Ecological Indicators 48 (2014) 560–569

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Quantitative assessment of the individual contribution of climate and human factors to desertification in northwest China using net primary productivity as an indicator

Wei Zhou [a], Chengcheng Gang [b], Fuchun Zhou [a], Jianlong Li [b,*], Xiaogang Dong [c], Chengzhang Zhao [c]

[a] Department of Resources and Environment, School of River & Ocean Engineering, Chongqing Jiaotong University, Chongqing 400074, China
[b] School of Life Science, Nanjing University, Hankou Road 22, Nanjing 210093, China
[c] College of Geography and Environment, Northwest Normal University, Lanzhou 730070, China

ARTICLE INFO

Article history:
Received 5 November 2013
Received in revised form 18 August 2014
Accepted 24 August 2014

Keywords:
Land degradation
Quantitative assessment
Climate variation
Human intervention
Northwest China

ABSTRACT

An accurate quantitative assessment of the relative roles of climate change and human activities in desertification is significant to understand the driving mechanisms deeply and control desertification development. In this study, we selected net primary productivity (NPP) as an indicator to discriminate the relative roles of climate and human factors in desertification during 2001–2010 in northwest China. The potential NPP and the difference between potential and actual NPPs were used to represent the impacts of climate change and human activities on desertification. Desertification expanded on 55.8% of the study area, within which 70.3% of the desertification expansion was caused by human activities compared with only 21.7% induced by climate change. On the contrary, 42.1% of desertification reversion was caused by human activities and 48.4% resulted from climate changes. The NPP variation also could be calculated to assess the relative roles and showed that 69% of NPP decrease was caused by human impacts compared with 15.2% induced by climate change. By contrast, 23.9% of NPP increase was caused by climate change, whereas 54% resulted from human activities. In addition, the relative roles of two factors possessed great spatial heterogeneity in six provinces. We developed three propositions. First, the desertification expansion was dominated by human activities, whereas desertification reversion was dominated by climate change, as typified by Xinjiang, Qinghai, and Gansu. Second, both desertification expansion and reversion were induced by human activities, as typified by the west of Inner Mongolia and Shaanxi. Third, climate change dominated the desertification expansion in Ningxia province.

1. Introduction

The determination of the driving cause of desertification has become the focus of desertification research. A great deal of disagreement about the driving factor of desertification remains (Rasmussen et al., 2001; Reynolds and Stafford Smith, 2002; Wang et al., 2006; Zheng et al., 2006). Many researchers have attributed the desertification in northern China to long-term over-grazing, extensive cutting, and widespread conversion of grassland to cropland (Wang and Zhu, 2003; Yang et al., 2005; Wang et al., 2006). Other studies have found that poor climate conditions, such as drought, severe wind erosion, temperature fluctuation, and winter precipitation, are the primary cause of desertification (Hai et al., 2002; Sun and Li, 2002). Nevertheless, some recent studies have shown that human activities control the desertification reversion (Xu et al., 2010; Wang et al., 2012) in selected study regions of northern China.

Using an optimal quantitative assessment method is actually crucial for assessing the relative role of climate and human factors in desertification (Veron et al., 2006). Quantitative assessment methods in previous studies primarily focus on statistical analysis, including regression models (Zhang et al., 2003), correlation analysis (Chang et al., 2003), and multiple variable analysis technology (Ma et al., 2007). Some studies have selected vegetation dynamic as an indicator to differentiate human-induced desertification from climate change-induced desertification (Evans and Geerken, 2004; Wessels et al., 2007; Xu et al., 2010). Net primary productivity (NPP) is the net amount of solar energy converted to chemical energy through photosynthesis and a sensitive indicator to climatic changes and human

* Corresponding author. Tel.: +86 02583592715.
E-mail address: jianlongli@gmail.com (J. Li).

http://dx.doi.org/10.1016/j.ecolind.2014.08.043
1470-160X/

impacts (Schimel, 1995). NPP has been adopted as an indicator to discriminate the impacts of climate change from those of human activities on ecosystem (Zheng et al., 2006; Wessels et al., 2008). Some researchers have used human appropriation of net primary production (HANPP) as an indicator to measure the impact of human activities on ecosystem in recent years (Rojstaczer et al., 2001; Haberl et al., 2002). Meanwhile, the relationship between NPP and desertification has been widely studied. The change of NPP has been a potential desertification evaluation indicator (Mouat et al., 1997). Some research based on long-term site observation has found that aboveground NPP is lower in desertified shrub lands than in remnant grassland in Chihuahuan desert of USA (Huenneke et al., 2002). Desertification leads to fragmented ecosystem structure and decreased carbon storage (Asner and Martin, 2004). Therefore, NPP can be a useful and reliable indicator of desertification in long term (Prince et al., 1998; Gonzalez, 2000). In this study, we select NPP as desertification assessment indicator.

China is one of several countries severely affected by desertification. The land desertification of China accounts for 27.3% of the total land area according to the first national survey on desertification land. Approximately 99.6% of this land is distributed in 12 provinces or autonomous regions in north and northwest China (CCICCD, 1996). Northwest China is located in regions sensitive to climate change and human intervention, includes most of China's desert, and is the origin of sandstorm in China (Wang et al., 2004a). A recent survey has shown that over 90% of grassland in north China suffered different degree of degradation and that degradation rate reached 6700 km^2 per year (Yang, 2002). Therefore, a deeper understanding of the driving cause of desertification is fundamental and a key point in desertification control. In this study, NPP was selected as an indicator to evaluate desertification status, potential NPP, and HNPP (the difference between potential NPP and actual NPP) for representing the impacts of climate change and human activities on desertification.

The objectives of this study are to (1) explore the desertification dynamics in northwest China, (2) distinguish the relative roles of climate change and human activities in desertification, and (3) determine the spatial distribution of the two driving factors that induce desertification expansion or reversion and the dominant factor for desertification.

2. Materials and methods

2.1. Study area

Northwest China is located in the innermost center (31°32′N–49°10′N and 73°15′E–111°50′E) of the Eurasian continent. This area covers an area of approximately 3.5 million km^2 and accounts for 36% of China's total land areas. Administratively, this area includes Xinjiang Uygur autonomous region, Qinghai province, Gansu province, Shaanxi province, Ningxia Hui autonomous region, and the west of Inner Mongolia autonomous region (IM). Climate belongs to arid and semi-arid, except Qinghai, which is characterized with rich solar–thermal resources, dry and rainless climate, strong evaporation, as well as high temperature between day and night. The high mountains with high precipitation, such as Altai, Tianshan, Kunlun, and Qilian mountains, block atmosphere circulation and create vast desert basin in rain shadow, such as Tarim, Junggar, and Qaidam basins (Shi et al., 2007). Northwest China also includes most of China's desert and Gobi. The regional difference of landform and climate is obvious, and vegetation shows dramatic horizontal and vertical zonalities.

Desertification is a process that operates principally in arid, semi-arid, and sub-humid areas and involves excessive pressure of human use, changes in land use, or changes in natural process (Mouat et al., 1997). This process leads to a general decrease in productivity and soil erosion (both by wind and water), salinization and alkalization of irrigated lands, or dryland salting. The excessive loss of soil nutrients and sometimes the depletion of soil seed bank affect the capacity of vegetation to recover and constitute the principal mechanism of irreversible damage to the environment (Squires, 2010). The impact of overgrazing on grassland also leads to land degradation (Li, 2009). In China, desertification has usually occurred in Gobi and deserts with mobile sand. The resulting adverse changes have been defined as land degradation characterized by wind erosion. Although other land degradation processes, such as water erosion and salinization, have also occurred in arid and semi-arid areas in China, their areas account for no more than 16% of the total areas of degraded land (SFAC, 2005); therefore, "sandy" desertification is the dominant process responsible for land degradation in China.

Under global warming and human intervention, northwest China's land desertification is becoming serious, and dust and sandstorms (DSSs) occur frequently and become severe. Therefore, quantitative assessment of desertification is essential to control and combat desertification and benefits the program to control DSS.

In this study, we excluded the hyper-arid regions in northwest of China based on the definition of desertification (UNCCD, 1994). The hyper-arid region and study area are shown in Fig. 1.

2.2. Data source and processing

Remote sensing (normalized difference vegetation index (NDVI) and land cover data), meteorological, and geographical data were obtained to estimate NPP based on Carnegie–Ames–Stanford approach (CASA) model. The 500 m 16-day moderate resolution imaging spectroradiometer NDVI data and global land cover product (MCD12Q1) were derived from http://ladsweb.nascom.nasa.gov/data/search.html. Maximum-value compositing procedure was used to merge the 16-day NDVI data and generate monthly NDVI. These remote sensing data were reprojected from the original integerized sinusoidal projection to an Albers equal area and WGS-84 datum by using ArcGIS V9.3 (ESRI, California, USA).

Meteorological data were obtained from China meteorological science data-sharing service system. The data include the monthly average temperature and total precipitation recorded by 210 meteorological stations, as well as the total solar radiation recorded by 45 stations in and around northwest China. Ordinary Kriging interpolation was performed to interpolate the meteorological data intended for producing raster images with 500 m spatial resolution. These monthly meteorological data were used to drive CASA model.

The meteorological data required for Thornthwaite memorial model are annual average temperature and total precipitation. These annual data were calculated from monthly meteorological data. Raster meteorological data were also extracted using the vector boundary of the study area. The images with the same spatial resolution and coordinate system as those used in CASA model were used for remote sensing.

2.3. Field measurement of NPP

To validate the accuracy of CASA model, field-measured NPP was collected. For forest, 20 forest NPP databases created by a previous research (Luo, 1996) were directly used in this study because these datasets have been widely used to validate forest NPP (Pan et al., 2004; Peng et al., 2009).

We also sampled 43 sites about shrub and grassland across northwest China from April to August of 2008 and 2009. At each

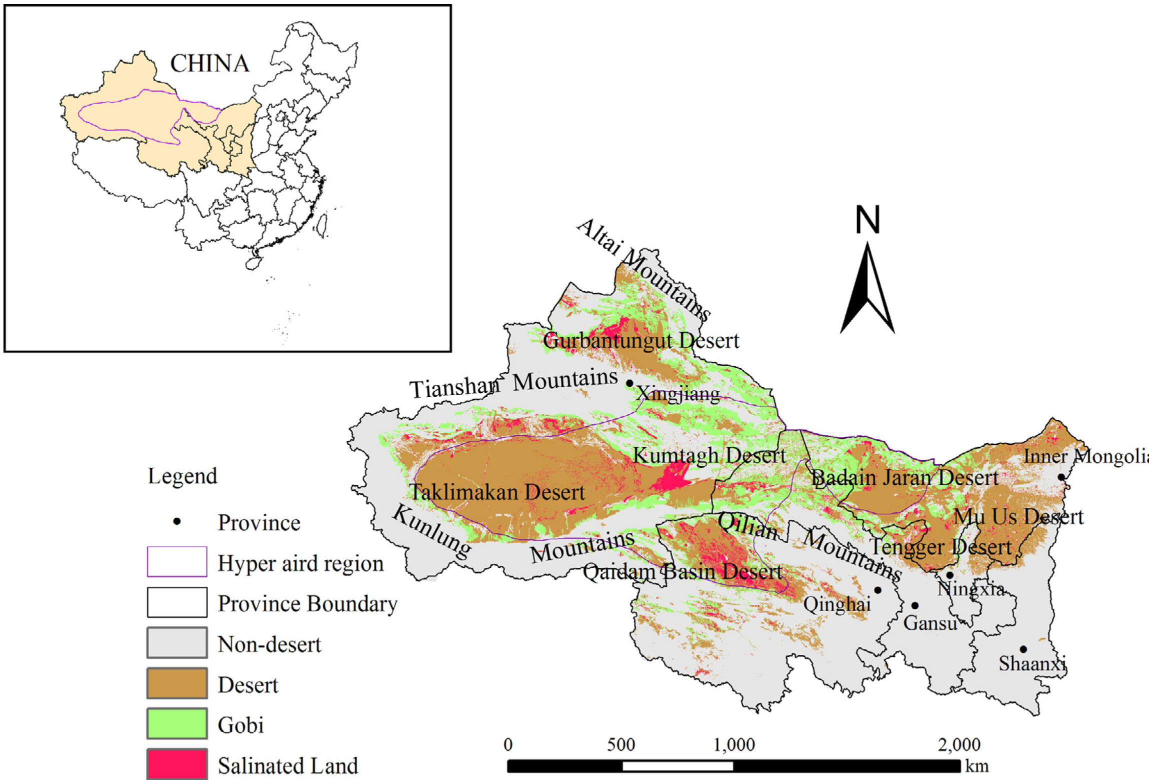

Fig. 1. Study area, which included six provinces, some of which enclose or border on the hyper-arid region, as demarcated by the P/ETP <0.05 boundary. P denotes precipitation, and ETP denotes evapotranspiration.

site (40 m × 40 m), we set four shrub quadrats (20 m × 20 m) and marked them as S1, S2, S3, and S4. Four small plots (5 m × 5 m) for grasslands in each shrub quadrat were sampled. For shrubs, to conduct non-destructive measurements of biomass, the following dimensions were measured in August: basal diameter, crown diameter (including the maximum and minimum), canopy diameter, and canopy height. We used existing shrub biomass equations to estimate foliage, root, above, and total biomass in dry weight (Li and Jia, 1998; Wang et al., 2004b; Zhao et al., 2004; He et al., 2005; Lin and Bai, 2010). For species without available root biomass equations, the average ratio of underground and aboveground biomass was applied to estimate total biomass (Li and Jia, 1998; Zhao et al., 2004; Huang et al., 2006). To calculate shrub NPP, we investigated in the quadrates twice, i.e., in August of 2008 and August of 2009. The biomass increment was the difference of the two years and was converted to carbon content using a conversion factor of 0.45, which was the shrub NPP.

For grassland field measurements, eight plots in S1 and S3 were investigated in early April, and another eight plots in S2 and S4 were investigated in August. All plants in each quadrat (5 m × 5 m) were harvested to determine aboveground biomass. To determine underground biomass, nine soil cores (8 cm diameter) were used to collect samples at 10 cm intervals. In the laboratory, root samples were soaked in deionized water and cleaned. Biomass samples were oven-dried at 65 °C to a constant mass. The NPP of grassland was the difference between the maximum (measured at the end of August) and the minimum biomass carbon (in early April).

2.4. Calculation of actual NPP

Vegetation dynamic is important in desertification and can reflect the complex interactions between climate change and human activities (Hanafi and Jauffret, 2008). In this study, annual NPP (gC m^{-2} yr^{-1}) was used to represent vegetation conditions and assess desertification dynamic.

Actual NPP was calculated using CASA model, which is a light use efficiency model based on resource balance theory (Potter et al., 1993; Field et al., 1995). In CASA model, NPP is the product of absorbed photosynthetically active radiation (APAR) and light use efficiency (ε). The basic principle of the model is described as follows:

$$\mathrm{NPP}(x,t) = \mathrm{APAR}(x,t) \times \varepsilon(x,t), \quad (1)$$

where x is the spatial location, t is time, APAR represents the canopy-absorbed incident solar radiation integrated over a given time period (MJ m^{-2}), and $\varepsilon(x,t)$ represents the actual light use efficiency (g C MJ^{-1}). APAR(x, t) and $\varepsilon(x, t)$ are calculated using Eqs. (2) and (3), respectively.

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

where SOL(x, t) is the total solar radiation (MJ m^{-2}) of pixel x in time t, and FPAR(x, t) is the fraction of the photosynthetically active radiation absorbed by vegetation. FPAR(x, t) can be determined by NDVI; 0.5 represents the proportion of the total solar radiation available for vegetation.

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

where $T_{\varepsilon 1}(x, t)$ and $T_{\varepsilon 2}(x, t)$ denote the temperature stress coefficients on light use efficiency, $W_{\varepsilon}(x, t)$ is the water stress coefficient that indicates the reduction in light use efficiency caused by moisture factor, and $\varepsilon_{\max}$ denotes the maximum light use efficiency under ideal conditions set as different constant parameters for various vegetation types (Zhu et al., 2006). A more detailed description of this algorithm can be found in Yu et al. (2011).

2.5. Validation of CASA model

NPP determined from field sampling was compared with the simulated values to verify the estimation accuracy of CASA model. Fig. 2 illustrates the correlation between the observed NPP and simulated NPP (R^2 = 0.732, $P < 0.001$) and indicates that the model's estimation accuracy is satisfactory. However, the estimated data are slightly larger than the field-observed data, which may be due to the differences in the scale of the observed and estimated data. Nevertheless, this difference has no effect on the results of trend analysis of NPP.

2.6. Estimation of potential NPP

Although researchers have developed several models for estimating NPP, such models are based on different climatic factors. The first widely used model, i.e., Miami model (Lieth, 1975), is derived from the least squares correlations between measured NPP data and corresponding temperature and precipitation data. Thornthwaite memorial model was established based on the data used in Miami model but modified to include Thornthwaite's potential evaporation model (Lieth and Box, 1972). In this study, we simulated potential NPP using the Thornthwaite memorial model, which is expressed as follows:

$$\mathrm{NPP} = 3000[1 - e^{-0.0009695(v-20)}], \quad (4)$$

where NPP is the annual NPP (g C m^{-2} yr^{-1}), and v is the average annual actual evapotranspiration (mm). The calculated equations are expressed as

$$V = \frac{1.05r}{\sqrt{1 + (1 + 1.05r/L)^2}}, \quad (5)$$

$$L = 3000 + 25t + 0.05t^3, \quad (6)$$

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

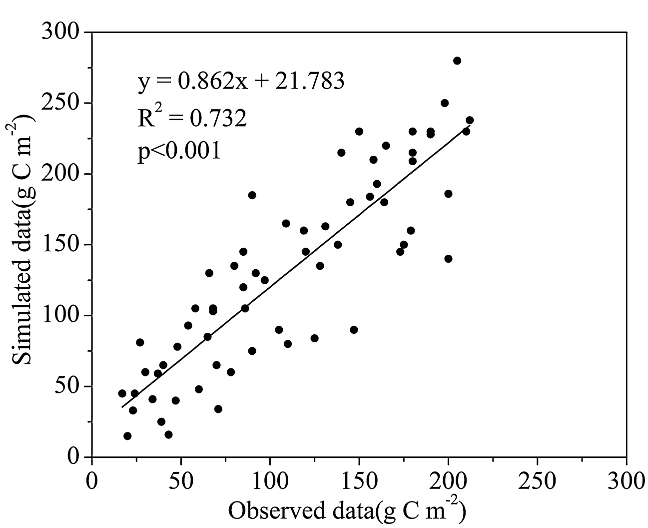

Fig. 2. Validation of CASA model in the northwest China through analyzing the correlation between the simulated NPP (g C/m^2) based on CASA model and field-observed NPP.

2.7. Desertification dynamic analysis

Vegetation dynamics measured by NPP are the most intuitive manifestation of land degradation and reflect the ecological process involved in land degradation. Therefore, NPP was selected to assess land degradation or restoration. The slope was determined by ordinary least squares regression. The formula is as follows:

$$\mathrm{Slope} = \frac{10 \times \sum_{i=1}^{10} i \times \mathrm{NPP}_i - (\sum_{i=1}^{10} i)(\sum_{i=1}^{10} \mathrm{NPP}_i)}{10 \times \sum_{i=1}^{10} i^2 - \sum_{i=1}^{10} i^2}, \quad (7)$$

where i is 1 for year 2001, 2 for year 2002, and so on (i = 1, 2, . . . 10). Ten years were considered because the study period was from 2001 to 2010. NPP$_i$ is the value of annual NPP in time of i year.

The total increment (or decrement) of NPP during the study period can be estimated for each pixel using the following equation:

$$\mathrm{NPP}_{\mathrm{variation}} = 9 \times \mathrm{slope} \quad (8).$$

2.8. Scenario design and quantitative assessment method

If the quantitative relation between the change of NPP induced by climate change and human activities is identified, the relative roles of climate change and human activities in desertification progress may be quantitatively assessed. In this study, we defined three kinds of NPP. The first kind is the actual NPP, which was calculated by CASA model. The second kind is the potential NPP that represents NPP change caused by climate change, which was estimated by Thornthwaite memorial model. The third kind is the NPP loss caused by human (HNPP, i.e., $\mathrm{NPP}_{\mathrm{potential}} - \mathrm{NPP}_{\mathrm{actual}}$) and reflects the impacts of human activities on vegetation productivity.

The effect of climate change and human activities on NPP can be calculated based on the slope of potential NPP (S_p) and HNPP using Eq. (7). A positive S_p indicates that climate change benefited vegetation growth and desertification reversal. A negative S_P indicates that climate change promoted desertification expansion. If S_H is negative, human activities benefited vegetation growth and desertification reversal. A positive S_H shows that human dominated desertification expansion.

The slope of actual NPP (S_A) represents desertification expansion or reversion. A positive S_A shows that desertification reversion occurred, whereas a negative S_A indicates that desertification expansion occurred. Six possible scenarios are defined in Table 1.

3. Results

3.1. Desertification dynamic based on actual NPP change trend

The overall change trend of vegetation NPP was decreasing (i.e., degradation) throughout the study area, although slightly, moderate, and significantly increasing occurred in some regions (Fig. 3A). Vegetation degradation was wide spread and accounted for 55.8% of the study area. Meanwhile, vegetation restoration area accounted for 44.2%, and the moderate increase region was scattered in the north of Shaanxi, south of Gansu, and the south and north slopes of Tianshan Mountains.

The change trends of potential NPP (S_p) (Fig. 3B) showed that climate was favorable to vegetation restoration in most regions of the study area. Areas with NPP increase trend accounted for 64.8% of the whole study area solely induced by climate change. Moderate vegetation restoration occurred in the south of Shaanxi, the central regions of Qinghai, northwest of Gansu, and southwest of Xinjiang because of the rising precipitation and declining temperature (Fig. 4). Regions with NPP decrease accounted for

Table 1
Six scenarios for assessing the relative roles of climate change and human activities in desertification.

		S_A	S_P	S_H	Definition
Desertification reversal	Scenario 1	>0	<0	<0	Human-induced desertification reversion
	Scenario 2	>0	>0	>0	Climate-induced desertification reversion
	Scenario 3	>0	>0	<0	Desertification reversion resulted from the interaction of climate change and human activities
Desertification expansion	Scenario 1	<0	>0	>0	Human-induced desertification expansion
	Scenario 2	<0	<0	<0	Climate-induced desertification expansion
	Scenario 3	<0	<0	>0	Desertification expansion resulted from the interaction of climate change and human activities

S_A: the slope value of actual NPP; S_P: the slope value of potential NPP; S_H: the slope value of HNPP (i.e., the difference between potential NPP and actual NPP).

35.2% of the study area (Fig. 3B) and mainly distributed in the west of IM, Ningxia, north of Shaanxi, east of Gansu, and south and north slopes of Tianshan Mountains. The decrease was due to the declining precipitation and rising temperature (Fig. 4). Moderate desertification distributed in the junction of three provinces, such as the middle of Ningxia, west of Shaanxi, and east of Gansu, where precipitation decreased and temperature increased (Fig. 4).

The impacts of human activities on vegetation NPP were represented as the slope of HNPP (S_H). Under the influence of human, the area was a negative S_H mainly distributed in Ningxia, Shaanxi, and Gansu, a fraction of Gansu, and the south and north slopes of Tianshan Mountains.

3.2. Relative roles of inter-annual climate change and human activities in desertification based on areas

Desertification and the relative role of two factors showed obvious spatial heterogeneity (Fig. 5). Desertification expansion was wide spread in northwest China and accounted for 55.8% of the study area (Fig. 5A), whereas desertification reversion area only accounted for 44.2%. Climate-induced desertification expansion accounted for 21.7% of the total expansion areas (Table 2), including Tianshan Mountains, Tengger Desert, and Mu Us Sandy Land (Fig. 5B), which may be resulted from declining precipitation and rising temperature (Fig. 4). Human-induced expansion was widely distributed in the study area and accounted for 70.3%. Desertification reversion induced by climate accounted for 48.4% compared with the 42.1% caused by human activities (Fig. 5C). The contribution of the combination of climate and human to desertification expansion was 7.9%, and that to desertification reversal was 9.5%.

The relative role of two factors in desertification in different provinces was different. Three propositions were given. First, the desertification expansion was dominated by human activities, whereas desertification reversal was induced by climate. This proposition was common in Xinjiang, Qinghai, and Gansu, especially in Qinghai, where 98.0% (345,744.5 km^2) of degradation was caused by human activities, and 92.4% (216,016 km^2) of vegetation restoration was caused by climate change (Fig. 6, Table 2). Second, both the desertification expansion and reversal

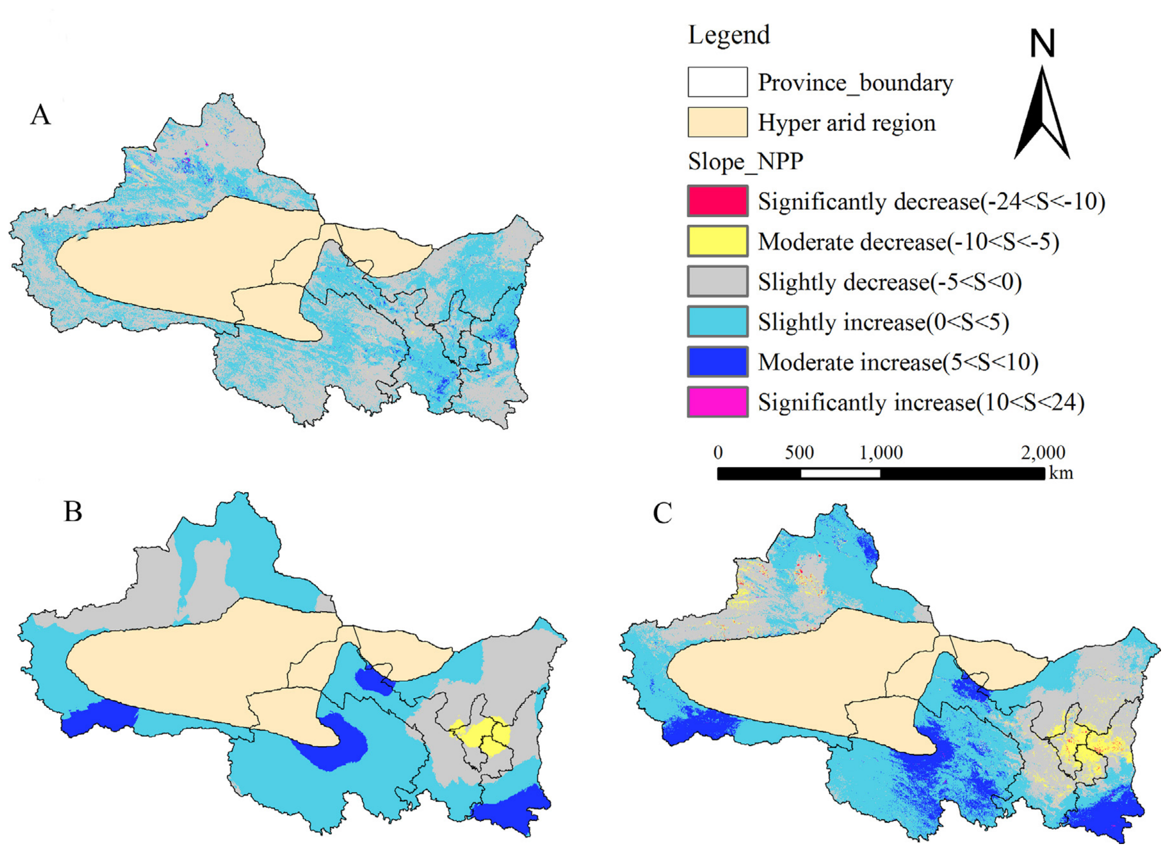

Fig. 3. Spatial distribution of slope values for (a) actual NPP estimated by CASA model, (b) potential NPP estimated by Thornthwaite memorial model, and (c) HNPP (i.e., the difference between potential NPP and actual NPP).

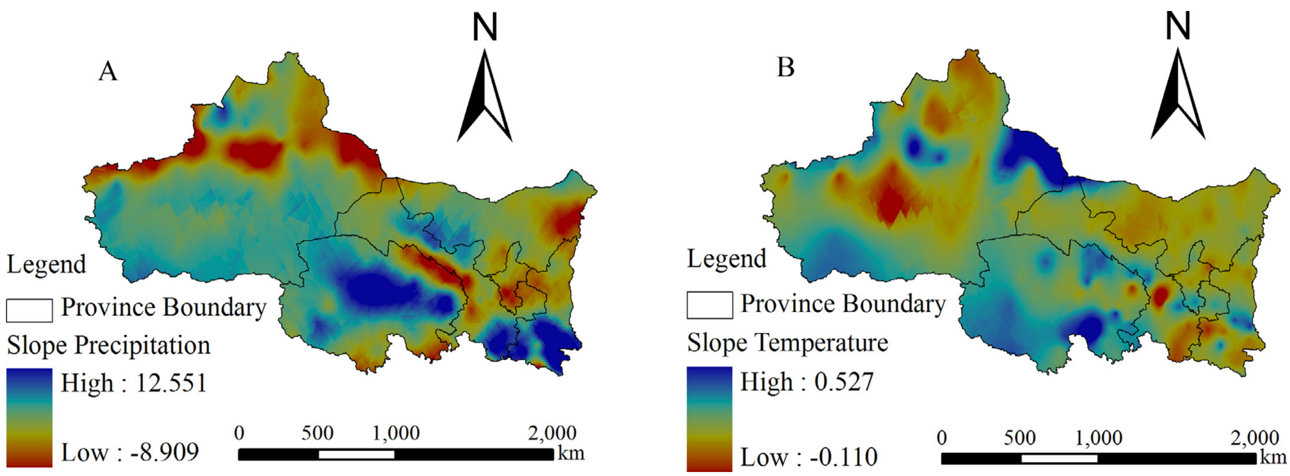

Fig. 4. Spatial distribution of slope values for the (a) annual total precipitation and (b) average temperature during 1981–2010.

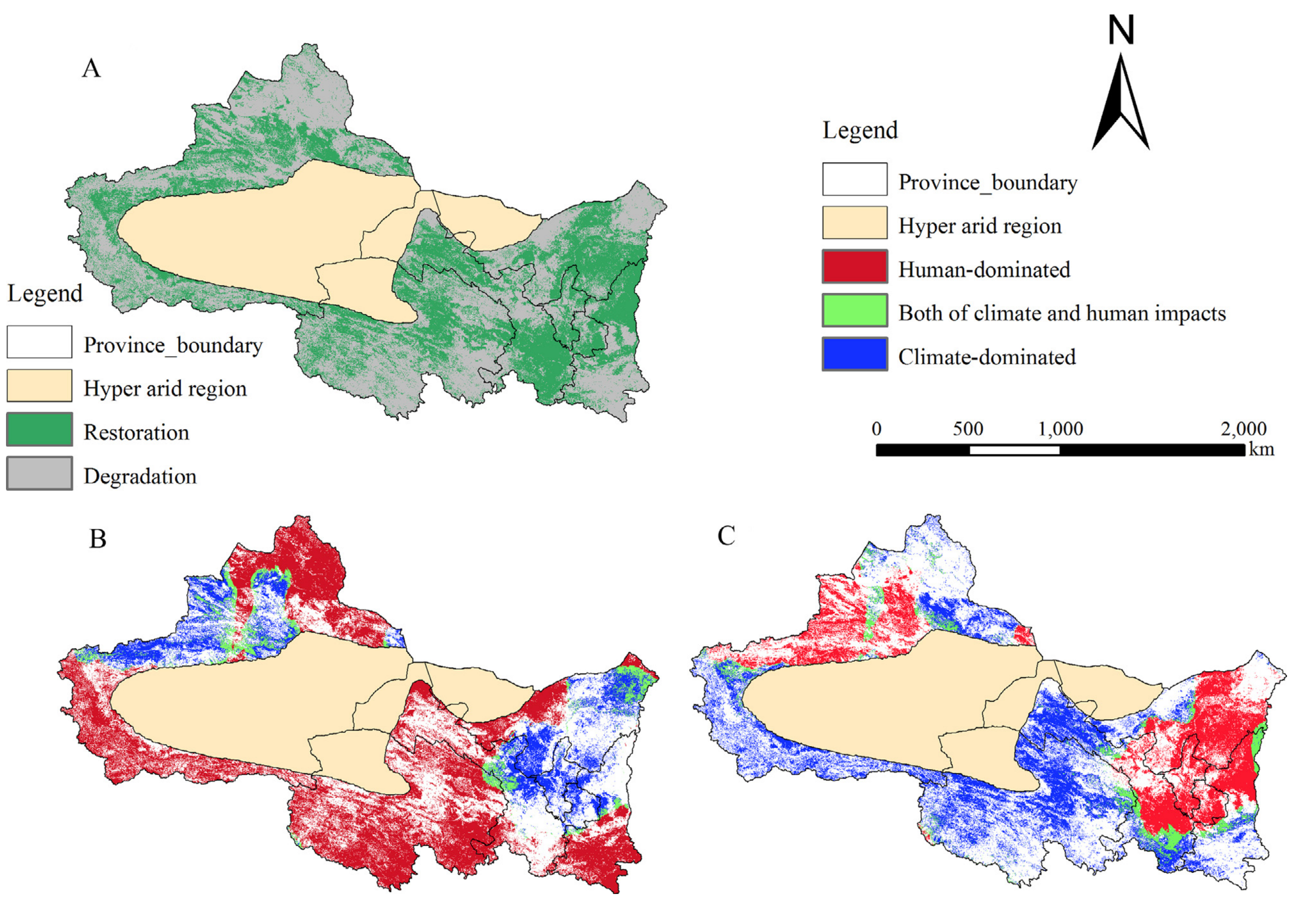

Fig. 5. Spatial distribution of (a) desertification expansion and reversal and (b) relative roles of climate change, human activities, and the combination of these two factors on desertification expansion and (c) desertification reversal.

were dominated by human activities in Shaanxi because it effectively implemented the Grain to Green Program and the Natural Forest Conversion Program, which benefit vegetation restoration. Third, climate dominated desertification expansion, and human activities dominated desertification reversal in the west of IM and Ningxia, especially in the latter. In Ningxia, 97.4% (20,749 km^2) of desertification expansion was caused by climate change, and 100% of desertification reversal was dominated by human activities (Fig. 6, Table 2) because of the declining precipitation and rising temperature trend in this area (Fig. 4).

3.3. Relative roles of inter-annual climate change and human activities in desertification based on NPP variation

To further assess the relative roles of the two factors, we calculated the desertification expansion and reversal based on NPP variation (Figs. 6C,D). NPP variation was estimated based on Eq. (8). Total NPP decreased by 286.8 Gg C ($Gg = 10^9$ g) from 2001 to 2010 because the degradation area is larger than the restoration area, and the mean NPP variation of the study area was $-0.12\,gC\,m^{-2}\,yr^{-1}$. The 69% of NPP decrease was caused by human

Table 2
Areas (km^2) and percentage (%) of desertification expansion and reversal caused by climate change, human activities, and a combination of the two factors.

		Region						
		Northwest	Xinjiang	Gansu	Qinghai	Inner Mongolia	Shaanxi	Ningxia
CE	Area	290,188	130,102	43,034	889	82,206.8	13,235.5	20,748.8
	Percent	21.7	23.6	33.9	0.3	47.7	12	97.4
HE	Area	939,416	365,242	71,058	345,744.5	65,495	91,190	0
	Percent	70.3	66.2	55.9	98	38	82.8	0
BE	Area	105,943	56,003	12,918	5996.5	24,686.8	5724.3	543.8
	Percent	8.0	10.2	10.2	1.7	14.3	5.2	2.6
CR	Area	513,008	162,501	90,167	216,016	20,833	23,183.5	0
	Percent	48.4	48	45.4	92.4	12.6	24.9	0
HR	Area	446,560	141,778	81,759	1864.8	136,594.5	53,949.3	30,590.8
	Percent	42.1	41.9	41.2	0.8	82.8	58	100
BR	Area	100,144	34,074	26,627	15,844.3	7614	15,921.8	0
	Percent	9.5	10.1	13.4	6.8	4.6	17.1	0

CE: the region that experienced desertification expansion dominated by climate change; HE: desertification expansion dominated by human activities; BE: desertification expansion dominated by the combination of climate and human factors; CR: desertification reversion dominated by climate change; HE: desertification reversion dominated by human activities; BR: desertification reversion dominated by the combination of the two factors.

activities, whereas 15.2% was caused by climate change. The proportion of the combination of climate change and human activities to desertificaiton expansion was 15.8%. Nevertheless, the increase of NPP caused by climate change and human activities was 23.9% and 54%, respectively. The contribution of the two factors to desertification reversion reached 22.1%. In all, human activities were the dominant factor for desertification expansion and reversal.

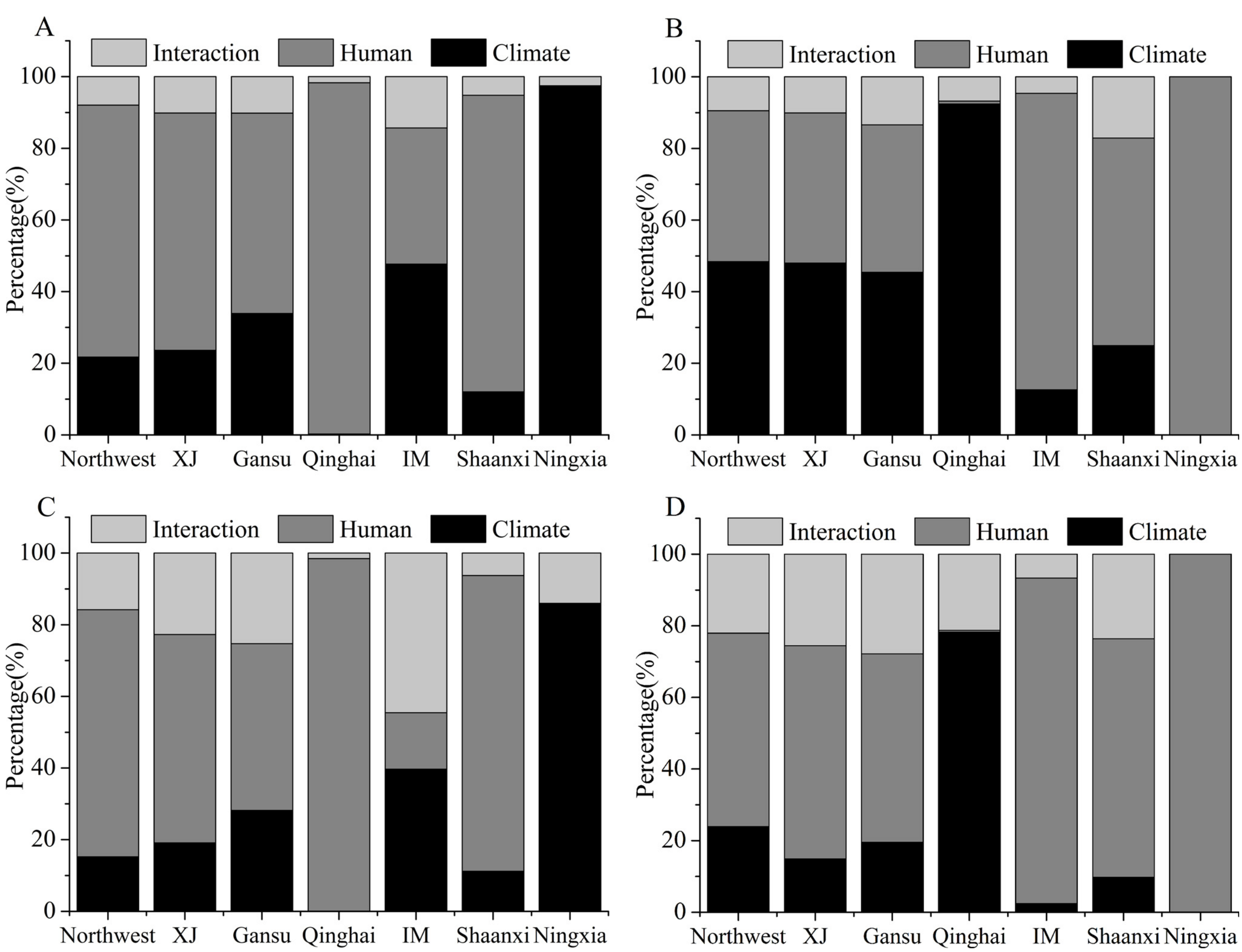

Fig. 6. Contributions of climate change and human activities to (a) desertification expansion, and (b) reversal based on area; contributions of climate change and human activities to (c) desertification expansion and (d) reversal based on NPP variation in different provinces.

Whether based on the desertification areas or NPP variation from 2001 to 2010, human activities were the dominant factors for desertification expansion. Nevertheless, climate change dominated desertification reversal based on desertification areas, whereas human activities dominated vegetation restoration based on NPP variation. Therefore, the effect of human activities was larger than that of climate change on carbon sequestration, which resulted from the implemention of environment protect programs.

4. Discussion

4.1. Methodology

An accurate assessment of land degradation-driving factors has theoretical and practical significances for preventing desertification development. Distinguishing the human impacts on desertification from those of climate change has traditionally been difficult. However, the methodology to assess their relative roles remains lacking. Statistical methods, such as regression and principal component analysis, are the predominant methods (Ma et al., 2007; Millington et al., 2007); however, they are always criticized for ignoring the ecological process of desertification and the driving mechanism involved in desertification (Wrbka et al., 2004). Several studies have been conducted recently to distinguish human-induced desertification from climate-induced desertification by comparing actual vegetation condition with potential one (Evans and Geerken, 2004; Herrmann et al., 2005; Wessels et al., 2007). This method has made it possible to analyze the desertification-driving factors. Therefore, in this study, we selected NPP as an indicator to assess desertification. Potential NPP and HNPP were used to assess the relative roles of climate change and human activities in desertification.

We also assessed the relative roles of climate and human factors in desertification based on the NPP variation, except on the desertification areas. Although the potential NPP and HANPP have successfully detected land degradation in previous research (Zika and Erb, 2009; Xu et al., 2010; Zhang et al., 2011), the relative role has been solely derived by statistical analysis based on desertification area. Desertification areas only reflect the desertification scope, whereas NPP variation reflects the desertification intensity or ecosystem carbon sequestration function. Therefore, the synthesized statistical analysis based on NPP variation and desertification areas may be useful to explore the driving mechanism of desertification.

4.2. Driving factors

Climate change may benefit vegetation growth (Zheng et al., 2006). Recent studies have suggested climate change from warm-dry to warm-wet in northwest China since the late 1980s, and some regions belong to significant conversion region, including the north of Xinjiang, Tianshan Mountains, west of Tarim Basin, and Qilian Mountains (Shi et al., 2007). Wang et al. (2004c) found that precipitation had a slight decline trend from 1951 to 2000 across China, but northwest China's precipitation significantly increased since 1986. Zhai et al. (2005) analyzed the precipitation change of China during 1950–2008 and found that precipitation increased significantly in the regions of Tianshan Mountains, southeast of Tibet, and west of Tarim Basin. In the current study, the annual precipitation showed an increase trend during 1981–2010 in these above-mentioned regions, as shown in Fig. 4. These findings were consistent with the previous report, and the actual NPP and potential NPP also increased in the above-mentioned regions (Fig. 3) because the rising of rainfall benefited the growth of vegetation, especially in dry land (Herrmann et al., 2005).

Human activities, such as overgrazing, conversion of grassland to cropland, overcutting of woody plants, and overexploitation of water resources, will lead to the degradation of natural vegetation. Some studies have concluded that human activities are the dominant factor in desertification development (Ma et al., 2007; Wang et al., 2006, 2012; Zhang et al., 2011). Our study confirmed this conclusion and found that 70.3% of desertification expansion was induced by human activities, whereas 48.4% of desertification reversion was caused by climate change. Especially in Qinghai, 98.0% of desertification expansion was induced by human activities, and 92.4% of desertification reversion was caused by climate changes. The precipitation indeed showed an increase trend in Qinghai, Xinjiang, and Gansu (Fig. 3), which would benefit the desertification reversal, as reported by Herrmann et al. (2005) and Zheng et al. (2006).

However, human activities such as forbidden grazing and conversion of cropland to grassland also promoted desertification reversal (Xu et al., 2010; Wang et al., 2012). The current total desertified land in China was less than that in the late 1990s, and some typical desertification regions, such as Horqin Sandyland and Mu Us Sandyland, experienced an obvious desertification reversion under the Chinese government's restoration programs (Wang et al., 2004d). Our study also found that human-induced desertification reversal accounted for 42.1%, mainly including IM, Shaanxi, and Ningxia. In Ningxia, 100% of desertification reversal was induced by human activities. The aforementioned three provinces effectively implemented ecosystem programs to mitigate land degradation, such as the Grain to Green Program, Grazing Withdrawal Program, and Natural Forest Conversation Program, in the past decades (Ouyang, 2007). The desertification reversal in Mu Us Sandyland and the zone along the Great Wall and Tengger Desert was induced by human activities (Fig. 5) because desertification control in these provinces has been enhanced since the 1990s (Wu, 2001; Wang et al., 2007, 2012). However, declining precipitation and rising temperature occurred in these regions (Fig. 4), and such climate change led to desertification expansion (Hai et al., 2002; Sun and Li, 2002).

In our study, the contribution of human activities to desertification reversal based on NPP variation was 54%, which was larger than its contribution based on areal extent (42.1%). This result demonstrated the dramatic positive impact of human activities on carbon sequestration or desertification reversal. Therefore, we should enhance the effectiveness of environment protect programs.

5. Conclusions

The relative roles of climate and human factors in desertification were assessed. The results showed that 55.8% of northwest China area experienced desertification expansion, whereas 44.2% of the area experienced desertification reversal. The relative roles of human activities and climate change in desertification expansion were 70.3% and 21.7%, respectively. On the contrary, 42.1% of desertification reversal was caused by human activities, and 48.4% resulted from climate changes. Additionally, the relative roles of the two factors in desertification based on NPP variation were calculated. The result revealed that 69% of vegetation deterioration was caused by human, whereas 15.2% was induced by climate change. By contrast, 54% of vegetation restoration was caused by human activities, whereas 23.9% resulted from climate changes. Therefore, whether the quantitative assessemnt was based on desertification expansion area or NPP variation, human activities dominated the desertification expansion.

The relative roles of the two factors varied greatly in the studied six provinces. We derived three propositions to explain the situation. First, climate changes dominated desertification reversal, whereas human activities dominated desertification expansion. Second, both desertification expansion and reversal were induced by human activities. Third, climate changes dominated desertification expansion, whereas human activities dominated desertification reversal. The difference between climate change and human activities, especially the effectiveness of environmental protection policies, determined the driving force of desertification. Therefore, we should enhance the effectiveness of ecological restoration programs. This enhancement would not only benefit the control of desertification and DSS (dust and sandstorms) but also increase carbon sequestration.

The methodology and synthesized analysis based on areal extent and NPP variations in this study can be ultilized in other regions to evaluate the driving causes of desertification.

Acknowledgments

This work was supported by the National Basic Research Program of China (2010CB950702), and the National Youth Science Fund (41201546). We are grateful to Dr. Victor Squires, Adelaide, Australia for the help in modifying the language and structure and Dr. Mao Fei for providing the hyper-arid region distribution diagram.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2014.08.043.

References

Asner, G.P., Martin, R.E., 2004. Biogeochemistry of desertification and woody encroachment in grazing systems. Ecosyst. Land Use Change 99–116.
China National Committee for the Implementation of the UN Convention to Combat Desertification (CCICCD), 1996. China country paper to combat desertification. Forestry Publishing House, Beijing, China, p. 36.
Chang, X.L., Lu, C.X., Gao, Y.B., 2003. Impacts of human economic activities on wind and sand environment in Kerqin sandy land. Resour. Sci. 25, 78–83 (in Chinese, with English abstract).
Evans, J., Geerken, R., 2004. Discrimination between climate and human-induced dryland degradation. J. Arid Environ. 57, 535–554.
Field, C.B., Randerson, J.T., Malmström, C.M., 1995. Global net primary production: combining ecology and remote sensing. Remote Sens. Environ. 51, 74–88.
Haberl, H., Krausmann, F., Erb, K., Schulz, N.B., 2002. Human appropriation of net primary production. Science 296, 1968–1969.
Hai, C.M., Ma, L., Wang, X.M., Li, L., 2002. Main factors analysis about soil desertification in typical section of interlock area of farming and pasturing: the case of Zhangbei county, Bashang area of Hebei province. Geogr. Res. 21, 543–550 (in Chinese, with English abstract).
Hanafi, A., Jauffret, S., 2008. Are long-term vegetation dynamics useful in monitoring and assessing desertification processes in the arid steppe, southern Tunisia. J. Arid Environ. 72, 557–572.
He, Y.H., Tian, Y.L., Ye, D.M., Qin, J.Q., Guo, L.S., 2005. Model of aboveground biomass of Nitraria tangutorum and relationship between biomass and leaf area. J. Desert Res. 25, 541–546 (in Chinese, with English abstract).
Herrmann, S.M., Anyamba, A., Tucker, C.J., 2005. Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. Global Environ. Change 15, 394–404.
Huang, M., Ji, J.J., Cao, M.K., Li, K.R., 2006. Model study of vegetation shoot and root biomass in China. Acta Ecol. Sin. 26, 4156–4163 (in Chinese, with English abstract).
Huenneke, L.F., Anderson, J.P., Remmenga, M., Schlesinger, W.H., 2002. Desertification alters patterns of aboveground net primary production in Chihuahuan ecosystems. Global Change Biol. 8, 247–264.
Li, G.T., Jia, S.Y., 1998. Study on biomass estimation models of xerophyte shrub. J. Inner Mongolia Forest. Coll. 20, 24–31 (in Chinese, with English abstract).
Li, X.L., 2009. Mechanisms of degradation in grazed rangelands. In: Li, X.L., Squires, V.R., Lu, X.S., Lu, Q., Wang, T., Yang, Y. (Eds.), Degradation and recovery in the pastoral lands of China. CABI, Wallingford, USA, pp. 45–60.
Lieth, H., Box, E., 1972. Evapotranspiration and primary productivity. Publ. Climatol. 25, 37–46.
Lieth, H., 1975. Modeling the primary production of the world. In: Lieth, H., Whittaker, R.H. (Eds.), Primary productivity of the Biosphere. Springer, Berlin, Germany, pp. 237–263.
Lin, Y., Bai, Y.F., 2010. Response of aboveground net primary production and population structure of Caragana microphylla to prescribed burning in a typical steppe of Inner Mongolia. Acta Prataculť. Sin. 19, 170–178 (in Chinese, with English abstract).
Luo, T.X., 1996. Patterns of Net Primary Productivity for Chinese Major Forest Types and Its Mathematical Models. Commission for Integrated Survey of Natural Resources, Chinese Academy of Sciences, Beijing Ph.D. Dissertation.
Ma, Y.H., Fan, S.Y., Zhou, L.H., Dong, Z.H., Zhang, K.C., Feng, J.M., 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.
Millington, J.D.A., Perry, G.L.W., Romero-Calcerrada, R., 2007. Regression techniques for examining land use/cover change: a case study of a Mediterranean landscape. Ecosystems 10, 562–578.
Mouat, D., Lancaster, J., Wade, T., Wickham, J., Fox, C., Kepner, W., Ball, T., 1997. Desertification evaluated using an integrated environmental assessment model. Environ. Monit. Assess. 48, 139–156.
Ouyang, Z., 2007. Ecological Construction and Sustainable Development in China. Science Press, Beijing, China.
Pan, Y.D., Luo, T.X., Birdsey, R., Hom, J., Melillo, J., 2004. New estimates of carbon storage and sequestration in China's forests: effects of age–class and method on inventory-based carbon estimation. Climatic Change 67, 211–236.
Peng, C.H., Zhou, X.L., Zhao, S.Q., Wang, X.P., Zhu, B., Piao, S.L., Fang, J.Y., 2009. Quantifying the response of forest carbon balance to future climate change in northeastern China: model validation and prediction. Global Planet. Change 66, 179–194.
Potter, C.S., Randerson, J.T., Field, C.B., Matson, P.A., Vitousek, P.M., Mooney, H.A., Klooster, S.A., 1993. Terrestrial ecosystem production: a process model based on global satellite and surface data. Global Biogeochem. Cy. 7, 811–841.
Prince, S.D., Colstoun, D., Brown, E., Kravitz, L.L., 1998. Evidence from rain-use efficiencies does not indicate extensive Sahelian desertification. Global Change Biol. 4, 359–374.
Rasmussen, K., Fog, B., Madsen, J.E., 2001. Desertification in reverse? Observations from northern Burkina Faso. Global Environ. Change 11, 271–282.
Reynolds, J.F., Stafford Smith, D.M., 2002. Do humans cause deserts? In: Reynolds, J. F., Stafford Smith, D.M. (Eds.), Global Desertification: Do Humans Cause Deserts?. Dahlem University Press, Berlin, pp. 1–21.
Rojstaczer, S., Sterling, S.M., Moore, N.J., 2001. Human appropriation of photosynthesis products. Science 294, 2549–2552.
State Forestry Administration of China (SFAC), 2005. Reports on desertification in China. http://www.forestry.gov.cn/manager/zhuanlan_url/file_up/fszs2006100952.doc (in Chinese).
Schimel, D.S., 1995. Terrestrial biogeochemical cycles: global estimates with remote sensing. Remote Sens. Environ. 51, 49–56.
Shi, Y.F., Shen, Y.P., Kang, E., Li, D.L., Ding, Y.J., Zhang, G.W., Hu, R.J., 2007. Recent and future climate change in northwest China. Climate Change 80, 379–393.
Squires, V.R., 2010. Desert transformation or desertification control? J. Rangel. Sci. 1, 17.
Sun, W., Li, B.S., 2002. The relation between coupling among the principal components of desertification factors and desertification in rear hills of Bashang since 1950. Geogr. Res. 21, 392–397 (in Chinese, with English abstract).
United Nations Convention to Combat Drought and Desertification in Countries Experiencing Serious Droughts and/or Desertification, Particularly in Africa. United Nations, New York.
Veron, S.R., Paruelo, J.M., Oesterheld, M., 2006. Assessing desertification. J. Arid Environ. 66, 751–763.
Wang, T., Zhu, Z.D., 2003. Study on sandy desertification in China: 1. Definition of sandy desertification and its connotation. J. Desert Res. 23, 209–214 (in Chinese, with English abstract).
Wang, X.M., Dong, Z.B., Zhang, J.W., Liu, L.C., 2004a. Modern dust storms in China: an overview. J. Arid Environ. 58, 559–574.
Wang, L., Zhang, H., Ha, S., Zheng, Q.H., Liu, L.Y., 2004b. A study on the estimating method of shrub upper biomass based on the crown diameter and plant height. J. Beijing Normal Univ. (Natural Science) 40, 700–704 (in Chinese, with English abstract).
Wang, Z.Y., Ding, Y.H., He, J.H., Yu, J., 2004c. An updating analysis of the climate change in China in recent 50 years. Acta Meteorol. Sin. 62, 228–236 (in Chinese, with English abstract).
Wang, T., Zhu, D., Zhao, H.L., 2004d. Study on sandy desertification in China: 4. Strategy and approach for combating sandy desertification. J. Desert Res. 115–123 (in Chinese, with English abstract).
Wang, X.M., Chen, F.H., Dong, Z.B., 2006. The relative role of climatic and human factors in desertification in semiarid China. Global Environ. Change 16, 48–57.
Wang, X.H., Lu, C.H., Fang, J.F., Shen, Y.C., 2007. Implications for development of grain-for-green policy based on cropland suitability evaluation in desertification-affected north China. Land Use Policy 24, 417–424.
Wang, T., Sun, J.G., Han, H., Yan, C.Z., 2012. The relative role of climate change and human activities in the desertification process in Yulin region of northwest China. Environ. Monit. Assess. 184, 7165–7173.
Wessels, K.J., Prince, S.D., Malherbe, J., Small, J., Frost, P.E., 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.
Wessels, K.J., Prince, S.D., Reshef, I., 2008. Mapping land degradation by comparison of vegetation production to spatially derived estimates of potential production. J. Arid Environ. 72, 1940–1949.

Wrbka, T., Erb, K., Schulz, N.B., 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.

Wu, W., 2001. Study on process of desertification in Mu Us Sandy Land for last 50 years, China. J. Desert 21, 164–169 (in Chinese, with English abstract).

Xu, D.Y., Kang, X.W., Zhuang, D.F., Pan, J.J., 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.

Yang, X., Zhang, K., Jia, B., Ci, L., 2005. Desertification assessment in China: an overview. J. Arid Environ. 63, 517–531.

Yang, R.R., 2002. Studies on current situation of grassland degradation and sustainable development in western china. Pratacult. Sci. 19, 23–27 (in Chinese, with English abstract).

Yu, D.Y., Shi, P.J., Han, G.Y., Zhu, W.Q., Du, S.Q., Xun, B., 2011. Forest ecosystem restoration due to a national conservation plan in China. Ecol. Eng. 37, 1387–1397.

Zhai, P.M., Zhang, X.B., Wan, H., Pan, X.H., 2005. Trends in total precipitation and frequency of daily precipitation extremes over China. J. Climate 18, 1096–1108.

Zhang, Y.S., Wang, L.X., Zhang, H.Q., Li, X.Y., 2003. Influence of environmental factor changes on desertification process in Shule River. Resour. Sci. 25, 60–65 (in Chinese, with English abstract).

Zhang, C.X., Wang, X.M., Li, J.C., 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.

Zhao, C.Y., Dong, S.Y., Chao, W.Y., An, J.P., 2004. Estimation of aboveground biomass of desert plants Chinese. J. Appl. Ecol. 15, 49–52 (in Chinese, with English abstract).

Zheng, Y.R., Xie, Z.X., Robert, C., Jiang, L.H., Shimizu, H., 2006. Did climate drive ecosystem change and induce desertification in Otindag sandy land, China over the past 40 years? J. Arid Environ. 64, 523–541.

Zhu, W.Q., Pan, Y.Z., He, H., Yu, D.Y., Hu, H.B., 2006. Simulation of maximum light use efficiency for some typical vegetation types in China. Chin. Sci. Bull. 51, 457–463.

Zika, M., Erb, K.H., 2009. The global loss of net primary production resulting from human-induced soil degradation in drylands. Ecol. Econ. 69, 310–318.