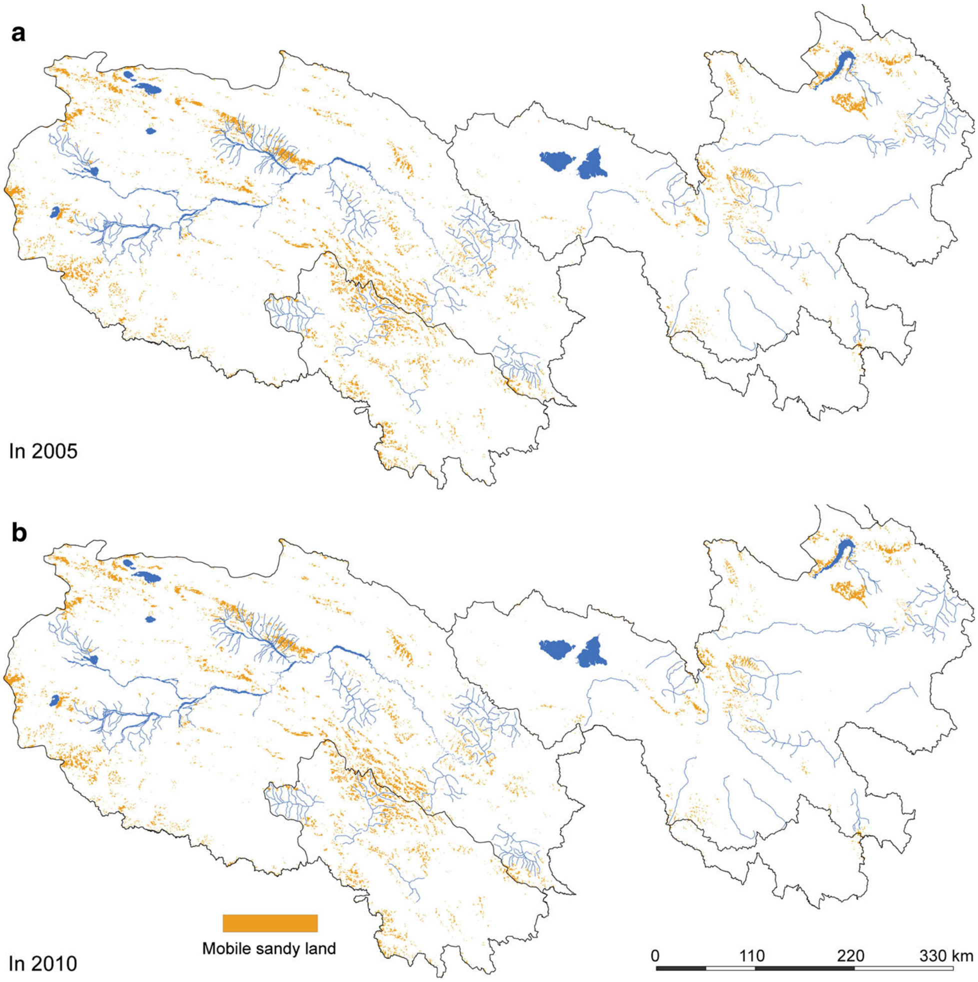


Fig. 8 Temporal trends in annual temperature, precipitation, and wind speed from 2000 to 2012 in the source regions of the Yellow, Yangtze, and Lantsang rivers. Curves were smoothed with a 13-year (2000–2012) moving average. The locations of meteorological stations are shown in Fig. 1

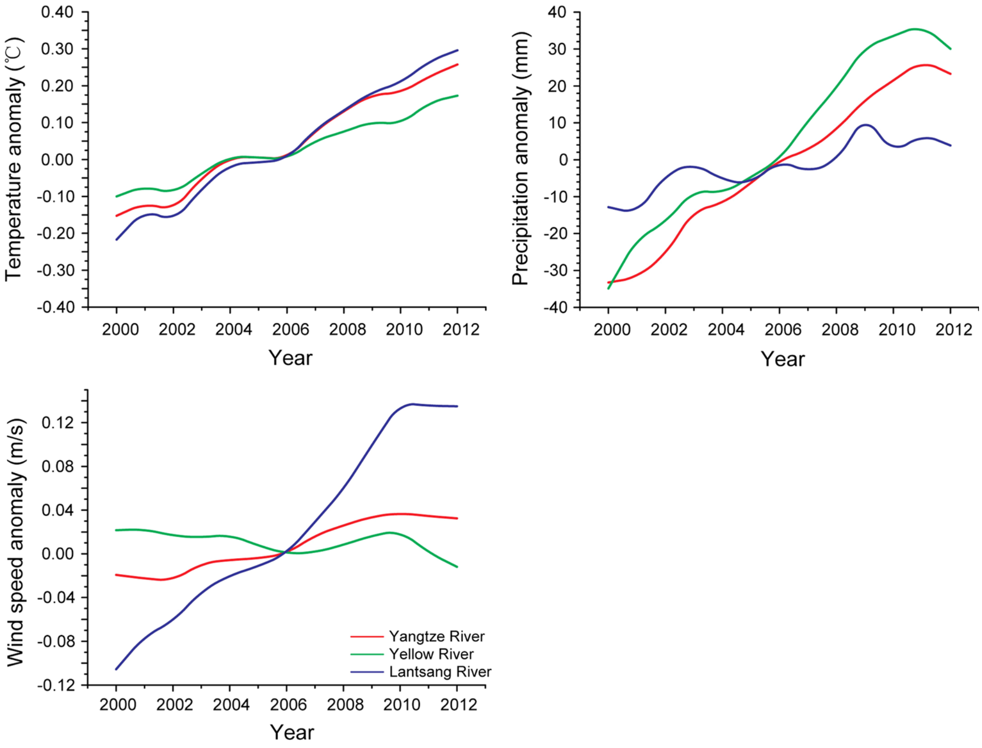
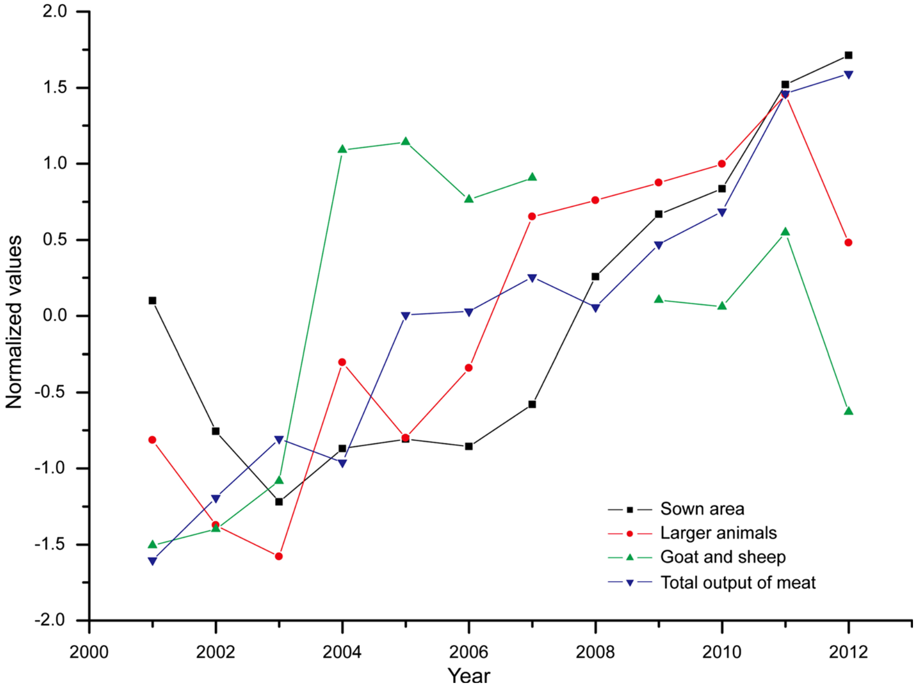


Fig. 9 Temporal trends in human activity (indicated by the sown area, numbers of large animals, numbers of goats and sheep, and total output of meat). Large animals include horses, camels, cattle, donkeys, and mules. Data are from the Qinghai Province Statistical Yearbook



lands, there are many small patches scattered across the grassland surface, and under the influence of climate change or human activities, sandy desertification can, and has, occurred (Fig. 6b). However, the commencement of the EPRP was not marked by significant variations in the area covered by mobile sandy lands. For instance, in 2005, the area of mobile sandy lands (S2 of the supplemental materials) in the source regions of the Yellow, Yangtze, and Lantsang rivers was 10,844, 26,047, and 6,797 km^2, respectively, and in 2010, it was 10,790, 25,873, and 6,786 km^2, respectively; i.e., only a 0.73 % variation in the area covered by mobile sandy land (Fig. 7). Taking into account the errors associated with the interpretation of remote sensing imagery, we suggest that there was no increase in sandy desertification over the past decade in the source areas of the three rivers.

Over the past decade, the average annual temperature has increased by nearly 0.5 °C, and there has been an increase in precipitation of nearly 70 mm (Fig. 8) across the study area. Although we cannot determine the specific contributions made by the rising temperatures and increased precipitation to vegetation rehabilitation, previous studies (e.g., Li et al. 2011) suggest that in this region, there are strong positive relationships between vegetation productivity and precipitation/temperature variations. In addition, the annual mean wind speed also increased over the past decade by about 0.24 m/s, which encourages the development of sandy desertification (Wang et al. 2007); however, there were some slight decreases in the area of sandy desertification across the three source areas. At present, although our study is based on current data and field surveys, we cannot be sure that the apparent reversal in sandy desertification over the past decade was due to the positive impacts of human activities or to other factors (Wang et al. 2013) that reduced eolian activity in the region.

Human activity in the Water Tower region mainly involves land reclamation for cultivation and grazing, which may have negative effects on vegetation rehabilitation (Wang et al. 2006). However, even after the EPRP was implemented in 2005, the land carrying capacities (sown area, number of large animals, and number of goats and sheep) have still increased (Fig. 9). The reason that the increasing impacts of human activities have not triggered desertification in these source regions may be that the human activities may still not exceed the carrying capacities of the land, or the NPP increases driven by climate change have provided enough biomass to support the increased human activity, and therefore, there was no increase in desertification across the source areas of the three rivers.

Conclusions

Over the past decade, there have been no problems with desertification in the source areas of the Yellow, Yangtze, and Lantsang rivers. Although human activity may have affected about 50 % of the study area, vegetation rehabilitation has occurred from the beginning of the century to the present day. After the EPRP was launched in 2005, the negative effects of human activities, such as agriculture, also increased, but have not triggered desertification in this region. Although we cannot determine whether it was the rising temperature or increased precipitation that enhanced vegetation productivity, our analysis shows that the dominant factors controlling vegetation rehabilitation were related to climate change. In the early twenty-first century, human activities have not played an important role in the ecological rehabilitation/destruction of China's Water Tower.

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References

Arnell NW (1999) Climate change and global water resources. Glob Environ Chang 9(Suppl 1):S31–S49

Chen G (2005) The status of the degraded pasture and its strategies of management in black beach of the headwater region of the Three Rivers. Sichuan Caoyuan 10:37–44

Chen D, Brutsaert W (1998) Satellite-sensed distribution and spatial patterns of vegetation parameters over a tallgrass prairie. J Atmos Sci 55(7):1225–1238

Chen G, Li X, Guo X (2007) Ecological protection and construction in Sanjiangyuan nature reserve. Qinghai People's Press, Qinghai

Cramer W, Kicklighter DW, Bondeau A, Moore LB, Churkina G, Nemry B, Ruimy A, Schloss AL (1999) Comparing global models of terrestrial net primary productivity (NPP): overview and key results. Glob Chang Biol 5:1–15

Dong Y, Chen K (2002) Status and driving force of sandy desertification in upper reaches of Yangtze River. Resour Environ Yangtze Basin 11:84–88

Dong Z, Hu G, Lu J, Yan C, Wei Z (2012) Aeolian desertification in the source regions of the Yangtze River and the Yellow River. Science Press, Beijing

Evans J, Geerken R (2004) Discrimination between climate and human-induced dryland degradation. J Arid Environ 57:535–554

Fan J, Shao Q, Liu J, Wang J, Harris W, Chen Z, Zhong H, Xu X, Liu R (2010) Assessment of effects of climate change and grazing activity on grassland yield in the Three Rivers Headwaters Region of Qinghai-Tibet Plateau, China. Environ Monit Assess 170:571–584

Fang X, Li J, Zhou S, Kang S (1998) Aeolian sand deposition in the source area of Yellow River and its significance. Acta Sedimentol Sin 16:40–44

Fang J, Piao S, He J, Ma W (2004) Increasing terrestrial vegetation activity in China, 1982–1999. Sci China (Ser C) 47:229–240

Feng J, Wang T, Qi S, Xie C (2004) Study on dynamic changes of land desertification and causal analysis in source region of Yellow River—a case study of Maduo County. J Soil Water Conserv 18:141–145

Feng J, Wang T, Qi S, Xie C (2005) Land degradation in the source region of the Yellow River, northeast Qinghai-Xizang Plateau: classification and evaluation. Environ Geol 47:459–466

Field CB, Behrenfeld MJ, Randerson JT, Falkowski P (1998) Primary production of the biosphere: integrating terrestrial and oceanic components. Science 281:237–240

Foggin JM (2011) Local communities and conservation on the Tibetan Plateau: two case studies of collaborative management in the Sanjiangyuan region. In: International symposium on the human dimensions of ecological conservation on the Tibetan Plateau. Qinghai Academy of Social Sciences, Xining, pp 50–60

Gautam PK (2010) Climate change and environmental degradation in Tibet: implications for environmental security in South Asia. Strateg Anal 34:744–755

Grosso SD, Parton W, Stohlgren T, Zheng D, Bachelet D, Prince S, Hibbard K, Olson R (2008) Global potential net primary production predicted from vegetation class, precipitation, and temperature. Ecology 89:2117–2126

Han Y, Xi X, Song L, Ye Y, Li Y (2004) Spatio-temporal sand-dust distribution in Qinghai-Tibet Plateau and its climatic significance. J Desert Res 24:588–592

Li B (1997) The rangeland degradation in North China and its preventive strategy. Sci Agric Sin 6(2):1–9

Li XR, Jia XH, Dong GR (2006) Influence of desertification on vegetation pattern variations in the cold semi-arid grasslands of Qinghai-Tibet Plateau, North-west China. J Arid Environ 64:505–522

Li H, Xiao P, Feng X, Wan W, Ma R, Duan H (2010) Lake changes in spatial evolution and area in source region of Three Rivers in recent 30 years. J Lake Sci 22:862–873

Li H, Liu G, Fu B (2011) Response of vegetation to climate change and human activity based on NDVI in the Three-River Headwaters region. Acta Ecol Sin 31(19):5495–5504

Li J, Cai H, Cheng Q, Qiao C, Chu H, Chen D, Xu S, Zhao X, Zhao L (2012) Characterizing the evapotranspiration of a degraded grassland in the Sanjiangyuan Region of Qinghai Province. Acta Prataculturae Sin 21:223–233

Liu X (2007) The investigation for degenerate grassland of "Degenerated Meadow" in Sanjiangyuan Nature Reserve. J Qinghai Norm U (Nat Sci) 1:93–96

Liu L, Zhang Y, Bai W, Yan J, Ding M, Shen Z, Li S, Zheng D (2006) Characteristics of grassland degradation and driving forces in the source region of the Yellow River from 1985 to 2000. J Geogr Sci 16(2):131–142

Liu J, Xu X, Shao Q (2008) Grassland degradation in the "Three-River Headwaters" region, Qinghai Province. J Geogr Sci 18:259–273

Pettorelli N, Vik JO, Mysterud A, Gaillard J-M, Tucker CJ, Stenseth NC (2005) Using the satellite-derived NDVI to assess ecological responses to environmental change. Trends Ecol Evol 20:503–510

Piao S, Fang J, Liu H, Zhu B (2005) NDVI-indicated decline in desertification in China in the past two decades. Geophys Res Lett 32:L06402. doi:10.1029/2004GL021764

Potter C (2004) Predicting climate change effects on vegetation, soil thermal dynamics, and carbon cycling in ecosystems of interior Alaska. Ecol Model 175:1–24

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

Qian S, Fu Y, Pan F (2010) Climate change tendency and grassland vegetation response during the growth season in Three-River Source Region. Sci China (Ser D) 53(10):1506–1512

Qin NS, Shi XH, Wang QC, Feng SQ (2008) Climatic and hydrological changes and consequences in Sanjiangyuan Region. China Meteorological Press, Beijing

Qinghai Provincial Government (2005) 7.5 Billion to protect Sanjiangyuan Region. http://www.qhei.gov.cn/xxkd/sjyxx/201309/t20130916_559009.shtml

Qinghai Provincial Government (2007a) Downstream business of ecological migrants in Sanjiangyuan develops in the course of explorations. http://xnsfgw.gov.cn/jgzn/jgsz/sstbgs/sstbgsxxdt/200708/t20070829_428883.shtml

Qinghai Provincial Government (2007b) http://www.qhei.gov.cn/xbkf/kflt/t20080714_277140.shtml

Shen X, Tan J (2012) Ecological conservation, cultural preservation, and a bridge between: the journey of Shanshui conservation center in the Sanjiangyuan region, Qinghai-Tibetan Plateau, China. Ecol Soc 17(4):38. doi:10.5751/ES-05345-170438

Tang H, Xiao F, Zhang Q, Shi J (2006) Vegetation change and its response to climate change in Three-River source region. Adv Clim Chang Res 2:177–180

Tao F, Yokozawa M, Zhang Z, Xu Y, Hayashi Y (2005) Remote sensing of crop production in China by production efficiency models: models comparisons, estimates and uncertainties. Ecol Model 183(4):385–396

UNEP (United Nations Environmental Programme) (1992) World atlas of desertification. In: Middleton N, Thomas D (eds) Edward Arnold, London

United Nations (1992) Results of the world conference on environment and development: agenda 21. UNCED (United Nations Conference on Environment and Development), Rio de Janeiro. United Nations, New York

Verbyla D (2008) The greening and browning of Alaska based on 1982–2003 satellite data. Glob Ecol Biogeogr 17:547–555

Wang G, Cheng G (2001) Characteristics of grassland and ecological changes of vegetations in the source regions of Yangtze and Yellow Rivers. J Desert Res 21(2):101–107

Wang G, Qian J, Cheng G, Lai Y (2001) Eco-environmental degradation and causal analysis in the source region of the Yellow River. Environ Geol 40(7):884–890

Wang G, Guo X, Cheng G (2002) Dynamic variations of landscape pattern and the landscape ecological functions in the source area of the Yellow River. Acta Ecol Sin 22:1587–1598

Wang Z, Liu C, Huete A (2003) From AVHRR–NDVI to MODIS–EVI: advances in vegetation index research. Acta Ecol Sin 23:979–987

Wang X, Chen F, Dong Z (2006) The relative role of climatic and human factors in desertification in semiarid China. Glob Environ Chang 16:48–57

Wang X, Hasi E, Zhou Z, Liu X (2007) Significance of variations in the wind energy environment over the past 50 years with respect to dune activity and desertification in arid and semiarid northern China. Geomorphology 86:252–266

Wang X, Chen F, Hasi E, Li J (2008) Desertification in China: an assessment. Earth Sci Rev 88:188–206

Wang Z, Song K, Hu L (2010) China's largest scale ecological migration in the Three-River Headwater Region. AMBIO 39:443–446

Wang X, Wang G, Lang L, Hua T, Wang H (2013) Aeolian transport and sandy desertification in semiarid China: a wind tunnel approach. Land Degrad Dev 24:605–612

Wen L, Dong S, Zhu L, Shi J, Liu D, Wang Y, Ma Y (2011) The effect of natural factors and disturbance intensity on spacial heterogeneity of plant diversity in alpine meadow. Acta Ecol Sin 31:1844–1854

Wessels KJ, Prince SD, Small J (2003) Monitoring land degradation in Southern Africa based on net primary productivity. IEEE Int Geosci Remote Sens Symp 5:3305–3307

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, Reshef I (2008) Mapping land degradation by comparison of vegetation production to spatially derived estimates of potential production. J Arid Environ 72:1940–1949

Wu Z (2009) Chinese deserts and its combating. Science Press, Beijing

Yan Z, Zhou H, Liu W, Zhou L (2003) Preliminary discuss on grassland degradation in the source region of Yangtze and Yellow Rivers. Grassl China 25:73–78

Yang J, Ding Y, Chen R (2006) Spatial and temporal of variations of alpine vegetation cover in the source regions of the Yangtze and Yellow Rivers of the Tibetan Plateau from 1982 to 2001. Environ Geol 50:313–322

Zhang Y, Liu L, Bai W, Shen Z, Yan J, Ding M, Li S, Zheng D (2006) Grassland degradation in the source region of the Yellow River. Acta Geogr Sin 61(1):3–14

Zhao X (2011) Grassland rehabilitation and sustainable management in the headwaters of Three Rivers. Science Press, Beijing

Zhao X, Zhou H (2005) Eco-environmental degradation, vegetation regeneration and sustainable development in the headwaters of Three Rivers on Tibetan Plateau. Bull Chin Acad Sci 20(6):471–476

Zheng YM, Zhang HY, Niu ZG, Gong P (2012) Protection efficacy of national wetland reserves in China. Chin Sci Bull 57:1116–1134

Zhu ZD, Chen GT (1994) Sandy desertification in China. Science Press, Beijing, pp 7–15

Zou XY, Li S, Zhang CL, Dong GR, Dong YX, Yan P (2002) Desertification and control plan in the Tibet Autonomous Region of China. J Arid Environ 51:183–198