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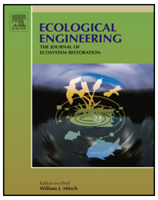

Response of vegetation activity dynamic to climatic change and ecological restoration programs in Inner Mongolia from 2000 to 2012

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A B S T R A C T

To address devastating land desertification and soil erosion and to improve human well-being, central government in China has implemented a number of ecological restoration programs. It is essential to rigorously monitor the dynamic of vegetation activity and evaluate the effectiveness of these programs, not only to provide scientific support for ecosystem monitoring in arid and semi-arid region, but also to assess the efficiency of ecological restoration policy. Taking Inner Mongolia as study area, we used 13 years (2000–2012) of both climatic data and MODIS NDVI data to (1) assess the spatiotemporal vegetation dynamic and map areas of significant vegetation restoration and degradation, (2) analyze the impacts of climatic changes on vegetation activity and map areas where vegetation activity dynamic was significantly affected by climatic change, (3) map main driving forces of significant vegetation restoration or degradation, (4) validate the zones where vegetation significant restoration were mainly impacted by ecological restoration programs with vegetation fractional cover data in 2000 and 2012. Results showed an overall greening (15.38% significant NDVI increasing) and partial degradation (1.64% significant NDVI decreasing) in Inner Mongolia. It was estimated that annual precipitation most strongly and significantly limited vegetation growth over 45.1% of Inner Mongolia, whereas sunlit hours significantly limited growth over 3.37% and air temperature significantly over 0.73% of Inner Mongolia. Among the 15.38% significant greening region, 5.86% was caused by climatic changes, 5.67% was caused by ecological restoration programs, and the other 3.8% was caused by multi-factors. Among the 1.64% significant degradation region, 0.17% was caused by climatic changes and other 1.47% can be explained by human activities, such as population growth and city expansion.

1. Introduction

Arid and semi-arid regions make up about 40% of the earth's land surface and are home to about 20% of the human population (Fernández, 2002). In China, the main arid and semi-arid lands are currently located in north-western parts of the country, including Inner Mongolia, Ningxia autonomous regions, Shanxi, Qinghai, Xinjiang provinces, and other nearby areas (Liu and Diamond, 2005): an estimated 2.62 million km^2 have been affected by desertification at the end of 2009, accounting for 27.3% of China's total land area (State Forestry Administration, 2011). Except Xinjiang province, Inner Mongolia is most seriously affected by desertification, with the desertified land area of 0.62 million km^2 until 2009, accounting for 52.2% of Inner Mongolia's total land area (State Forestry Administration, 2011). The term of desertification in this paper refers to land degradation in the arid, semi-arid and dry sub-humid areas as result of various factors including climatic variation and human activities. The term of sandification in the paper refers to the land degradation characterized by appearance of sand or gravel on ground surface as result of various reasons in all climatic zones (State Forestry Administration, 2011).

The central government has proposed a science-based approach to development designed to realize balanced sustainable development (Ma, 2006). Especially since 2000, there have been rapid and extensive changes in forestry policy in China. Investments in the forestry sector since 2000 have exceeded the total investments during the period 1949–1999 (Wang et al., 2007). In its scale, the number of participants, and the magnitude of the

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investment, China’s afforestation projects are largest in the world (Liu and Diamond, 2005; Uchida et al., 2005; Zhang et al., 2000). The six large-scale ecological restoration programs are most pronounced, including “Beijing–Tianjin Sand Source Control Program”, fourth phase of “Three-north Shelterbelt Forest Construction Project”, “Natural Forest Conservation Program”, “Grain for Green Project”, “Wildlife Protection and Nature Reserve Development Program” and “Fast-Growing and High-Yielding Timber Base Construction Program” (Zhang et al., 2000). Inner Mongolia is the key implementation provinces in the six large-scale ecological restoration programs.

For the first time since the establishment of People's Republic of China, desertification has been reversed, from an annual increase of 3436 km^2 at the end of the 20th century, to the average annual reduction of 7585 km^2 from 1999 to 2004 and annual reduction of 2491 km^2 from 2004 to 2009 (State Forestry Administration, 2005, 2011). As to Inner Mongolia, the average annual reduction of desertified land areas is 3211 km^2 from 1999 to 2004 and 934 km^2 from 2004 to 2009 (State Forestry Administration, 2005, 2011).

Nevertheless, there is an ongoing debate on the effectiveness of the national ecological restoration programs in China as well as in Inner Mongolia. On one hand, numerous researchers and government officials claimed that ecological restoration programs have successfully combated desertification and the vegetation coverage and biomass has been improved (Tian et al., 2014; Wang et al., 2007; Wu et al., 2013; Yin and Yin, 2010; Zhang et al., 2000). Liu et al. (2008) found that the “Natural Forest Conservation Program” and the “Grain to Green Program” have not only increased vegetative cover, enhanced carbon sequestration, and reduced dust to other countries by controlling soil erosion, but also provided important experiences and lessons for other ecosystem service programs in China and many other parts of the world. Wu et al. (2013) evaluated the effectiveness of “Beijing–Tianjin Sand Source Control Program”, and suggested that the vegetation activity in Beijing–Tianjin Sand Source Region has been improved due to the implementation of ecological restoration program. Tian et al. (2014) found that the vegetation coverage in Jungar Banner, Inner Mongolia has been significantly improved as a result of numerous ecological restoration programs. On the contrary, many social scientists and scholars argued that ecological restoration programs in arid and semi-arid regions may not work well (Cao, 2008; Jiang, 2005; Wang et al., 2010). Jiang (2005) believed that the large-scale afforestation in the Three Norths has produced largely unfavorable results. Cao (2008) further asserted that these costly programs have yielded little success thus far and afforestation could lead to increased ecosystem deterioration and wind erosion because it has ignored climatic, pedological, hydrological and landscape factors. Wang et al. (2010) suggested that the importance of “Three-North Shelterbelt Forest Construction Project” seems to have been overstated and there is little unassailable evidence to support those claims that the huge investment in the program has beneficial effects on combating desertification and controlling dust storms.

To some extent, these divergences derived from different judging criteria. In fact, taking vegetation restoration into consideration, the goals of ecological restoration programs are to increase vegetation activity (such as vegetation coverage, biomass, leaf area index and net primary productivity) and enrich the value of ecosystem services provided by vegetation (Cai, 2008). Thus, increasing or decreasing vegetation activity can be utilized to assess the success or failure of ecological restoration programs. Due to the robust relationship between normalized difference vegetation index (NDVI) and vegetation production, NDVI has commonly been used as a proxy of vegetation activity (Boschetti et al., 2013; Jobbágy et al., 2002). The MODIS NDVI products with multiple spatial resolutions (250 m, 500 m and 1 km) and multiple temporal resolutions (8 days, 16 days and 1 month) have always been used for vegetation dynamic research (Fensholt and Proud, 2012; Wu et al., 2013, 2014). In this research, vegetation activity refers to green vegetation cover as determined by MODIS NDVI.

In addition, variations in vegetation and the relationship and interaction of vegetation with climate have become important issues in global change research (Hall-Beyer, 2003; Kawabata et al., 2001; Park and Sohn, 2010; Piao et al., 2006, 2011a,b,c; Wang et al., 2011). Previous studies suggest that climatic factors, such as rainfall, air temperature and solar radiance, is the main factors influencing the vegetation activity and vegetation production in arid and semi-arid regions (Nemani et al., 2003; Yang et al., 2012; Yu et al., 2012; Zhang et al., 2014). Nemani et al. (2003) assesses a climate-driven increase in global terrestrial net primary

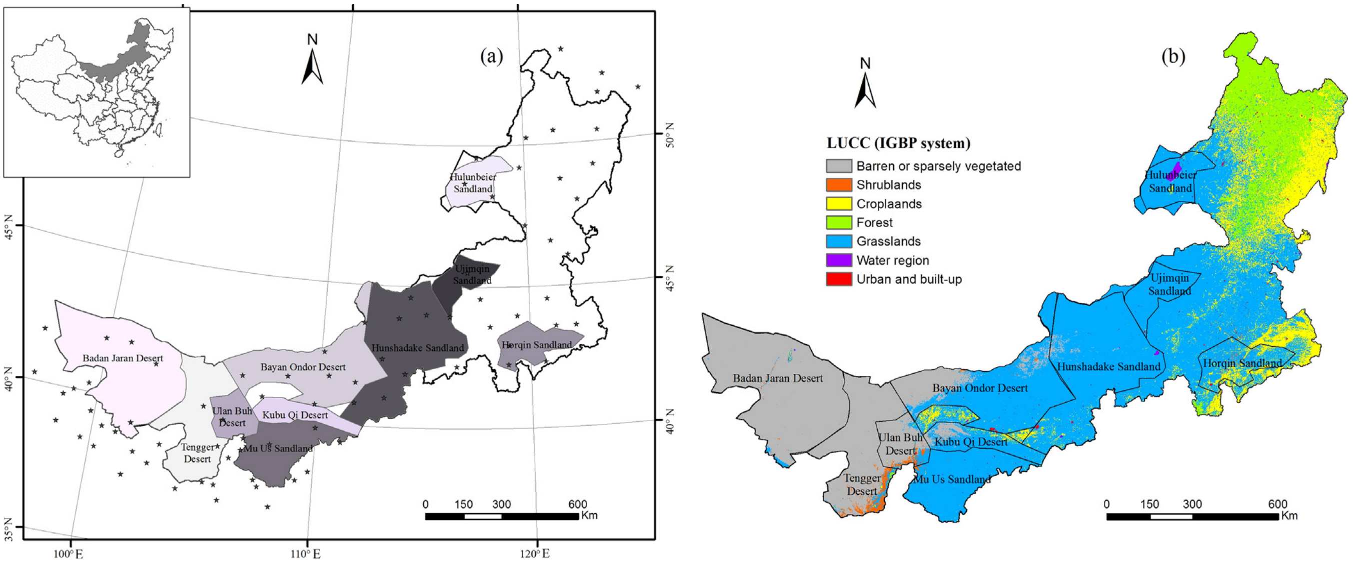

Fig. 1. (a) Location of study area and spatial distributions of these five deserts, five sandlands and 85 ground meteorological stations, and (b) land cover map in Inner Mongolia derived by MODIS MCD12Q1 product in 2012.

production from 1982 to 1999. During the past five decades, the most pronounced warming trend is found in Northern China (Piao et al., 2010). In line with such warming trend, the precipitation pattern has also undergone a substantial change during the past several decades in Northern China (Fang et al., 2005; Park and Sohn, 2010).

A key question is how the vegetation activity has changed in Inner Mongolia under both the climatic change and ecological restoration programs. Satellite vegetation indices, which represent direct observations of the physiologically functioning greenness level by capturing the amount of photo synthetically active radiation absorbed by chlorophyll in green leaves, have allowed the scientific community to further analyze the vegetation activity in their spatial and temporal dimensions and their relation with climate change (Myneni et al., 1995). Nevertheless it is very difficult to separate the effects of climate change and ecological restoration programs on the vegetation activity dynamic in arid and semi-arid regions (Wu et al., 2013). Few detailed and systemic assessments had evaluated the response of vegetation activity dynamic to climatic change and ecological restoration programs in Inner Mongolia. Previous studies investigated the vegetation cover change and its response to climate change and ecological restoration programs in small and limited area of Inner Mongolia (Yang et al., 2012; Tian et al., 2014). Consequently, it is unclear about the spatial distribution of changes in vegetation activity and how climate change and ecological restoration programs have influenced it in Inner Mongolia. So, studies of vegetation activity dynamic and its responses to climatic change and ecological restoration programs with 1 km spatial resolution in whole Inner Mongolia are limited.

In this study, we used the time series climate and NDVI data in combination with the characteristics of vegetation dynamic caused by climate change and ecological restoration programs to distinguish driving forces of vegetation significant restoration and degradation at 1 km spatial resolution. The scientific interests of our research focus on (1) monitoring the spatiotemporal vegetation dynamic and mapping areas of significant vegetation restoration and significant vegetation degradation at 1 km spatial resolution, (2) analyzing the impacts of climatic changes on vegetation activity and mapping areas where vegetation activity dynamic was significantly affected by climatic change at 1 km spatial resolution, (3) separating influence of climate change and

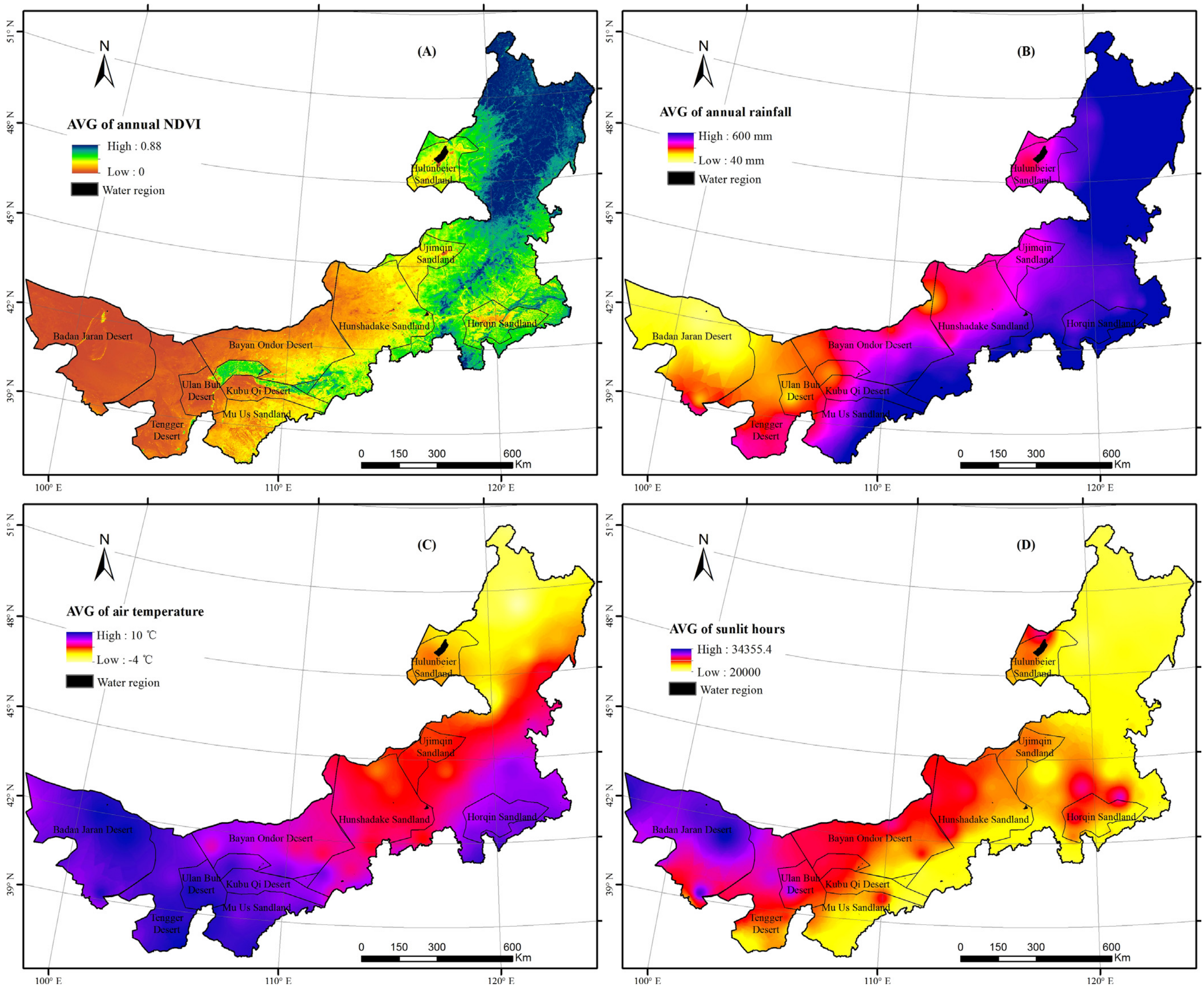

Fig. 2. Spatial patterns of 13-year (2000–2012) averaged (a) annual NDVI, (b) annual precipitation, (c) annual average air temperature and (d) and annual sunlit hours.

ecological restoration programs on vegetation dynamic and mapping main driving forces of significant vegetation restoration or degradation.

2. Study area and datasets

2.1. Study area

Inner Mongolia autonomous region in China, located between 37°N to 53°N latitude and 96°E to 126°E longitude (Fig. 1) was selected as the study area. Inner Mongolia is located in the Eurasia internal with mean elevation of 1014 m. The total area of Inner Mongolia is 1.18 million, which occupies 12.3% of China's land area (the third largest province of China). Most of the study area is under influence of East Asian monsoon, which makes it the temperate continental monsoon climate zone. And climate of the study area is characterized by a strong seasonality and variability of rainfall, with a long dry season in winter and a short summer rainy period. Mean annual average air temperature increases from −4 °C in the northeast to 10 °C in the southwest (Fig. 2c) and mean annual sunlit hours increases from 2400 h in the northeast to 3422 h in the southwest (Fig. 2d). Inner Mongolia is marked by a steep east-west gradient in mean annual rainfall, with mean annual precipitation less than 150 mm in the west to mean annual precipitation more than 600 mm in the east (Fig. 2b). 70% of the mean annual precipitation is concentrated in June, July and August. Spring and autumn rainfall accounts for 28%, winter rainfall accounts for 2% (You et al., 2002).

The east-west gradient of precipitation causes a gradual change of vegetation from desert in the west to forests dominated by tree species in the east (Fig. 1b). According to the MODIS Land Cover Type 1 data defined by the International Geosphere Biosphere Programme (IGBP), grasslands accounts for 51.2%, barren or sparsely vegetated accounts for 27.9%, croplands accounts for 7.4%, mixed forest accounts for 5.2%, cropland/natural vegetation mosaic accounts for 2.6%, woody savannas accounts for 2.3%, open shrublands accounts for 1.1%, and other land types (Evergreen broadleaf forest, snow and ice, permanent wetlands, evergreen needleleaf forest, closed shrublands, urban and built-up, water, savannas, deciduous needleleaf forest and deciduous broadleaf forest) account for 2.3%.

Inner Mongolia, with very high rates of barren land and a lot efforts been put into stopping desertification, is one of the key areas of combating desertification and sandification in China. There are five deserts (Kubu Qi desert with an area of about 26,984 km^2, Bayan Ondor desert with an area of about 105,184 km^2, Badan Jaran desert with an area of about 135,032 km^2, Tengger desert with an area of about 76,845 km^2 and Ulan Buh desert with an area of about 24,422 km^2) and five sandlands (Mu Us sandland with an area of about 55,683 km^2, Hunshadake sandland with an area of about 127,670 km^2, Horqin sandland with an area of about 32,947 km^2, Hulunbeier sandland with an area of about 29,200 km^2 and Ujimqin sandland with an area of about 26,017 km^2) in Inner Mongolia (Jing, 2004). The distribution of these five deserts and sandlands are shown in Fig. 1a. We investigated the vegetation activity dynamic and its response to climatic change and ecological restoration programs in Inner Mongolia, and in the five deserts and five sandlands in Inner Mongolia.

2.2. Satellite data with time series

The MODIS product MOD13A2 NDVI data from 2000 to 2012 were obtained and used to estimate the dynamic of vegetation activity. The MOD13A2 vegetation indices products are computed from atmospherically corrected bi-directional surface reflectance, which have been masked for water, clouds, heavy aerosols, and cloud shadows. It is provided every 16 days using the maximum value composite method, which minimized cloud contamination, atmospheric effects and solar zenith angle effects at 1 km spatial resolution (Holben, 1986). The blue, red, and near-infrared reflectance, centred at 469 nm, 645 nm, and 858 nm, respectively are used to determine daily vegetation indices.

The serial correlation of temporal data is a well know problem that can strongly bias the detection of trend in NDVI time series

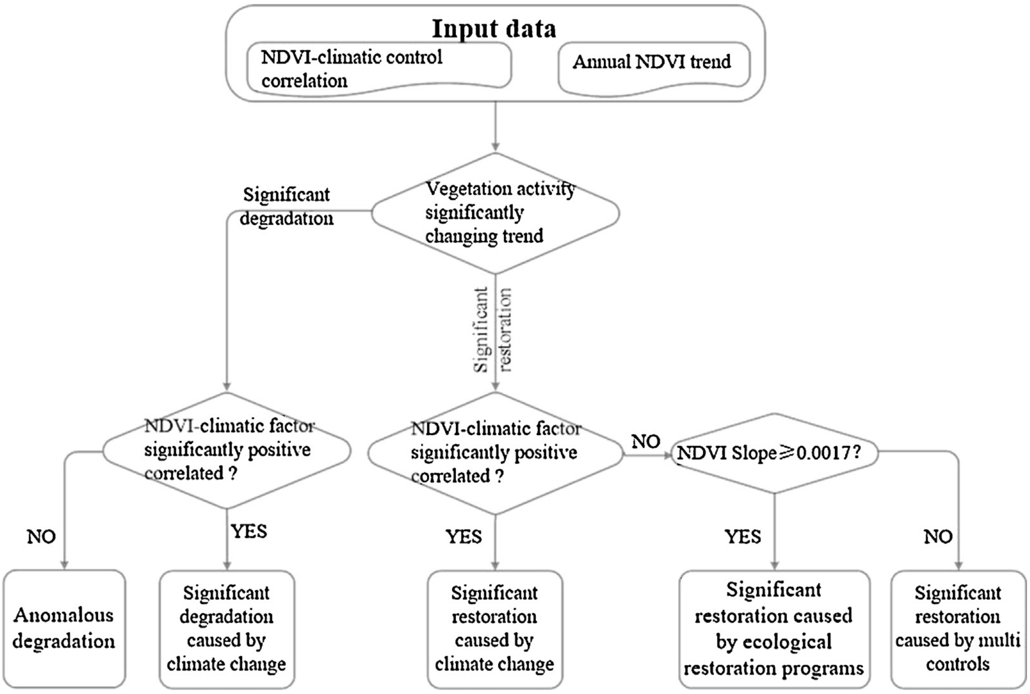

Fig. 3. Flowchart used to identify main driving forces of vegetation significant restoration and degradation.

analysis (De Beurs and Henebry, 2005; Eklundh, 1998). In this study, we conducted an integrated data, like Bai et al., 2008 and Boschetti et al. (2013), on the base of 16-day NDVI in order to minimize the risk of serial correlation in the data before performing statistical analysis. The syntheses value produced by the 16-day NDVI values over the period from the 177th day to the 288th day in one year were used as annual NDVI to indicate annual vegetation activity. Numerous investigators have used syntheses NDVI due to the effectiveness in detecting and quantifying interannual changes in vegetation productivity (Fensholt and Rasmussen, 2011; Fensholt et al., 2006; Ricotta et al., 1999; Seaquist et al., 2009).

2.3. Climate data with time series

The ground observed annual rainfall, annual average air temperature and annual sunlit hours data from 85 spatially well-distributed meteorological stations in and out of the Inner Mongolia covering the period from 2000 to 2012 were obtained from the China meteorological data sharing service system (http://cdc.cma.gov.cn/home.do) (Fig. 1a). The inverse distance weighted (IDW) interpolation method was used to get the annual precipitation, annual average air temperature and annual sunlit hours in the whole study area with a spatial resolution of 1 km (Fig. 2b–d).

2.4. Ancillary data

For the landscape level analysis, the MODIS Land Cover Type product (MCD12Q1) with spatial resolution of 500 m in 2012 was collected. MCD12Q1 contains five classification schemes, which describes land cover properties derived from observations spanning a year's input of Terra and Aqua MODIS data. In this study, the first classification scheme (also the primary land cover scheme) of MCD12Q1 was used, and it identifies 17 land cover classes (11 natural vegetation classes, 3 developed and mosaicked land classes, and three non-vegetated land classes) defined by the International Geosphere Biosphere Programme (IGBP). The 17 land cover classes were grouped into 7 types, including forest, shrublands, grasslands, croplands, barren or sparsely vegetated, urban and built-up, and water (Fig. 1b). And the water region is

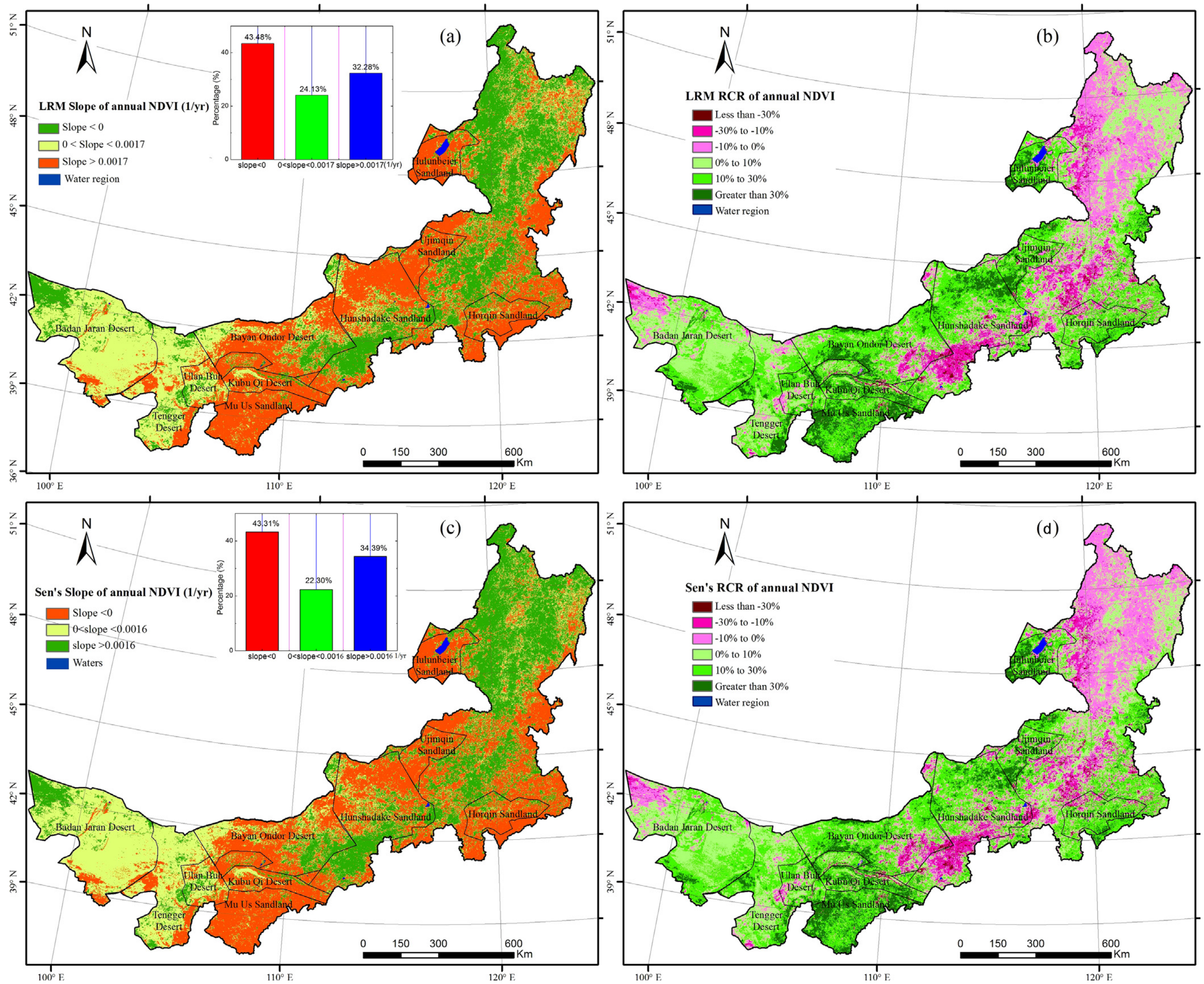

Fig. 4. (a) Slope of annual NDVI from 2000 to 2012 calculated by LRM (0.0017 year^{-1} indicates the mean value of Inner Mongolia), (b) slope of annual NDVI from 2000 to 2012 calculated by Sen's non-parametric method (0.0016 year^{-1} indicates the mean value of Inner Mongolia), (c) RCR of annual NDVI from 2000 to 2012 calculated by LRM, and (d) RCR of annual NDVI from 2000 to 2012 calculated by Sen's non-parametric method.

masked out, where the vegetation activity is considered as no change.

In addition, we digitized the deserts and sandlands distribution map in Inner Mongolia (Jing, 2004) to obtain information on distributions of these five deserts and five sandlands and transferred to vector maps by using ArcGIS 10.0 (Fig. 1a).

3. Methods

3.1. Slope and relative change rate of NDVI

3.1.1. Linear regression method (LRM)

The linear regression method was applied to detect and analyse annual NDVI trend in the time series. The slope estimated by LRM indicated the mean temporal change in the studied variable. Positive slopes indicate increasing trends, which is also called vegetation restoration in this research, while negative slopes indicate decreasing trends, which is also called vegetation degradation in this research (Fensholt and Proud, 2012; Ma and Frank, 2006; Piao et al., 2011a,b,c; Stow et al., 2003). LRM is described as follows:

$$y = a + bx + e \tag{1}$$

where y is the NDVI value of each year from 2000 to 2012, x is 2000 to 2012, a is the intercept, b is slope of annual NDVI and e is random error.

3.1.2. Sen's non-parametric method (Sen)

In addition to the linear regression method, Sen's method was applied to estimate the slope of NDVI in Inner Mongolia as comparison. If a linear trend was present in a time series, then the true slope (change per unit time) could be estimated using a simple nonparametric procedure developed by Sen (Sen, 1968). Sen's slope estimator did not require the data to be distributed normally. This method is resistant to outliers and therefore is more suitable for processing short or noisy series with respect to ordinary linear square regression. Therefore, it has been gradually applied in vegetation dynamics studies (Cai, 2008; Fernandes and G Leblanc, 2005; Wu et al., 2013). The magnitude of the slope was assessed using the Sen's non-parametric method (Sen, 1968). As well as with linear regression method, positive values of Sen's slope indicated increasing trends, while negative values of Sen's slope indicated decreasing trends.

Sen's slope, was computed as follows:

$$\text{Sen'sslope} = \text{Median}(Q_i) = \text{Median}\left(\frac{x_j - x_i}{j - i}\right) \text{for} i = 1, \cdots, N \tag{2}$$

where x_i and x_j are the NDVI values at time i and j ($j > i$), respectively. Median was the median function. If N is odd, then Sen's slope is computed by:

$$\text{Sen'sslope} = \text{sort}(Q)_{(N+1)/2} \tag{3}$$

If N is even, then Sen's slope is computed by:

$$\text{Sen'sslope} = \frac{1}{2}(\text{sort}(Q)_{N/2} + \text{sort}(Q)_{N+2/2}) \tag{4}$$

3.1.3. Relative changing rate (RCR)

Taking the differences between regions into consideration, the relative change (increase or decrease) in the rate of annual NDVI from 2000 to 2012 was estimated like Wu et al. (2013) as follows:

$$\text{RCR} = \frac{\text{slope}}{\text{mean}} \times 13 \times 100\% \tag{5}$$

where RCR is the relative changing rate, slope is the slope of annual NDVI estimated by LRM and Sen's method, mean is the average of annual NDVI over the 13 years from 2000 to 2012.

3.2. NDVI-climate factors correlation analysis

Temperature, radiation, and water interact to impose complex and varying limitations on vegetation activity in different parts of the world (Churkina and Running, 1998). To provide a comprehensive interpretation of climate change impacts on plant growth, we first constructed a map of the relative contributions of climatic controls on vegetation activity in Inner Mongolia. The NDVI-rainfall, NDVI-air temperature and NDVI-sunlit hours Pearson correlation coefficient (R) and significant level (p) between annual NDVI and each climatic control over the 13 years study period were calculated with 1 km spatial resolution respectively by programming in MATLAB. R indicates the linear relationship between two variables. p indicates the significant correlation level between two variables. If the R value between NDVI and climatic control is positive and the p value between NDVI and climatic control is lower than 0.05, we believe the NDVI-climatic control is significantly positive correlated.

3.3. Driving forces analysis

According to the influence of climate change and ecological restoration programs on vegetation activity dynamic, the threshold segmentation method was used to separate influence of climate change and ecological restoration programs. If NDVI-climatic control is significantly positive correlated, then climate change is defined as the main driving force of vegetation activity dynamic. If ecological restoration program is the main driving force for vegetation restoration, then the land use of that region should change from non-vegetation area to vegetation area or from sparse

Table 1
Mean NDVI value, slope of annual NDVI from 2000 to 2012, relative changing rate (RCR) of annual NDVI by two trend analysis methods in Inner Mongolia, five deserts and five sandlands.

Area	Mean NDVI	Slope (LRM) (yr^{-1})	RCR (LRM) (%)	Slope (sen) (yr^{-1})	RCR (sen) (%)
Ulan Buh Desert	0.12	0.0015	14.42	0.0014	13.36
Ujimqin Sandland	0.35	0.0053	20.56	0.0050	20.55
Tengger Desert	0.11	0.0011	11.32	0.0010	10.75
Mu Us Sandland	0.25	0.0055	28.24	0.0056	29.50
Kubu Qi Desert	0.21	0.0043	26.53	0.0039	24.72
Hunshadake Sandland	0.31	0.0017	9.04	0.0013	7.32
Horqin Sandland	0.41	0.0039	11.27	0.0039	12.25
Bayan Ondor Desert	0.21	0.0018	12.56	0.0015	12.14
Badan Jaran Desert	0.08	0.0006	7.73	0.0006	8.61
Hulunbeier Sandland	0.36	0.0049	22.20	0.0052	31.19
Inner Mongolia	0.37	0.0017	8.93	0.0016	9.22

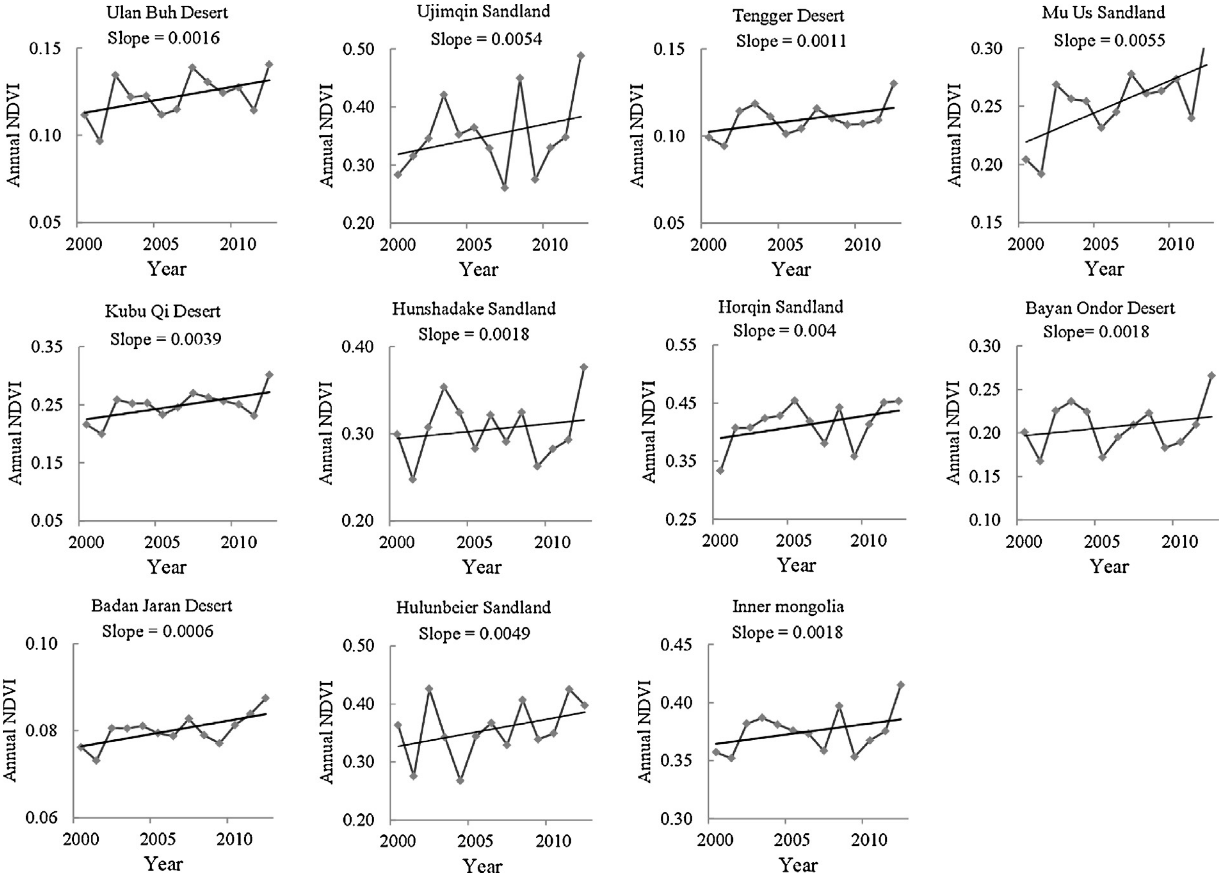

Fig. 5. Line chart indicating the trend of annual NDVI in Inner Mongolia, five deserts and five sandlands from 2000 to 2012.

vegetation to denser vegetation, which means the vegetation activity should be significantly increased and annual NDVI slope greater than the mean value of Inner Mongolia.

In order to identify regions where annual vegetation change is mainly influenced by ecological restoration programs, we analysed the temporal dynamics of annual NDVI over the 13 year study period in correspondence with areas where correlation between annual NDVI and climate change is not significant. We identified five categories of driving forces according to the flowchart in Fig. 3: (1) "significant vegetation restoration caused by climate change" where in the analysed time period NDVI increased significantly (95% significant level) and NDVI-climatic control is significantly positive correlated (95% significant level); (2) "significant vegetation degradation caused by climate change" where in the analysed time period NDVI decreased significantly and NDVI-climatic control is significantly positive correlated; (3) "significant vegetation restoration caused by ecological restoration programs" where in the analysed time period NDVI increased significantly, while NDVI-climatic control is not significantly positive correlated and annual NDVI slope greater than the mean value of Inner Mongolia; (4) the other vegetation significant restoration regions are called "significant vegetation restoration caused by multi factors", underlying that the influence may be not only climate change and ecological restoration programs, but also other drivers, such as agricultural land-use etc. and (5) the other vegetation significant degradation regions are called "anomalous degradation", which can be explained by population growth or city expansion. The reason for listing anomalous degradation regions is to clearly map regions where vegetation activity significantly degraded and climate change is not the main driving forces.

Table 2
Percentages of the annual NDVI increased and decreased, significant greening (SG), significant degradation (SD) and not significant regions in Inner Mongolia, five deserts and five sandlands.

Area	Increased (%)	Decreased (%)	SG (%)	SD (%)	Not significant (%)
Ulan Buh Desert	79.77	20.23	16.86	0.19	82.95
Ujimqin Sandland	90.43	9.57	3.48	0.25	96.27
Tengger Desert	83.74	16.26	15.75	0.07	84.18
Mu Us Sandland	97.40	2.60	48.20	0.16	51.63
Kubu Qi Desert	92.81	7.19	37.39	1.81	60.80
Hunshadake Sandland	68.87	31.13	3.42	0.98	95.61
Horqin Sandland	78.09	21.91	27.50	1.21	71.28
Bayan Ondor Desert	78.16	21.84	4.84	0.22	94.95
Badan Jaran Desert	77.17	22.83	38.29	0.73	60.99
Hulunbeier Sandland	82.36	17.64	5.32	2.80	91.89
Inner Mongolia	56.52	43.48	15.38	1.64	82.98

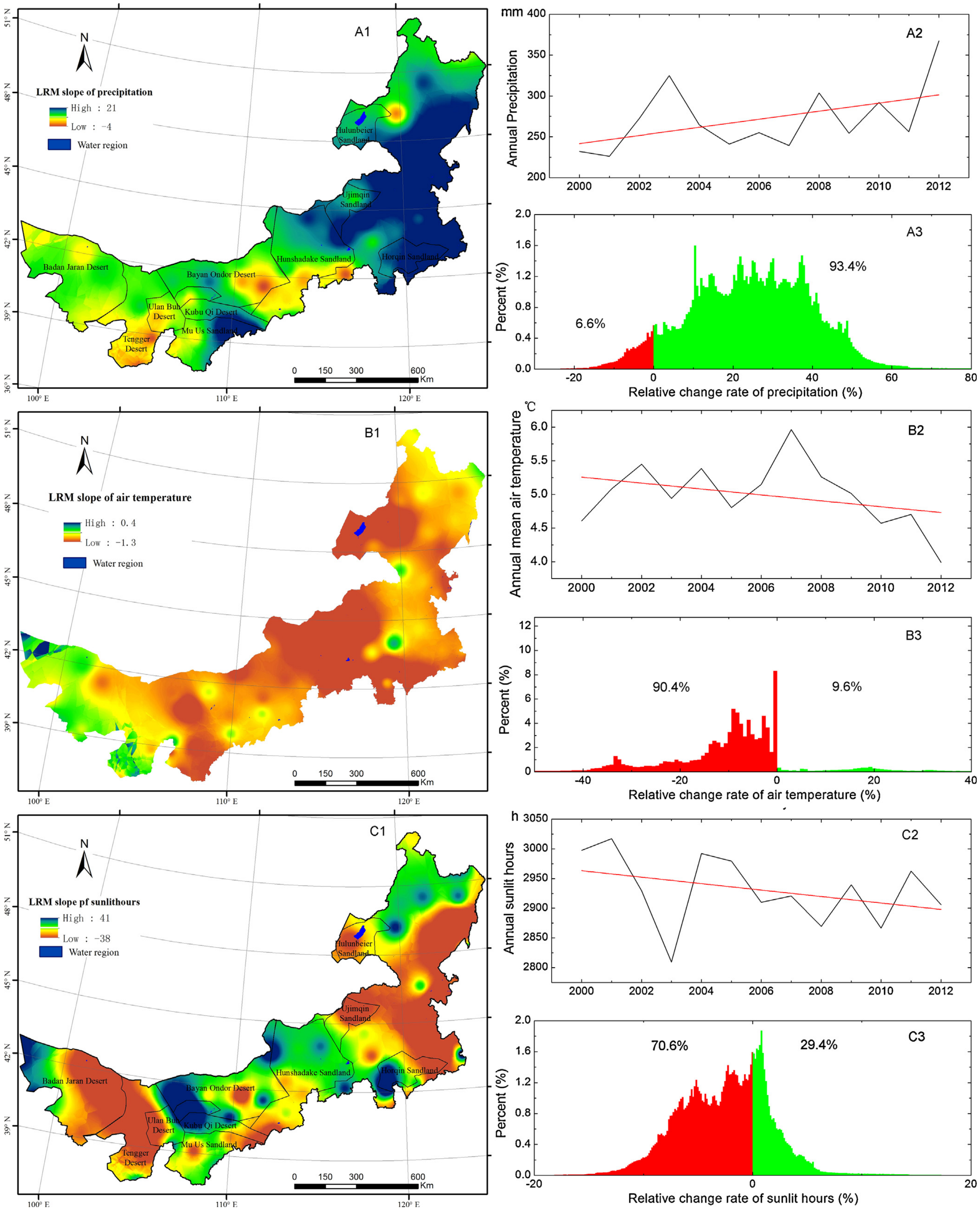

Fig. 6. (A1)–(C1), slope of annual precipitation, annual mean air temperature and annual sunlit hours from 2000 to 2012 calculated by LRM method; (A2)–(C2), line chart indicating the average trend of annual precipitation, annual mean air temperature and annual sunlit hours from 2000 to 2012; (A3)–(C3), histogram of relative change rate of annual precipitation, annual mean air temperature and annual sunlit hours from 2000 to 2012.

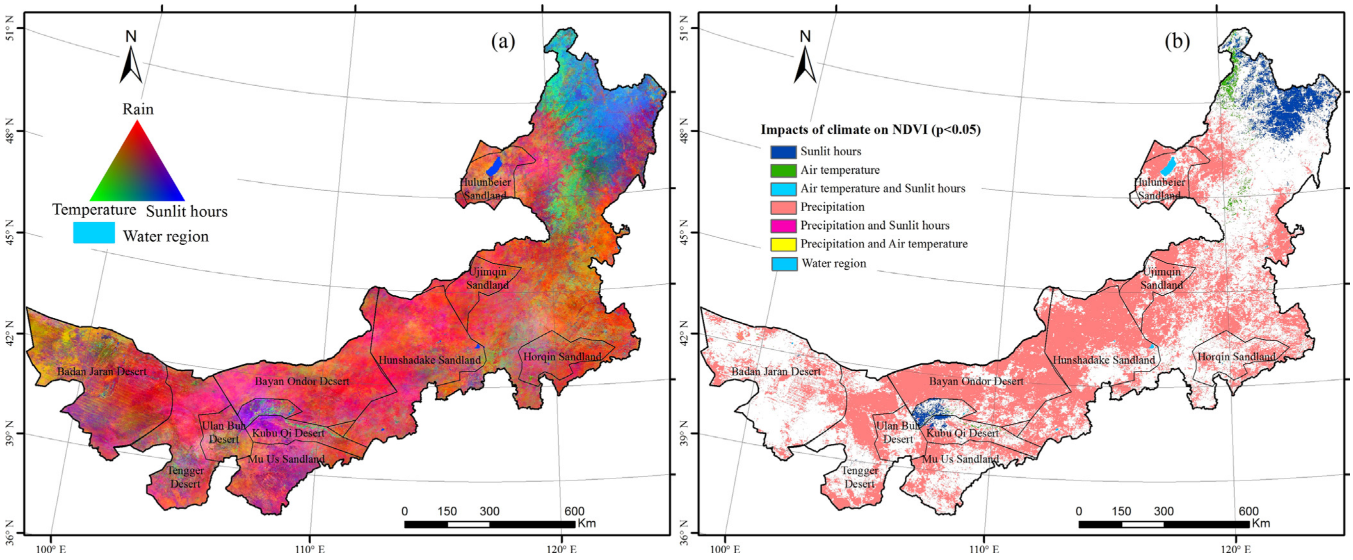

Fig. 7. Geographic distribution of climatic constraints to plant growth derived from annual climate statistics from 2000 to 2012.

4. Results

4.1. Trend analysis of annual NDVI

4.1.1. Temporal dynamics and spatial heterogeneity analysis

The average annual NDVI from 2000 to 2012 was 0.37 for the overall Inner Mongolia and is marked by a steep east–west decreasing gradient (Fig. 2a) which is resulted from the decreased annual rainfall from east to west (Fig. 2b).

Fig. 4 indicates the trend of annual NDVI in Inner Mongolia from 2000 to 2012 using LRM and Sen's non-parametric method. For each pixel, the slope and relative changing rate were calculated by programming in MATLAB. The increasing trend in annual NDVI was observed over the entire study area, indicating that the overall state of vegetation in the area increased obviously from 2000 to 2012.

As to the overall study area, the slope of annual NDVI by LRM and Sen's non-parametric method was 0.0017 year^{-1} and 0.0016 year^{-1}, with RCR of 8.93% and 9.22%, respectively. As to the spatial distributions of slope and RCR for different methods, comparisons between Fig. 4a–d demonstrates that the annual NDVI trend estimated by these two methods coincides well. These indicate that the vegetation activity dynamic estimated by LRM and Sen's non-parametric method are almost the same. Comparisons between Figs. 1b and 4 show that the vegetation degradation pixels mainly distributed in the northeast and central regions of Inner Mongolia with a relatively high cover by natural vegetation and the land use mainly dominated by forest. A small part of the west barren land also shows vegetation degradation, which may result from extreme drought in 2005, 2009 and 2011. Regions where NDVI increasing rate is higher than the mean value of Inner Mongolia are mainly distributed in the grasslands area. Regions where NDVI increasing rate is lower than the mean value of Inner Mongolia are mainly distributed in the west barren land area.

The percentage of annual NDVI increased was 56.52% for LRM, and the percentage of significant vegetation restoration and degradation was 15.38% and 1.64% respectively (Fig. 8a). The significant vegetation restoration area is mainly distributed in

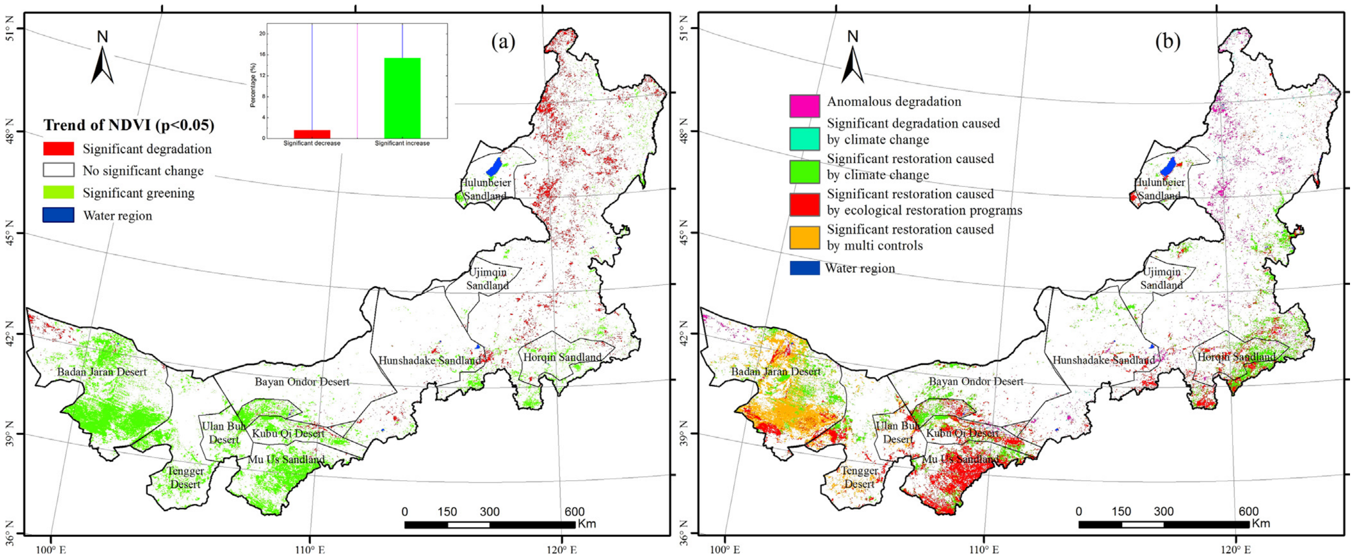

Fig. 8. (a) Distribution of significant greening and significant degradation ($p < 0.05$), and (b) distribution of driving forces for vegetation significant greening and significant degradation.

Table 3
Percentages of regions where vegetation activity dynamic is significantly correlated with annual precipitation, annual mean air temperature and annual sunlit hours in Inner Mongolia, five deserts and five sandlands.

	Precipitation	Air temperature	Sunlit hours	Climatic factors
Ulan Buh Desert	48.06%	0.09%	0.40%	48.54%
Ujimqin Sandland	74.31%	0.02%	0.01%	74.34%
Tengger Desert	52.72%	0.02%	0.07%	52.82%
Mu Us Sandland	41.03%	0.01%	0.04%	41.08%
Kubu Qi Desert	48.24%	1.09%	5.34%	54.48%
Hunshadake Sandland	73.13%	0.03%	0.02%	73.19%
Horqin Sandland	39.40%	0.15%	0.01%	39.59%
Bayan Ondor Desert	78.41%	0.01%	0.06%	78.49%
Badan Jaran Desert	25.20%	0.07%	0.03%	25.27%
Hulunbeier Sandland	56.01%	0.07%	0.25%	56.35%
Inner Mongolia	45.11%	0.73%	3.37%	49.19%

western Inner Mongolia dominated by barren land and grassland. The significant vegetation degradation area is mainly distributed in eastern Inner Mongolia dominated by forest.

4.1.2. NDVI trend analysis in the five deserts and five sandlands

These five deserts and five sandlands mainly distribute in the west and central part of Inner Mongolia, where the annual rainfall is low (always lower than 400 mm) (Figs. 1b and 2b). Comparisons between the mean annual NDVI from 2000 to 2012 indicate that the mean NDVI values of these five deserts and five sandlands are all lower than the mean value of Inner Mongolia, which mainly attributed to the low annual rainfall (Table 1,Fig. 5).

Due to the consistency of NDVI trend estimated by LRM and Sen's non-parametric method, we just analyse the results derived by LRM method for simpleness. The annual NDVI trends for all deserts and sandlands increased, with the largest slope in Mu Us Sandland (0.0055 year^{-1}) followed by Ujimqin Sandland (0.0053 year^{-1}), Hulunbeier Sandland (0.0049 year^{-1}) and Kubu Qi Desert (0.0043 year^{-1}). The lowest slope was in Badan Jaran Desert (0.0006 year^{-1}), followed by Tengger Desert (0.0011 year^{-1}) and the slope values were lower than the mean slope value in Inner Mongolia (0.0017 year^{-1}). The highest RCR is also in Mu Us Sandland (28.24%), followed by Kubu Qi Desert (26.53%), Hulunbeier Sandland (22.2%) and Ujimqin Sandland (20.56%). The lowest RCR was in Badan Jaran Desert (7.73%), followed by Hunshadake Sandland (9.04%), and only the RCR value of Badan Jaran Desert is lower than the mean RCR value of Inner Mongolia. As to the percentage of annual NDVI increased in each deserts and sandlands, the values of five deserts and five sandlands are all higher than the mean value of Inner Mongolia. Nevertheless, the percentage of increased annual NDVI in Mu Us Sandland, Kubu Qi Desert and Ujimqin Sandland are higher than 90%, the percentage of increased annual NDVI in Tengger Desert and Hulunbeier Sandland are higher than 80% and the percentage of significant greening in Mu Us Sandland, Kubu Qi Desert and Badan Jaran Desert are higher than 35%. Results show that although the drought climate in these five deserts and five sandlands, the vegetation activity in these regions have been significantly increased Table 2.

4.2. Trend analysis of climatic factors

Fig. 6 indicates the trend of annual precipitation, annual mean air temperature and annual sunlit hours in Inner Mongolia from 2000 to 2012 using LRM. For each 1 km pixel, the slope was calculated by programming in MATLAB. The increasing trend in annual precipitation was observed over the entire study area, which is the same with NDVI trend. The percentage of annual precipitation increased was 93.4%, annual mean air temperature increased was 9.6%, and annual sunlit hours increased was 29.4%.

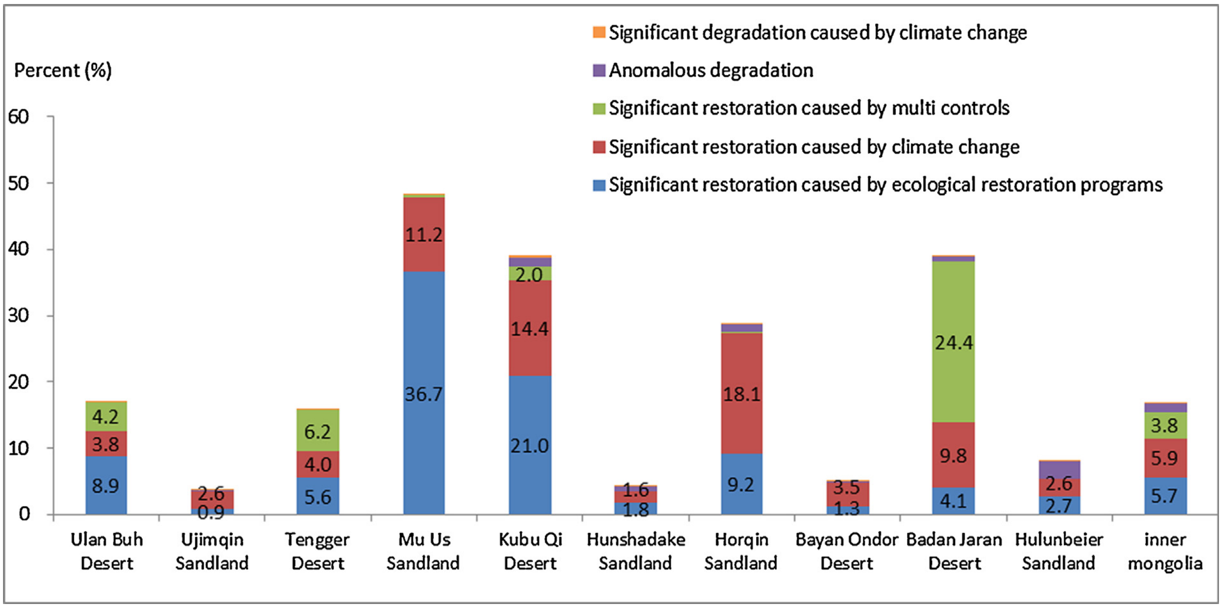

Fig. 9. Percentage of driving forces for vegetation significant restoration and degradation in Inner Mongolia, five deserts and five sandlands (For interpretation of the references to color in the text, the reader is referred to the web version of this article.).

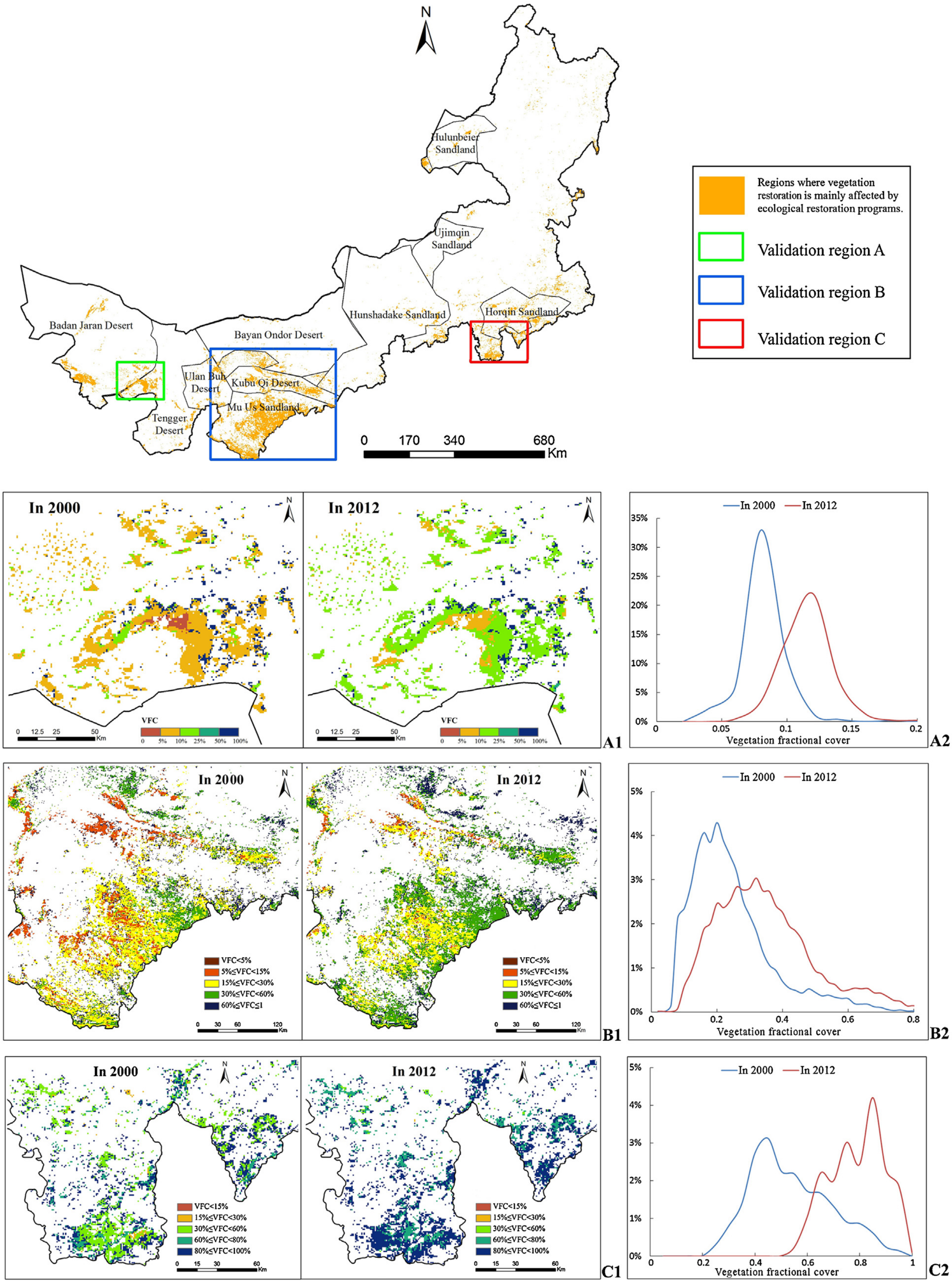

Fig. 10. Three regions where vegetation significant restoration is mainly caused by ecological restoration programs (top) in correspondence of vegetation fractional cover in 2000 (left column), 2012 (middle column) and probability distribution of vegetation fractional cover in 2000 and 2012 (right column).

4.3. Impacts of climatic changes on NDVI

4.3.1. Impact of climate change on vegetation activity dynamic in Inner Mongolia

To provide a comprehensive interpretation of climate change impacts on plant growth, we first constructed a map of the relative contributions of climatic controls on vegetation activity. Fig. 7(a) is the RGB composite image, where R, G, B indicates the R value between NDVI–precipitation, NDVI–air temperature and NDVI–sunlit hours respectively. Fig. 7(b) is processed by overlapping the areas where NDVI is significantly correlated with precipitation, air temperature and sunlit hours respectively.

We estimated that annual precipitation most strongly and significantly limits vegetation growth over 45.1% of Inner Mongolia, whereas sunlit hours significantly limits growth over 3.37% at some region of the northeast Inner Mongolia, and air temperature significantly over 0.73% at a small part of the northeast Inner Mongolia. Our research coincides with previous studies, which also indicate precipitation is a main factor affecting the vegetation activity in arid and semi-arid regions (Yang et al., 2012; Yu et al., 2012; Zhang et al., 2014).

Pixels mainly affected by annual precipitation frequently appear in central part of Inner Mongolia (grasslands area as is shown in Fig. 1b), where the annual rainfall and annual NDVI are in the middle level of Inner Mongolia.

4.3.2. Impact of climate change on vegetation activity dynamic in the five deserts and five sandlands

Consistent with Inner Mongolia, precipitation influence vegetation activity at most regions of the five deserts and five sandlands. And precipitation most strongly influence vegetation activity in Bayan Ondor Desert (78.41%), followed by Ujimqin Sandland (74.31%) and Hunshadake Sandland (73.13%) Table 3.

4.4. Driving forces identification

4.4.1. Distribution of driving forces

Processes of vegetation degradation and greening are complex and related to multiple causes. In this section, we illustrate the distribution of driving forces for vegetation significant restoration and degradation in Inner Mongolia. Among the 15.38% significant greening region, 5.86% was caused by climatic changes, 5.67% was caused by ecological restoration programs, and the other 3.8% caused by multi-factors. Among the 1.64% significant degradation region, 0.17% was caused by climatic changes and other 1.47% was anomalous degradation which can be explained by human factors, such as population growth and city expansion, whose level reaches the ecosystem carrying capacity.

Comparisons between Figs. 1b, 2a and 8b show that the anomalous degradation pixels occur mainly in forested area (east of Inner Mongolia), where the annual rainfall and annual NDVI is higher than other regions in Inner Mongolia. Pixels where vegetation significant restoration are mainly affected by ecological restoration programs frequently occur in barren or sparsely vegetated area, where the annual rainfall and annual NDVI is lower than east of Inner Mongolia.

4.4.2. Driving forces in the five deserts and five sandlands

Fig. 9 reports statistics of occurrence of significant vegetation restoration caused by ecological restoration programs (blue), significant vegetation restoration caused by climate change (red), significant vegetation restoration caused by multi controls (green), anomalous degradation (purple) and significant vegetation degradation caused by climate change (yellow) in Inner Mongolia, five deserts and five sandlands. Distribution of driving forces in each desert and each sandland differs a lot. The percentage of pixels where significant vegetation restoration is mainly caused by ecological restoration programs is highest in Mu Us Sandland (36.69%), followed by Kubu Qi Desert (20.96%). The percentage of pixels where significant vegetation restoration is mainly caused by climate change is highest in Horqin Sandland (18.13%), followed by Kubu Qi Desert (14.39%) and Mu Us Sandland (11.18%). In Badan Jaran Desert, 24.37% shows vegetation significant restoration caused by multi controls. The percentage of pixels where significant vegetation degradation is mainly caused by climate change is lower than 0.5% in every sandland and desert, and the anomalous degradation area lower than 3%.

4.4.3. Data interpretation

In order to prove the reliability of our analysis and further evaluate the impacts of ecological restoration program on vegetation activity, analysis of the regions where vegetation significant restoration is mainly caused by ecological restoration programs was conducted. Fig. 10, top, shows the distribution of three validation regions. Validation region A is distributed at the border of Tengger Desert and Badan Jaran Desert, validation region B is mainly distributed in Mu Us Sandland and Kubu Qi Desert, and validation region C is distributed in the south of Horqin Sandland.

If ecological restoration programs are the main driving force of vegetation restoration, the region should change from non-vegetation area to vegetation areas or from sparse vegetation cover to denser vegetation cover. Fig. 10 indicates that the land use in validation region A has changed from non-vegetation areas to vegetation areas, the land use in validation region B has changed from sparse vegetation to dense vegetation and the vegetation in validation region C has become much denser. Hence, the regions where vegetation significant restoration were mainly caused by ecological restoration programs extracted by our method are reliable.

Moreover, Lee and Sohn (2011) examined the trends in dust over Mongolia and China. They found that an increasing trend of dust occurred in Mongolia, while a decreasing trend of dust events occurred in China. Hence, the ecological restoration programs have reached good results.

5. Discussion and conclusion

The results indicate that the vegetation activity in Inner Mongolia has been improved in most regions, and decreased in partial locations from 2000 to 2012. Based on the above analysis, we draw the following nine detailed conclusions.

1) The increasing trend in annual NDVI was observed over Inner Mongolia, with an overall greening (15.38% show significant restoration) and partial degradation (1.64% show significant degradation) in Inner Mongolia.
2) The vegetation restoration in these five deserts and five sandlands are obvious.
3) The anomalous degradation pixels occur mainly in forested area (east of Inner Mongolia) where NDVI and annual precipitation are higher and natural forest cover is higher.
4) Vegetation activity dynamics estimated by LRM and Sen's method are almost the same.
5) NDVI-climatic controls correlation analysis estimated that annual precipitation most strongly and significantly limits vegetation growth over 45.1% of Inner Mongolia, whereas sunlit hours significantly limits growth over 3.37% and air temperature significantly over 0.73% of Inner Mongolia.
6) Among the 15.38% significant greening region, 5.86% was caused by climatic changes, 5.67% was caused by ecological restoration programs and the other 3.8% caused by multi-factors, indicating that ecological restoration programs and

annual precipitation are the two leading driving forces for vegetation restoration in Inner Mongolia.

7) Among the 1.64% significant degradation region, 0.17% was caused by climatic changes and other 1.47% can be explained by human factors, such as population growth and city expansion.
8) The largest annual NDVI slope occurs in Mu Us Sandland (0.0055 year^{-1}) and the percentage of pixels where vegetation significant restoration is mainly affected by ecological restoration programs is highest in Mu Us Sandland (36.7%), indicating that the ecological restoration programs in Mu Us Sandland have largely improved the vegetation activity.
9) Although the vegetation activity in Inner Mongolia has been improved obviously in the past 12 years, there are still large areas of desertified or sandified lands. And areas vulnerable to sandification are located in the western and northern Inner Mongolia, with low NDVI and annual precipitation (Fig. 2).

These findings will enrich our knowledge about the impact of ecological restoration programs on vegetation activity in arid and semi-arid regions and will support a scientific basis for the implement and management of ecological restoration programs.

Meanwhile, the area in western and northern China is still in preliminary recovery with weak self-regulation capability, poor stability, thus difficult to form steady ecological system in a short period (State Forestry Administration, 2011). Further efforts should be made on pushing forward ecological project implementation, optimizing policy mechanism and strengthening the continuous monitoring of vegetation activity dynamic and its driving forces at pixel scale.

In addition, further research should be done to contrast the NDVI where restoration programs have taken place with non-restored similar areas, so as to validate and revise the method. And the uncertainties caused by cloud cover, low spatial resolution and IDW interpolation should also by deeply analyzed in the future.

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