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Relative contribution of climate change and human activities to vegetation degradation and restoration in North Xinjiang, China

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Abstract. Climate change and human activities are the two primary driving factors in the vegetation degradation process, and the assessment of their relative roles in vegetation degradation is important to understand the driving mechanisms of vegetation degradation. In this study, net primary productivity (NPP) was selected as an indicator to distinguish the relative roles of climate change and human activities in vegetation degradation and restoration from 2001 to 2010 in North Xinjiang, China. The potential NPP and the human appropriation of NPP were served as the indicator of the effects of climate change and human activities in vegetation degradation and restoration. The results showed that human activities were the dominant factor that induced vegetation degradation, accounts for 55% (153 720 km^2) of the total degradation, whereas 25% (69 336 km^2) of the total degradation resulted from climate change; the combination of human activities and climate change was the cause in 20% (55 429 km^2) of the total degradation. In contrast, 61% (66 927 km^2) of the total vegetation restoration was dominated by human activities and 29% (31 553 km^2) was caused by climate change; the areas of vegetation restoration caused by the combination of human activities and climate change were 10 551 km^2 (10%). The relative roles of the two factors possessed great spatial heterogeneity in five vegetation types. Climate dominated degradation expansion and human activities dominated vegetation restoration in forest. Both the degradation and restoration were dominated by human activities in grassland. In desert, degradation was dominated by human activities and vegetation restoration by climate. In cropland and crop/natural vegetation mosaic, degradation was dominated by both human activities and climate change and restoration was dominated by human activities. These results demonstrated that human activities played a demonstrably positive role in vegetation restoration, and ecological restoration projects were effective on mitigating vegetation degradation and also promoting restoration in the southern areas of North Xinjiang.

Additional keywords: driving factors, dynamic, net primary productivity (NPP), vegetation status.

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Introduction

Vegetation degradation refers to the succession process in which the land loses its production potential due to human or natural factors. Currently, vegetation degradation is one of the most serious global environmental issues in arid, semi-arid and dry sub-humid areas, which, in the form of desertification in arid and semi-arid areas, result from various factors, including climatic change and human activities (UNCCD 1994). Over 250 million people are directly affected by desertification and about one billion people in over 100 countries are at risk (Adger *et al.* 2000). China is also facing a severe desertification problem, especially in north-western regions of China, where the desertification process influences regional ecological environment and impedes the local socioeconomic development. Owing to its rapid spread, desertification has become a focus of academic study (Wang *et al.* 2004; Ma *et al.* 2007; Wessels *et al.* 2008). Currently, understanding the driving mechanisms of desertification is the basic and most central problem considered in research on the control of desertification (Jia *et al.* 2003; Ma *et al.* 2007).

Previous studies have shown that desertification in the Sahel (e.g. Lamprey 1975) can be due to variations in rainfall rather than human-induced vegetation degradation (Prince *et al.* 1998; Nicholson 2005). Sun and Li (2002) suggested that a high number of windy days per year and a variety of climatic factors were the primary causes of desertification or vegetation degradation. Otherwise, numerous researchers have attributed the rapid desertification in arid and semi-arid Chinese regions to human activities such as over-grazing, over-reclamation, and extensive cutting (e.g. Wang *et al.* 1991, 2004; Wang and Zhu 2001; Zhao *et al.* 2005). Although both climate change and human activities are considered to be causing vegetation degradation in arid and semi-arid areas of north-west China, their relative roles should be evaluated and assessed to help resolve the uncertainty over which is the primary cause (Wang *et al.* 2005), which could be useful for us to develop more appropriate interventions for mitigating the vegetation degradation.

Many studies have been conducted to assess the relative roles that climate and human factors play in vegetation degradation (Evans and Geerken 2004; Wessels *et al.* 2007; Wang *et al.* 2012; Li *et al.* 2015). Traditional method of quantitative assessment refers to developing statistical relationships between driving factors and desertification such as using a regression model (Li *et al.* 2004; Lin *et al.* 2005), principle component analysis (Li *et al.* 2007; Jiang *et al.* 2008) and factor analysis (Ma *et al.* 2007). However, because the statistical method ignores the ecological processes involved in vegetation degradation and its driving factors, it is difficult to apply to research at the pixel scale (Wrbka *et al.* 2004). Several studies have been conducted based on vegetation datasets to distinguish climate and human causes in the process of desertification or vegetation degradation (Evans and Geerken 2004; Wessels *et al.* 2007, 2008; Liu *et al.* 2015; Miao *et al.* 2015). However, the understanding of the relative roles of climate change and human activities in vegetation degradation in arid and semi-arid areas in China is still limited, and this needs to be clarified to better control desertification and develop rehabilitation strategies at different scales in this ecological fragile area.

Net primary productivity (NPP) is the total amount of organic matter accumulated effectively by vegetation per unit area and time (Lieth 1975). As an important parameter of the ecosystem functioning and the carbon cycle, NPP is influenced by both natural and anthropogenic factors. In order to better understand the scale and potential effect that human activities are having on ecosystems, HANPP, the 'human appropriation of net primary production' was developed by Vitousek *et al.* (1986), Wright (1990), and Haberl (1997). Haberl (1997) defines HANPP as the difference between the amount of NPP that would be available in an ecosystem in the absence of human activities (NPP_0) and the amount of NPP which actually remains in that ecosystem, or in the ecosystem that replaced it under current management practices (NPP_t). HANPP can be defined as following equation:

$$\mathrm{HANPP} = \mathrm{NPP_0} - \mathrm{NPP_t} = \mathrm{NPP_0} - (\mathrm{NPP_{act}} - \mathrm{NPP_h})$$

where NPP_{act} represents the NPP of the actual vegetation and NPP_h represents the NPP harvested by humans. Approaches based on HANPP have been used to monitor vegetation degradation and vegetation cover changes (Prince *et al.* 2009). In this research, HANPP was used to estimate the roles of human activities on vegetation degradation and vegetation restoration in arid and semi-arid areas in north-western China.

As one of main arid and semi-arid regions in north-western China, North Xinjiang is facing a larger challenge than before due to climate change and population pressure (Xu and Wei 2004). With the population growth and economic development, substantial land use and cover change occurred due to over-grazing and over-cultivation, which has led to several ecological problems such as desertification and low productivity of land (Zhou *et al.* 2002; Cui 2003). Moreover, climate variation and intense human activities resulted in the aggravation of vegetation degradation. This has begun to attract governmental and citizen concerns for ecological and environmental protection of the area. In recent years, China's government implemented a series of ecological restoration programmes to mitigate the widespread ecological damage. As a typical region of arid and semi-arid areas in China, the ecological systems have very low rates of productivity and are extremely sensitive to climate change and human activities. Therefore, we selected North Xinjiang as the focus area primarily for evaluating the relative roles of climate change and human activities on vegetation degradation and vegetation restoration, and assessing the effects of the vegetation restoration programmes on mitigating vegetation degradation in the region from 2001 to 2010. For this purpose we chose the time period from 2001 to 2010 because this decade was the key period for implementation of ecological restoration projects in the study area.

The objectives of this study are: (1) to separately investigate the status of vegetation degradation and restoration in different vegetation types in North Xinjiang from 2001 to 2010; (2) to distinguish and assess the relative roles of climate change and human activities on vegetation degradation and restoration in different vegetation types in North Xinjiang.

Materials and methods

Research area

The research area is located in the north portion of the Xinjiang Uygur Autonomous Region of China (Fig. 1), in the centre of the Eurasian continent. The North Xinjiang is the north-western border of China, adjacent to the Republics of Kazakhstan, Russia, and Mongolia on the western, northern, and eastern sides, respectively. The area includes 10 cities or counties: Yining, Tacheng, Altai, Bole, Changji, Urumqi, Kuytun, Shawan, Karamay and Shihezi. The main mountain ranges are the Altai Mountain in the north and the Tianshan Mountains to the south. Junggar basin is located in the central part. There is a large area of desert in North Xinjiang, the Gurbantonggut desert. The climate of North Xinjiang features a temperate continental arid and semi-arid climate characterised by an abundance of light and heat, scarce precipitation, and intensive evaporation. It has 2550–3500 h of sunshine annually, an average annual temperature of 5–7°C, and an annual actual evaporation of 1500–2300 mm compared with the annual precipitation of 100–200 mm. Furthermore, precipitation in the form of rain is heavier in western than eastern areas in this region, as well as in the mountains than on the flat basins. The frost free season is 140–195 days. Desert, grassland and oasis dominate the research area. The

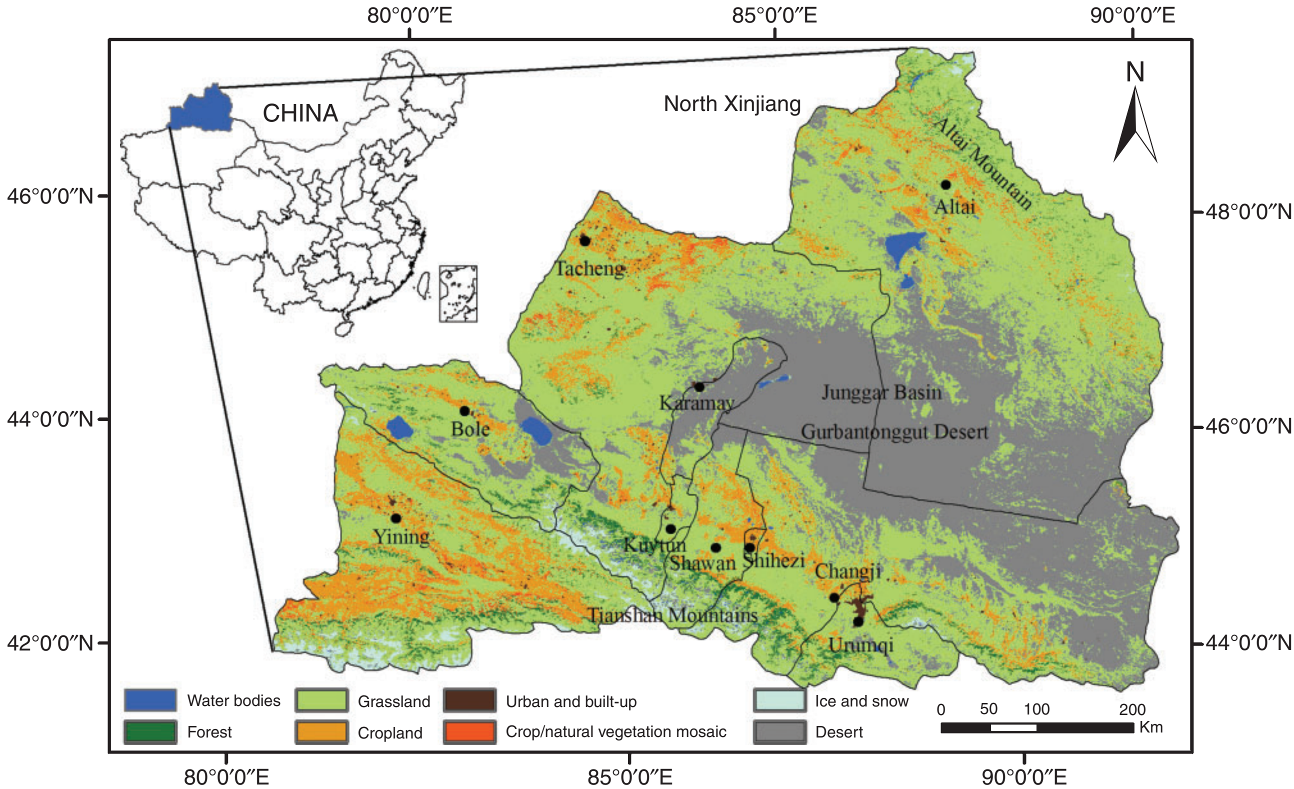

Fig. 1. Location of North Xinjiang, land use and land cover patterns in 2001. The land use and land cover patterns was based on International Geosphere Biosphere Program (IGBP) global vegetation classification scheme at 500-m spatial resolution. Seventeen LCLU classes were reclassified into eight dominant categories based on the IGBP classification scheme.

vegetation includes small shrubs and semi-shrubs, typical of the desert temperate, which is made up of few species with low coverage.

Data sources and processing

NDVI (Normalised Different Vegetation Index) data

MODIS data and geo-spatial meteorological data were chosen as input parameters to the CASA (Carnegie-Ames-Stanford Approach) model (Potter *et al.* 1993) for calculating NPP in North Xinjiang. 500-m resolution MODIS-derived 16-day composite vegetation indices (MOD13A1) NDVI data from 2001 to 2010 were downloaded from EOS data gateway. A 32-day composite product of the maximal values was produced for a time series based on these data. These data were re-projected to the Albers equal area projection and WGS84 datum from the original Integerised Sinusoidal Projection using the MODIS reprojection tool and nearest neighbour re-sampling method.

Land use and land cover data

The MODIS Collection 5 Land Cover Type product (MCD12Q1) based on IGBP global vegetation classification scheme at 500-m spatial resolution was used as land use and land cover data for North Xinjiang. The land cover map was acquired through EOS Data Gateway at the Land Processes Distributed Active Archive Centre (LP DAAC) for 2001. The IGBP classification has 17 LCLU (Land Cover and Land Use) classes, including 11 natural vegetation classes, three developed and mosaicked land classes, and three non-vegetated land classes. In this paper, the land cover maps were reclassified into following eight dominant categories based on the IGBP classification scheme: (1) water bodies, (2) forest, (3) grassland, (4) cropland, (5) urban and built-up, (6) crop/natural vegetation mosaic, (7) snow and ice, (8) desert.

Meteorological data

Meteorological data including monthly mean temperatures, monthly total precipitation and monthly total solar radiation data from 2001 to 2010, were obtained from China Meteorological Data Sharing Service System. The climatic data collected from 56 observation stations in or around North Xinjiang were interpolated by Kriging method using ArcGIS version 9.3 (ESRI, Redlands, CA, USA) to produce raster images. These images are of the same temporal and spatial resolutions (500 m × 500 m) as the remote-sensing images used for further analysis. The meteorological data required for Thornthwaite Memorial model is annual mean temperature and annual total precipitation from 2001 to 2010. These annual averages were calculated from the monthly meteorological data and interpolated into an image with 500-m resolution.

Methods

Estimation of potential NPP

Potential NPP refers to the NPP calculated based on climate factors, without human activities interferences since 2001. It was simulated by the Thornthwaite Memorial model, which is based on the Miami model and developed based on the meteorological data (Lieth 1975), including Thornthwaite's potential evaporation model (Lieth and Box 1972).

The Thornthwaite Memorial model calculates NPP (g C m^{-2} a^{-1}) in terms of the mean annual actual evapotranspiration, and was expressed as follows:

$$\mathrm{NPP} = 3,000(1 - e^{-0.0009695(E-20)}) \quad (1)$$

where E is the mean annual actual evapotranspiration (mm). The calculated equations are expressed as:

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

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

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

Estimation of actual NPP

Vegetation cover reflects the complex interactions between climate change and human activities, thus its dynamic will be important in the process of vegetation degradation (Hanafi and Jauffret 2008; Xu *et al.* 2010). Vegetation cover was selected to represent the vegetation condition and analysis of the impacts of climate change and human activities on vegetation degradation. NPP can be modelled using a relation with Absorbed Photosynthetically Active Radiation (APAR), modified by the effects of environmental factors that reduce light-use efficiency, such as temperature and water stress (Potter *et al.* 1993). As it is possible to estimate NPP based on satellite data and surface data on a large-scale, the CASA model has had widespread use in recently years, and it is also a robust model in describing spatial and temporal patterns of NPP (Potter *et al.* 1993; Imhoff *et al.* 2004; Yu *et al.* 2009, 2011). In the CASA model, NPP is the product of the modulated APAR and a light-use efficiency factor (ε) (Zhu *et al.* 2007):

$$\mathrm{NPP}(x,t) = \mathrm{APAR}(x,t) \times \varepsilon(x,t) \quad (4)$$

$$\mathrm{APAR}(x,t) = \mathrm{SOL}(x,t) \times \mathrm{FPAR}(x,t) \times 0.5 \quad (5)$$

where NPP(x, t) is NPP (g C m^{-2} a^{-1}) in the geographic coordinate of a given location x and time t. APAR(x, t) (MJ m^{-2} mon^{-1}) represents the photosynthetically active radiation absorbed by pixel x in t time while ε(x, t) represents the actual light use efficiency (g C MJ^{-1}) of pixel x in t time; SOL(x, t) is total solar radiation (MJ m^{-2}) of pixel x in t time. FPAR(x, t) is the fraction of PAR absorbed by vegetation canopy, and it can be determined by NDVI. 0.5 stands for the fraction of total solar radiation that can be used by vegetation (0.38 – 0.71μm); ε(x, t) can be expressed by the following equation:

$$\varepsilon(x,t) = T_{\varepsilon 1}(x,t) \times T_{\varepsilon 2}(x,t) \times W_{\varepsilon}(x,t) \times \varepsilon_{\max} \quad (6)$$

where $T_{\varepsilon1}(x, t)$ and $T_{\varepsilon2}(x, t)$ are temperature stress coefficients which reflect the reduction of light-use efficiency caused by temperature factor. $W_{\varepsilon}(x, t)$ is the moisture stress coefficient, which indicates the reduction of light-use efficiency caused by moisture factor. ε_{max} is the maximum light-use efficiency under ideal condition.

Validation of CASA model and parameters

The estimation accuracy of the CASA model was verified by using observed NPP values for grassland vegetation (39 data points) in July 2010. Fig. 2 presents the results of the correlation analysis between the observed and estimated NPP. The correlation was significant ($R^2 = 0.690$, $P < 0.001$), which indicates that the model's estimation accuracy is satisfactory for the purposes of this study and also that the CASA model can be used to support research of NPP changes in the research area.

Evaluation methodology for climate change and human activities in vegetation degradation or vegetation restoration

The vegetation pattern on the land surface resulted from the interactive effect of climate change and human activities. The impacts of climate change and human activities on NPP were measured based on the potential NPP and HANPP, respectively. The least-square regression method (Mu *et al.* 2013) can be used to analyse the change trend of vegetation dynamic in a time series, and was used to estimate the trends for potential NPP, actual NPP, and HANPP over time. The slope calculation for each variable was obtained by the following equation:

$$\theta_{slope} = \frac{n \times \sum_{i=1}^{n} i \times \mathrm{NPP}_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} \mathrm{NPP}_i}{n \times \sum_{i=1}^{n} i^2 - \left(\sum_{i=1}^{n} i\right)^2} \quad (7)$$

where θ_{slope} is linear regression slope representing the trends of potential NPP, actual NPP or HANPP change; n is the number of years; NPP_i is the annual NPP at the year i.

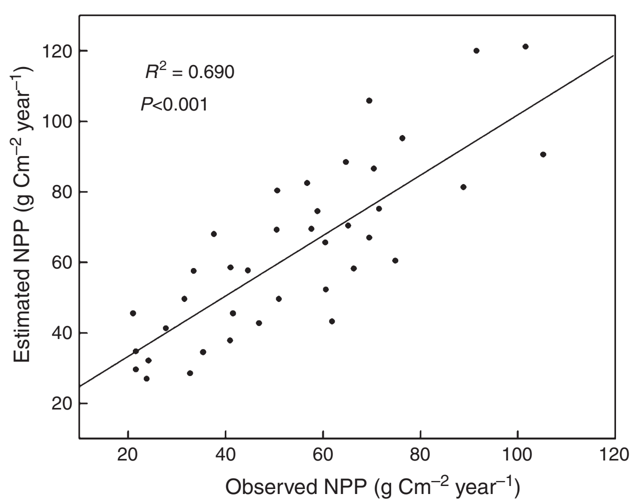

Fig. 2. Correlation between estimated NPP and observed NPP for grassland in July 2010 (39 data points).

The variation in vegetation productivity is represented using the slope of the curve for actual NPP to assess the actual vegetation status. To assess vegetation situation and the effect of climate change and human activities on vegetation degradation and restoration in North Xinjiang from 2001 to 2010, the Slope NPP values was divided into six levels: obviously decreasing, moderately decreasing, slightly decreasing, slightly increasing, moderately increasing and obviously increasing. The slope of the curve for potential NPP was used to assess the effects of climate change and was expressed as Slope NPP_p, which predicts the vegetation conditions with no human activities. The slope of HANPP was used to assess the anthropogenic influences in terrestrial NPP during the research period. Positive Slope HANPP indicates that human-induced vegetation degradation occurs, whereas negative Slope HANPP means vegetation restoration resulted from human activities. The larger the magnitude of the HANPP value, the greater is the impacts of human activities on the vegetation during the research period. The combination of these provides eight possible scenarios for assessing the relative role of climate change and human activities in vegetation degradation or vegetation restoration (Table 1). Overall, the flowchart of the method used in this research is shown in Fig. 3.

Results

Assessment of vegetation status based on actual NPP change

Simple linear regression slope based on actual NPP from 2001 to 2010 showed that a slightly decreasing trend appeared in the most of northern and central North Xinjiang, whereas a slight increase occurred in the area of southern parts of the research region; a moderate increase was scattered in the central areas of the region (Fig. 4*a*). Vegetation restoration occurred in south-central areas, including Changji, Shawan, Kuytun, Yining, central area of Bole and north-west of Urumqi, where there is a high human population. Areas with a slight reduction in vegetation productivity were found throughout the Junggar Basin, in most areas of Altai, and in the north-central and eastern areas of Tacheng (Fig. 4*a*).

Table 1. Evaluation methodology for the relative roles of climate change and human activities on vegetation degradation or vegetation restoration under different scenarios

Scenarios	Slope NPP_p	Slope HANPP	Description
		Vegetation degradation (*Slope* $NPP_{act}<0$)	
Scenario 1	Slope $NPP_{P>0}$	Slope HANPP > 0	Human activities dominated vegetation degradation
Scenario 2	Slope $NPP_{P<0}$	Slope HANPP > 0	Both human activities and climate change induced vegetation degradation
Scenario 3	Slope $NPP_{P<0}$	Slope HANPP < 0	Climate change dominated vegetation degradation
Scenario 4	Slope $NPP_{P>0}$	Slope HANPP < 0	Error[A]
		Vegetation restoration (*Slope* $NPP_{act}>0$)	
Scenario 1	Slope $NPP_{P<0}$	Slope HANPP < 0	Human activities dominated vegetation restoration
Scenario 2	Slope $NPP_{P>0}$	Slope HANPP < 0	Both human activities and climate change induced vegetation restoration
Scenario 3	Slope $NPP_{P>0}$	Slope HANPP > 0	Climate change dominated vegetation restoration
Scenario 4	Slope $NPP_{P<0}$	Slope HANPP > 0	Error[B]

[A]Error represents that both climate and human activities benefited vegetation restoration but the outcome was degradation.
[B]Error represents that both climate and human activities favoured vegetation degradation but vegetation was restored.

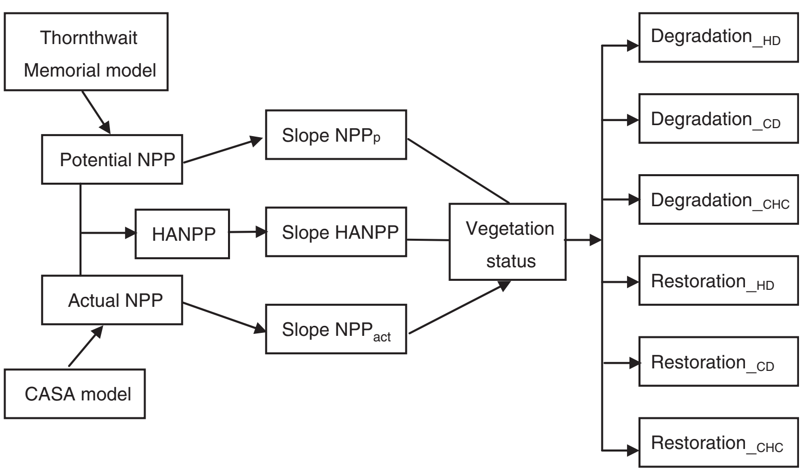

Fig. 3. Flowchart of method used in the research. HD, Human activities impacts dominated; CD, Climate change impacts dominated; CHC, Combination of human activities and climate change impacts.

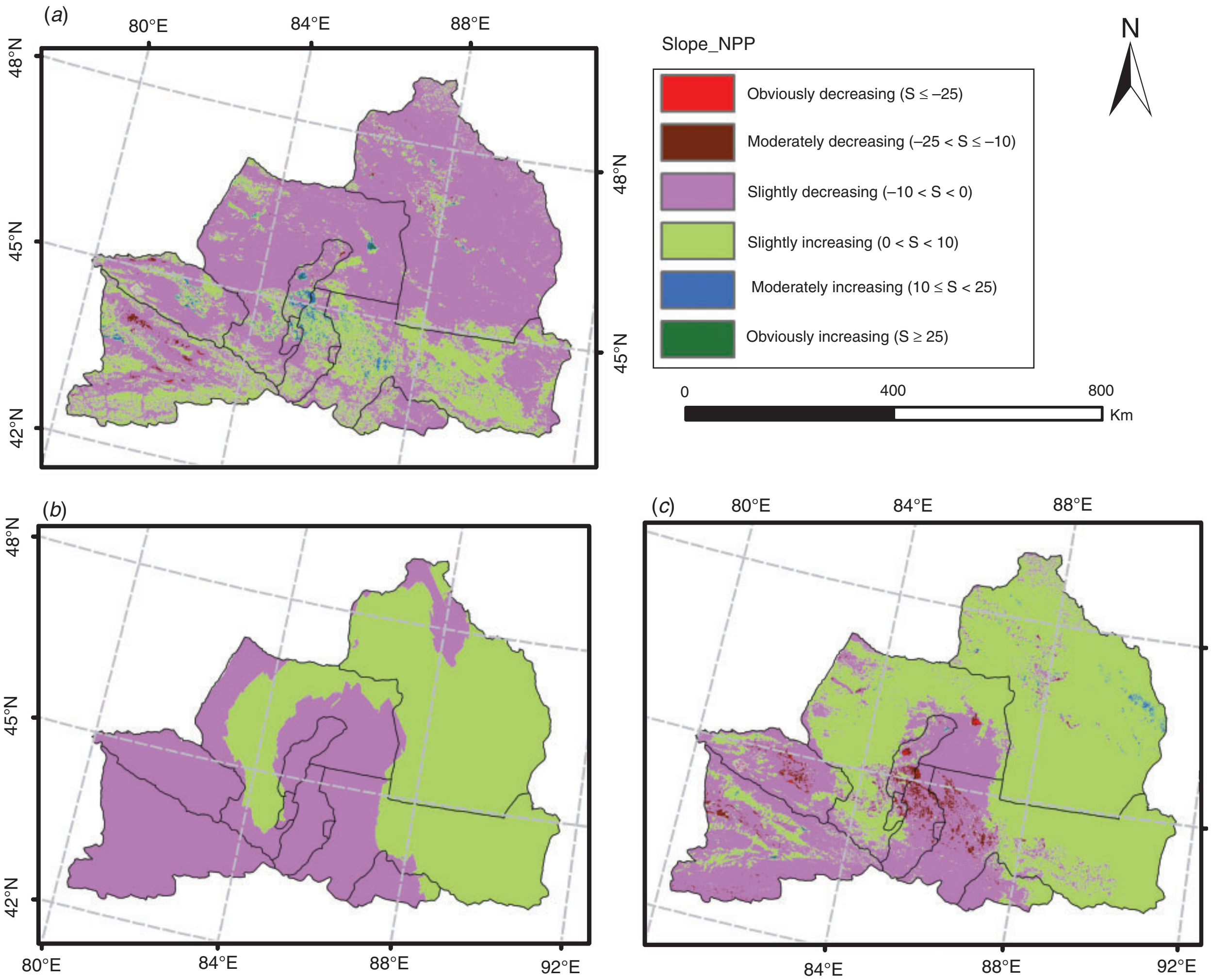

Fig. 4. Spatial distribution of the change trend (slope values) of (*a*) actual NPP, (*b*) potential NPP, and the (*c*) HANPP calculated as the difference between potential NPP and actual NPP from 2001 to 2010.

The key finding is that most of the area (66–74%) of all land types underwent a slight degradation, and most of the remainder (24–32%) underwent a slight restoration; the areas that underwent obvious or moderation degradation or restoration were very small (<2%) (Table 2). The degraded area was distributed in northern and central parts of the research region. The vegetation restoration mainly occurred in the southern parts (Fig. 4*a*).

Relative roles of climate change and human activities in vegetation degradation based on NPP change trend

The change trends of potential NPP (Slope NPP_p) (Fig. 4*b*) show that the climate benefited vegetation restoration in the most eastern areas of the research region, but induced vegetation degradation in the western areas of the region from 2001 to 2010. Climate-induced slight degradation occurred in the areas, whereas climate-induced slight vegetation restoration occurred mostly in Altai, eastern parts of Changji and central-northern areas of Tacheng. Human activities induced vegetation degradation (i.e. HANPP slightly increased) in the eastern, north and north-western parts of the region including Altai, Tacheng and eastern parts of Changji from 2001 to 2010, whereas human-induced vegetation restoration occurred (i.e. HANPP decreased) in the western and central-southern areas including Yinning, Bole, Shawan, Shihezi, Karamay, western areas of Changji and Urumqi (Fig. 4*c*).

Degradation and the relative role of two factors exhibited obvious spatial heterogeneity (Fig. 5). Overall, human activities dominantly induced vegetation degradation in eastern North Xinjiang, whereas in western North Xinjiang the vegetation degradation was mainly caused by climate change. Degradation expansion was widely spread in northern parts of North Xinjiang and accounted for 72% of the study area (Table 2, Fig. 5*a*), whereas restoration area only accounted for 28%. As to the relative roles of climate change and human activities in vegetation degradation, human activities dominated vegetation degradation in most area of Altai, central-northern and southern Tacheng and eastern areas of Changji, whereas climate dominated vegetation degradation in most areas such as Yining, Bole, Shawan, western areas of Changji and Urumqi. Both human

Table 2. The area percentages of different vegetation degradation or restoration levels based on actual NPP in different vegetation types (%)

Vegetation status		Forest	Grassland	Cropland	CNV[A]	Desert	Whole area
Degradation	Obvious degradation	0.0	0.0	0.1	0.0	0.0	0.0
	Moderate degradation	0.1	0.4	1.0	0.3	0.0	0.4
	Slight degradation	71.9	72.6	66.5	69.4	74.5	71.5
Restoration	Slight restoration	28.0	25.8	32.2	30.3	24.1	27.1
	Moderate restoration	0.0	1.1	0.2	0.0	1.3	1.0
	Obvious restoration	–	0.0	–	–	0.2	0.1

[A]CNV means Crop/Natural Vegetation mosaic.

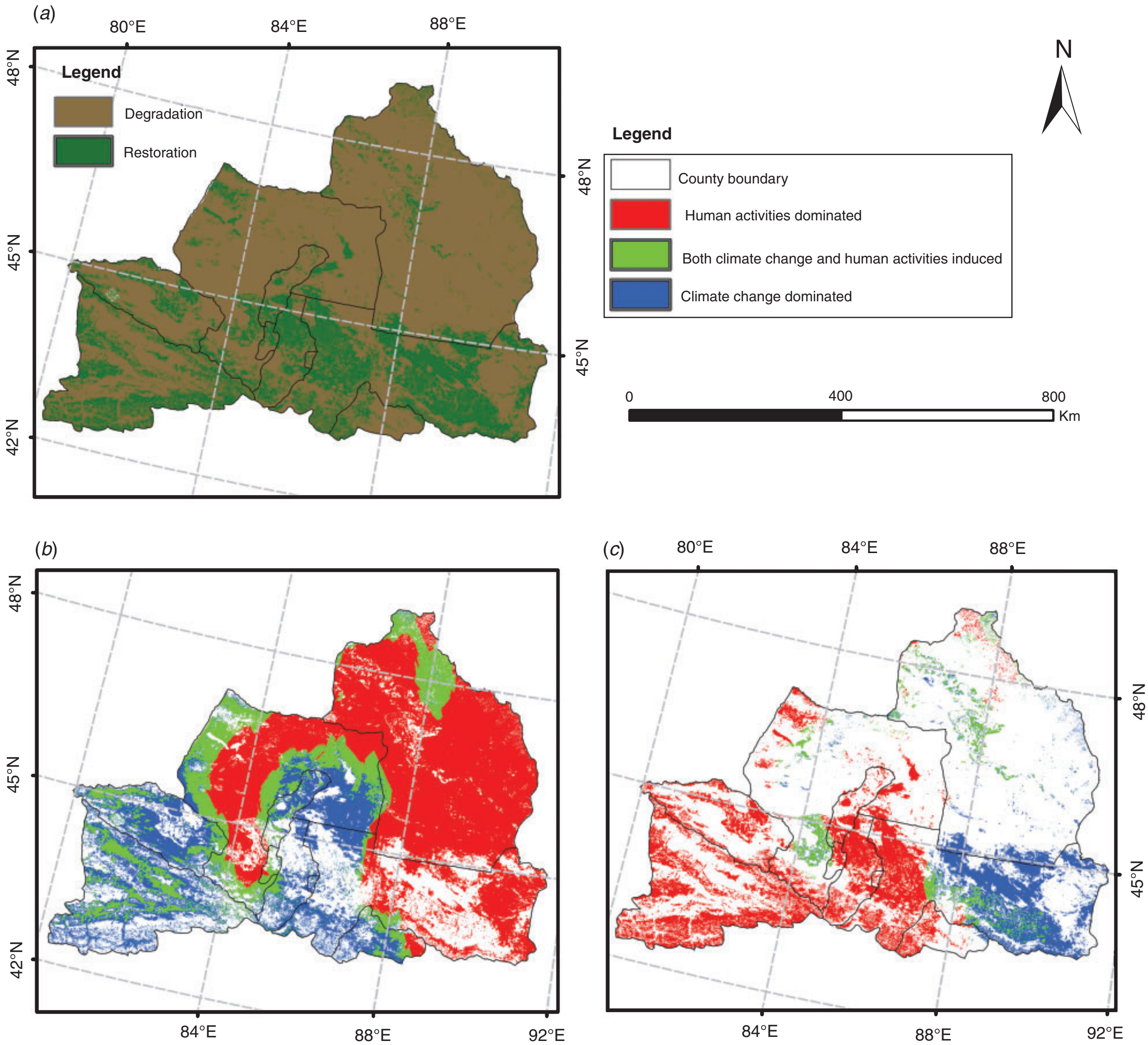

Fig. 5. (*a*) Spatial distribution of vegetation status, (*b*) the factors responsible for vegetation degradation and (*c*) restoration from 2001 to 2010.

activities and climate change caused vegetation degradation in northern areas of Altai, western and eastern and southern parts of Tacheng, central-eastern Yining, northern Karamay, northern Changji and central-eastern Urumqi.

Figure 5*c* shows the spatial distribution of the two factors (human activities and climate change) responsible for vegetation restoration from 2001 to 2010. Vegetation restoration mainly occurred in the southern regions of the study area, and was dominated by human activities in the central and south-western parts of the research region, including Yining, Bole, Shawan, Shihezi, western Changji and Urumuqi, and by climate change in the south-east areas, such as the central-eastern areas of Changji, and by both human activities and climate change in scattered parts of the central-southern parts of North Xinjiang, such as southern Tacheng, southern Changji and central Altai.

Table 3 shows the areas and percentages where vegetation changes were driven by human activities, climate change and combination of the two factors from 2001 to 2010. Human activities was the dominant factor that induced vegetation degradation, accounting for the largest area of degradation, whereas climate change and the combination of human activities and climate change resulted in smaller area of degradation (Table 3). Human activities were also the dominant factor in vegetation restoration, with the largest area of restoration, whereas climate change and the combination of human activities and climate change led to less restoration, respectively (Table 3).

Table 3. The area and percentage of human activities, climate change and combination of the two factors impacted vegetation degradation and restoration from 2001 to 2000

Vegetation status	Driving factors[A]	Areas (km^2)	Percentage (%)
Degradation	HD	153720	55
	CD	69336	25
	CHC	55429	20
Restoration	HD	66927	61
	CD	31553	29
	CHC	10551	10

[A]HD, Human activities impacts dominated; CD, Climate change impacts dominated; CHC, Combination of human activities and climate change impacts. The percentages are the proportion of climate- or human-dominated or combination of the two factors impacted vegetation degradation or restoration for the total degradation or restoration regions.

Relative roles of climate change and human activities in vegetation degradation in different vegetation types

The relative roles of the two factors in vegetation degradation were different in different vegetation types. The area of human-dominated degradation in forest was smaller than that of climate change and the combination of climate and human factors (Table 4). The total area of grassland degradation was the largest of all vegetation types, in which human-dominated degradation accounted for the maximum, climate-dominated degradation accounted for the minimum area, and both climate and human factors contributed to nearly a quarter of the degradation area. In cropland, the area of human-induced degradation and climate driven degradation were about the same of the total cropland degradation area. The influence of humans and climate was similar for crop/natural vegetation mosaic. For desert, the area of human activities-dominated degradation was much larger than that of climate-dominated and the combination of climate and human factors, respectively (Table 4). Three different manifestations were observed in degradation of the five vegetation types. First, climate was more dominant than human activities, especially in forest and crop/natural vegetation mosaic. Second, human activities dominated degradation more than climate in grassland and desert. Third, the contributions of climatic and human factors to vegetation degradation were equal in cropland.

The area of human-induced vegetation restoration was much larger than that of climate-induced restoration, particularly in forest, grassland, cropland, and crop/natural vegetation mosaic, as shown in Table 4. Conversely, climate dominated restoration more than human activities in desert. The combination of both factors contributed to the minimum area of restoration in all vegetation types (Table 4). Four different scenarios were evident. First, where climate dominated degradation expansion

Table 4. The area and percentage of human activities, climate change and combination of the two factors impacted vegetation degradation and restoration for different vegetation types

Driving factors		Vegetation types				
		Forest	Grassland	Cropland	CNV[A]	Desert
HD_degradation	Areas (km^2)	1990	83 863	9947	1433	55 152
	Percentage (%)	28	55	37	37	66
CD_degradation	Areas (km^2)	3027	33 693	10 025	1571	19 257
	Percentage (%)	42	22	37	41	23
CHC_degradation	Areas (km^2)	2178	35 302	7149	869	9311
	Percentage (%)	30	23	26	22	11
HD_restoration	Areas (km^2)	2622	37 631	10 273	1592	9040
	Percentage (%)	94	67	79	95	31
CD_restoration	Areas (km^2)	133	11 595	1563	45	17 838
	Percentage (%)	5	21	12	3	62
CHC_restoration	Areas (km^2)	44	7044	1189	44	1825
	Percentage (%)	2	13	9	3	6

[A]CNV means crop/natural vegetation mosaic.

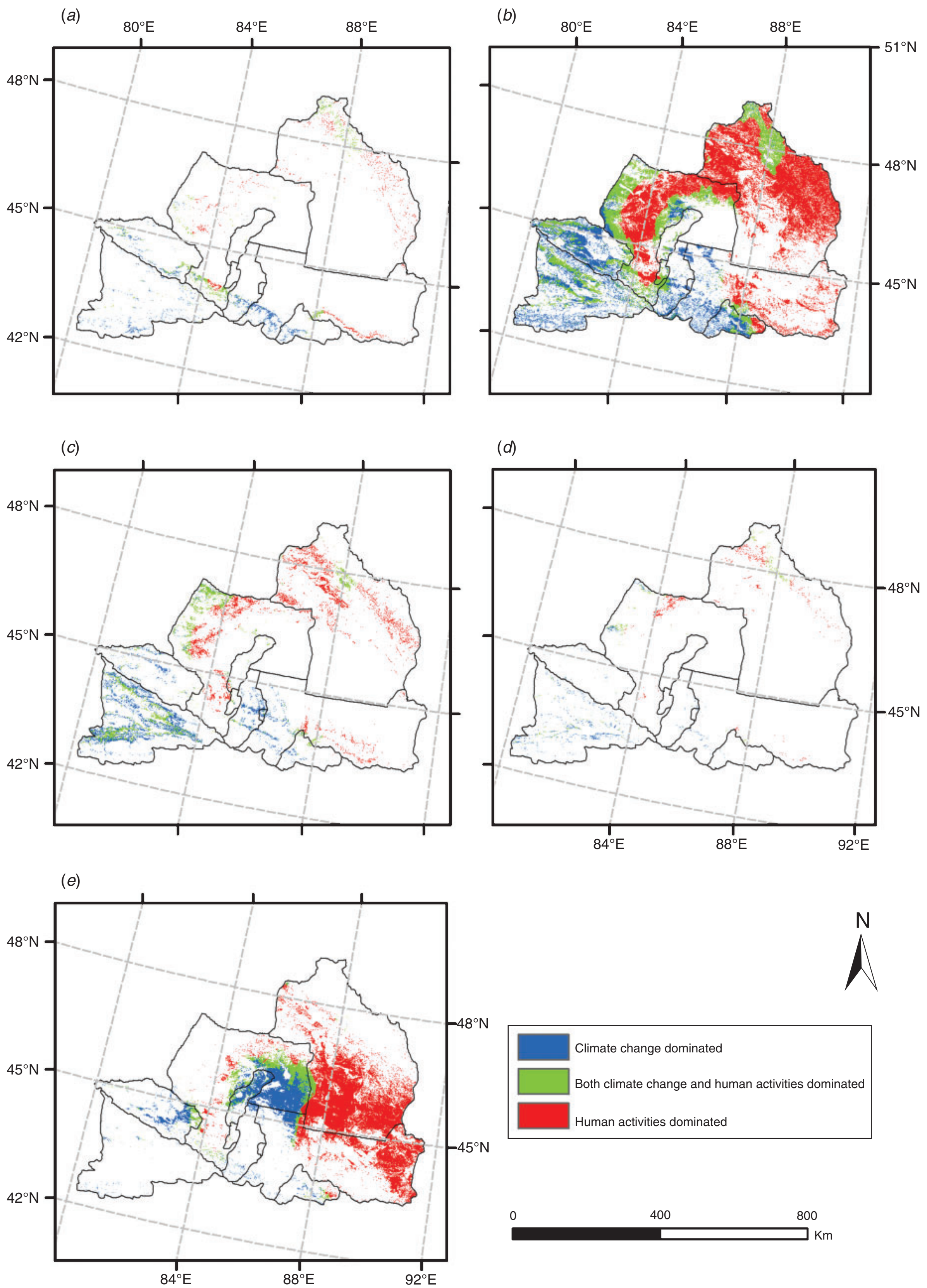

Fig. 6. Spatial distribution of the factors responsible for vegetation degradation in (*a*) forest, (*b*) grassland, (*c*) cropland, (*d*) crop/natural vegetation mosaic, and (*e*) desert of North Xinjiang.

and human activities dominated vegetation restoration, occurred in forest, where near half of degradation was induced by climate, and almost the whole restoration was caused by human activities (Table 4). Second, in grassland, where both the degradation and restoration were dominated by human activities. Third, in desert, where degradation was dominated by human activities and vegetation restoration by climate (Table 4). Fourth, in cropland and crop/natural vegetation mosaic where degradation was dominated by both human activities and climate change and vegetation restoration was dominated by human activities.

The contributions of climate and human factors to vegetation degradation in different vegetation types of North Xinjiang were spatially heterogeneous (Fig. 6). Forest, grassland, cropland and crop/natural vegetation mosaic degradation dominated by climate change mainly occurred in the western-southern and central-southern parts of the region, whereas the degradation dominated by human activities in the northern parts, western and eastern parts of the study region; vegetation degradation dominated by the combination of climate and human factors was scattered mainly in the central-western, northern and southern areas of North Xinjiang (Fig. 6*a*–*d*). In desert, degradation dominated by climate change mainly occurred in the central and central-western parts, whereas human activities dominated mainly in central-eastern parts; the combination of both climate change and human activities was the driver in the central areas of the study region (Fig. 6*e*).

With respect to vegetation restoration, the spatial distribution of the driving factors from 2001 to 2010 is shown in Fig. 7. Human activities dominated vegetation restoration of forest and crop/natural vegetation mosaic mainly in the western-southern areas of the region, and the combination of climate change and human activities partly caused vegetation restoration in a very few areas of central-western Tianshan Mountains; climate change played no active role in vegetation restoration of forest and crop/natural vegetation mosaic over the study period (Fig. 7*a*, *d*). In grassland and cropland, climate change was the driver for vegetation restoration mainly in the south-eastern parts of the study region, and human activities dominated the restoration in the central-southern and western areas; the combination of climate change and human activities was the driver mainly in scattered areas in central-southern and southern parts (Fig. 7*b*, *c*). Climate change dominated vegetation restoration of desert in the south-eastern areas of North Xinjiang, and human activities dominated the vegetation restoration in the central areas; the combination of climate change and human activities was the driver in scattered parts in the central areas of North Xinjiang (Fig. 7*e*).

Discussion

Although vegetation changes and vegetation degradation process can be reliably monitored via a combination of satellite observations and in-situ data, there has been considerable controversy over the relative roles of climate change and human activities in the process of vegetation degradation or vegetation restoration. Some studies suggested that human activities were the main cause of territorial land desertification and vegetation restoration (e.g. Wang *et al.* 1991, 2004; Wang and Zhu 2001; Zhao *et al.* 2005; Becerril-Piña *et al.* 2015; Tun *et al.* 2015; Miao *et al.* 2016). Other studies considered that the role of human activities in the process of vegetation degradation or restoration was often overestimated, and climate change was the dominant factor in the process of degradation or restoration (Wang *et al.* 2005, 2008). However, these results had not good comparability because the research methods used were too qualitative. In this research, we used a quantitative approach to obtain more quantitative findings. NPP was chosen as the indicator to quantitatively assess the relative roles of climate change and human activities on the vegetation degradation and vegetation restoration. Potential NPP and HANPP were used to determine the relative impacts of climate change and human activities on vegetation degradation and restoration. Through the analysis of all the possible scenarios based on the relationship between changes of NPP caused by climate change and human activities, and vegetation degradation or restoration, it was possible to evaluate the relative roles of climate change and human activities on vegetation degradation and vegetation restoration. Moreover, the methodology used revealed the mechanisms responsible for the observed changes in NPP to understand the factors driving vegetation degradation and restoration.

Climate change influences the growth of vegetation through affecting the factors such as precipitation and temperature (Liu *et al.* 2015; Miao *et al.* 2015). Recent research suggests that temperature has increased during the past 50 years, and precipitation has increased during the past 10 years in the local regions of North Xinjiang (Liu *et al.* 2010; Xu and Wei 2004), and these changes would ultimately affect vegetation productivity. Climate change may benefit vegetation growth (Zhang *et al.* 2016). Previous studies have shown that climate change from warm dry to warm wet in North Xinjiang since 1980s, which caused significant land conversion (Shi *et al.* 2007). Our findings were consistent with the previous report, and the potential NPP increased in the eastern and northern areas of North Xinjiang (Fig. 4).

However, human interferences such as the overgrazing, over-logging, and other forms of excessive utilisation of land and water resources have destroyed the land vegetation cover and have caused regional vegetation degradation in the study area. Over the past 50 years, North Xinjiang has experienced a large scale of land reclamation, which occupied the most natural oases and turned much grassland to artificial oases, increasing the area of artificial oases area by approximately three times since 1949. However, these human activities resulting from socioeconomic development and population growth have led to overexploitation of grassland and forest and drastic conversion from grassland into cropland, and this has caused the increase desertification and vegetation degradation due to the rapid expansion of cropland and urban build-up and shrinkage of natural vegetation in other arid areas (Gansu and Shanxi) and in North-west China (Zhang *et al.* 2003; Zhou *et al.* 2003; Li and Wang 2004). Our findings show that human activities were the dominant factor that induced vegetation degradation in 55% of the total degradation.

Conversely, human activities can also play an active role in vegetation restoration by fencing, forbidding grazing, and returning farmland to grassland and forest. However, it has traditionally been difficult to quantitatively assess the roles of human activities in the process of vegetation degradation. The traditional analysis based on the socioeconomic statistical data is

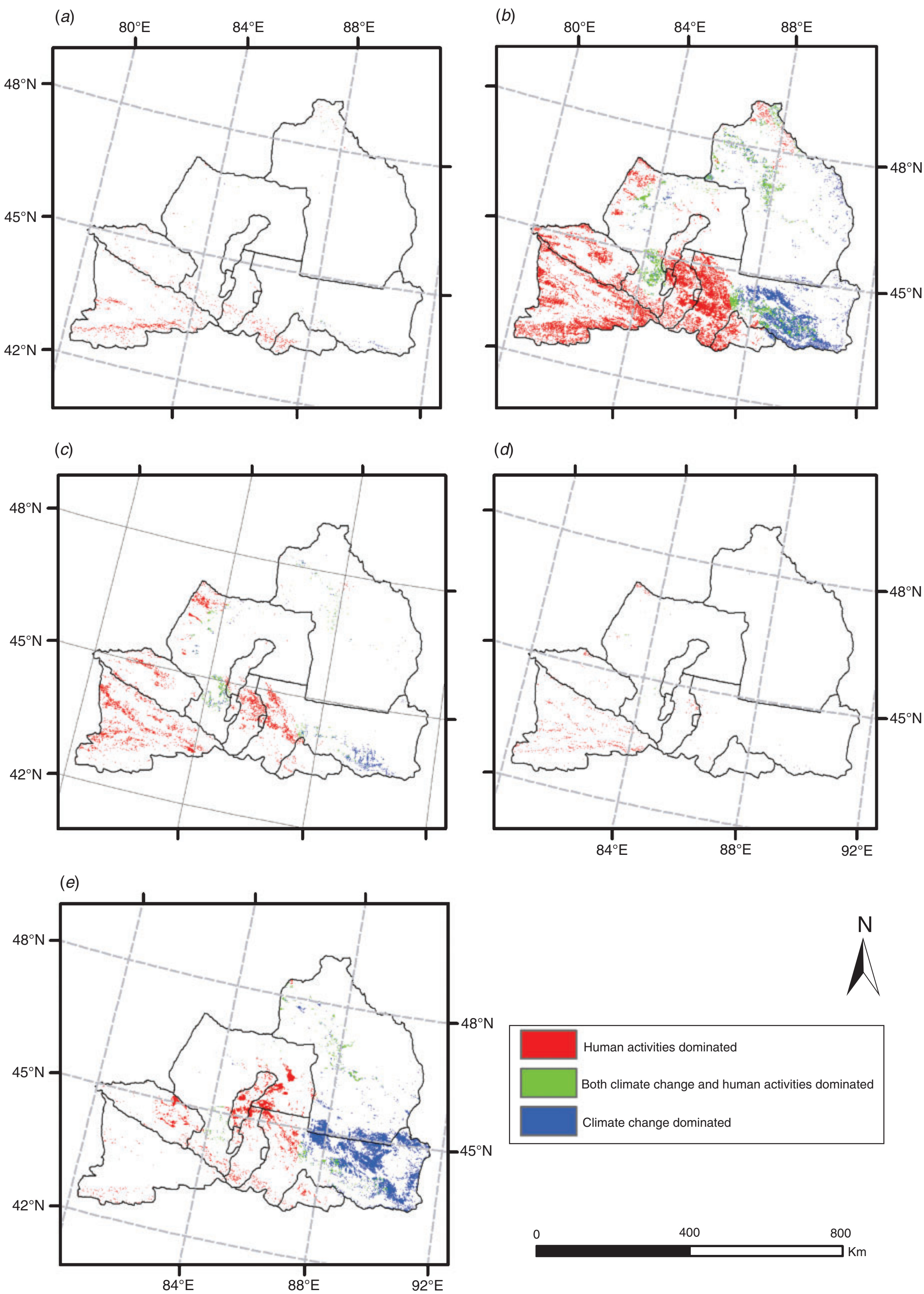

Fig. 7. Spatial distribution of the factors responsible for vegetation restoration in (a) forest, (*b*) grassland, (*c*) cropland, (*d*) crop/natural vegetation mosaic, and (*e*) desert of North Xinjiang.

not only limited by the limitations of the data itself, but it is also difficult to reflect the role of policy factors such as fencing to control livestock grazing in the process of vegetation degradation. Moreover, the socioeconomic data is also unable to reflect the spatial differences characteristic at a fine scale.

The characteristics of climate change and human activities during this period can be used to interpret relative roles of climate change and human activities in vegetation degradation or restoration. From 2001 to 2010, in the eastern parts of North Xinjiang, the climate became more suitable for the growth of vegetation, but the HANPP showed a slight positive trend for the eastern region during this period, which indicated that the negative effects of human activities on vegetation were greater than active restoration efforts, and caused a vegetation degradation from 2001 to 2010. By contrast, in the western and central-southern parts of North Xinjiang, the climate became less suitable for the vegetation restoration from 2001 to 2010, whereas the HANPP showed a slight negative trend for the western and central-southern region during this period, which indicated that the net effects of human activities on vegetation were positive, resulting in a vegetation restoration. Overall, human activities dominated vegetation degradation and vegetation restoration. Our findings show that human activities were the dominant factor that induced vegetation restoration in 61% of the total vegetation restoration. National and local ecological projects and environmental protection policies are considered to be the drivers of this, such as the Grain for Green Program, the Natural Forest Protection Project and the Sloping Land Conversion Project to protect the country's fragile and fragmented environment (Xu *et al.* 2006). The Grain for Green Program launched in 1999 is the most renowned large-scale initiative to restore degraded, desertified and cultivated land on steep slopes through banning grazing and farming. The Natural Forest Protection Project covers 17 provinces (or municipalities), and aims to ban logging in the south-west, to substantially reduce harvests in the north-east and other areas, and to strengthen management and protection in all natural forest regions (Xu *et al.* 2006). The Sloping Land Conversion Project was officially launched by the central government in 2000, involving 25 provinces (or municipalities) of China. These active human activities have produced positive effects on the vegetation restoration in the research region, which suggests that programmes like these are effective, at least for restoring vegetation. Our study indicates these projects significantly enhance terrestrial ecosystem vegetation productivity. This study may be useful for human management of mitigating vegetation degradation and benefit the ecological restoration programmes to contrapuntally implement ecological restoration project and reduce human disturbances, as well as to control and combat degradation in future.

Conclusion

Human activities were the dominant factor in causing vegetation degradation compared with climate change in the study region from 2001 to 2010. In contrast, the total vegetation restoration was also dominated by human activities compared with climate change. Human activities played a key role in vegetation restoration in the central-southern and western areas of North Xinjiang, and in vegetation degradation in the eastern and north-western and north-eastern areas of the study region from 2001 to 2010. By contrast, climate change dominated vegetation restoration in the south-eastern areas of the research region and vegetation degradation in the south-western and central-southern areas.

Four different outcomes were observed in different vegetation types. First, climate dominated degradation expansion and human activities dominated vegetation restoration in forest. Second, both the degradation and restoration were dominated by human activities in grassland. Third, degradation was dominated by human activities and vegetation restoration by climate in desert. Fourth, degradation was dominated by both human activities and climate change and vegetation restoration was dominated by human activities in cropland and crop/natural vegetation mosaic. Vegetation restoration of grassland and forest was dominated by human activities and attributed to vegetation restoration projects such as afforestation and returning farmland to forestland or grassland. It was noteworthy that climate change did not play a positive role in forest restoration over the research period; this was different from the other vegetation types. These results also demonstrated that these ecological restoration projects were effective on alleviating vegetation degradation and promoting vegetation restoration in the southern areas of North Xinjiang.

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