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Increasing terrestrial vegetation activity of ecological restoration program in the Beijing–Tianjin Sand Source Region of China

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ABSTRACT

China's capital city, Beijing, has been suffering from sandstorms due to grassland degradation and the large distribution of deserts in western and Northern China, named as the Beijing–Tianjin Sand Source Region (BTSSR). To improve the ecological condition in the BTSSR and to reduce its impacts, the Chinese government has adopted the Beijing–Tianjin Sand Source Control Program since 2001. It is necessary to rigorously evaluate the effectiveness of this 10 years' program, not only as an essential topic of environmental change in an ecologically vulnerable area, but also as an important aspect of policy efficiency assessments. Toward this aim, this study assessed vegetation changes both temporally and spatially in the areas under the program from 2000 to 2010 with the Moderate-resolution Imaging Spectroradiometer (MODIS) monthly Normalized Difference Vegetation Index (NDVI) data and trend analysis method. The results showed an overall improvement and its spatial variation in vegetation activity. The annual NDVI increased by 0.0121 year^{-1} over 64.33% of the total area, with the greatest increasing trend of NDVI occurring in the spring. However, the change in NDVI varied remarkably in space. This study identified a southwest-to-northeast band in the study area where NDVI decreased notably, while most of the BTSSR experienced a positive trend of NDVI. Although the cause of the increased NDVI in the BTSSR remains uncertain, drought may result in a non-significant increasing trend in vegetation activity and the ecological restoration program may be one of the main driving forces behind the increasing trend in vegetation activity. All of these findings will enrich our knowledge of human activities that impact vegetation in arid and semi-arid environments and will provide a scientific basis for the management of ecological restoration programs.

1. Introduction

Since the late 1990s, several major ecological restoration programs including the 'Three-North Shelterbelt Project', the 'Beijing–Tianjin Sand Source Control Program' and the 'Grain for Green Project' have been initiated in China to deal with increasingly severe ecological problems, such as desertification, sand storms, soil erosion, flooding and wildlife habitat loss (SFA, 2000–2010; Yin and Yin, 2010; Yu et al., 2011; Zhang et al., 2012). Among these programs, the Beijing–Tianjin Sand Source Control Program was enacted in 2001 to reduce the problems caused by sandstorms in Northern China, especially in the capital city of Beijing. Due to grassland degradation and the large distribution of deserts in western and Northern China called the Beijing–Tianjin Sand Source Region (BTSSR), Northern China has been suffering from sand storm for a long time (Wu et al., 2012). To improve the ecological condition of the BTSSR and to reduce its impacts, the Chinese government has launched the Beijing–Tianjin Sand Source Control Program, which has been implemented by some key measures and policies, including enclosure of grassland, conversion of cropland to forest or grassland (i.e., grain for green), reforestation and afforestation by aerial seeding or closing hill, and grazing prohibition or rotation or rest.

Nevertheless, there is an ongoing debate on the effectiveness of the national ecological restoration programs in China as well as Beijing–Tianjin Sand Source Control Program. On one hand, numerous Chinese researchers and government officials have claimed that ecological restoration programs had successfully combated desertification and controlled dust storms (Zhang et al., 2000; Yang and Ci, 2008; Wang et al., 2007; Yin and Yin, 2010). For example, Liu et al. (2008) found that the overall ecological effects of ecological restoration program are positive. They found that the carbon sequestration increased after afforestation by closing

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hill and reforestation, while the soil erosion had been alleviated after the implementation of ecological restoration program. On the other hand, several experts argued that ecological restoration programs in semi-arid and arid regions may not work well (Wang et al., 2010; Jiang, 2005). Wang et al. (2010) suggested that there was little evidence to support those claims that the large-scale afforestation program might have some beneficial effects on reducing dust storms and combating desertification. Moreover, they thought that the importance of ecological restoration program seemed to be overstated. Cao (2008) further asserted that afforestation could lead to increased ecosystem deterioration and wind erosion because it has ignored climatic, pedological, hydrological and landscape factors (Cao et al., 2011). 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, to some extent, increasing or decreasing vegetation activity can be utilized to assess the success or failure of ecological restoration programs. Furthermore, the Beijing–Tianjin Sand Source Control Program, which was originally planned for the period of 2001–2010, has been implemented for 10 years as a strategic and significant ecological restoration project. Therefore, it is necessary to assess the effects of this program.

During the past five decades, the most pronounced warming trend is found in Northern China (including northeastern China and Inner Mongolia) (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). Meanwhile, Northern China has experienced intense drought during the past decade (Piao et al., 2010). Recently, the BTSSR has suffered particularly from drought. For example, an intense and prolonged drought affected several provinces of the BTSSR (Shanxi, Hebei and Beijing) in 2009 (Qiu, 2010; Barriopedor et al., 2012).

A key question is how the vegetation has changed over the past decade in the BTSSR under both the national ecological restoration program and climate change. Several studies have documented how vegetation responded to climatic changes and human intervention in the BTSSR. For example, Liu et al. (2011) found that the NDVI had increased from 2000 to 2008 in the BTSSR based on MODIS NDVI data. However, the ecological restoration program was originally planned for the period of 2001–2010 in two phases (first phase: 2001–2005 and second phase: 2006–2010), it is necessary to assess the vegetation change over the whole 10 years. Besides, this study only focused on the annual trend of NDVI in the BTSSR, studies of vegetation change in this area through multiple temporal scales are limited. Gao et al. (2008) and Shi et al. (2010) found vegetation coverage and NPP in 2005 were higher than in 2001 based on NDVI data and detailed field investigation, but these studies only focused on the short-term trends and could not describe long-term vegetation dynamics in the BTSSR. In addition, some researchers investigated the vegetation dynamics in the typical sub-areas (e.g., Otindag sandy land and Horqin sandy land) and counties (e.g., Duolun county, Inner Mongolia) of the BTSSR (Zhang et al., 2012; Li et al., 2009; He and Lv, 2003; Zhao et al., 2011). However, these studies only focus on the vegetation dynamics in small or limited areas and are therefore unable to obtain regional vegetation dynamics.

Because current studies only focus on short-term trends in limited areas, they are unable to describe the long-term and regional vegetation dynamics. Moreover, studies on vegetation change in the BTSSR through multiple temporal scales are limited. Consequently, it is unclear of the effectiveness of ecological restoration programs in the BTSSR, how the annual, seasonal and monthly vegetation activities have changed across the BTSSR and whether the vegetation activity is increasing over the past decade. If the program did improve the regional vegetation, then could it work anywhere in the BTSSR? These questions have important implications for decision makers in future ecological restoration work. In this paper, we used the MODIS NDVI data from 2000 to 2010 to (1) assess the effectiveness of ecological restoration program in the BTSSR, (2) investigate the trend of annual, seasonal and monthly vegetation activities in the BTSSR over the past decade and (3) identify the possible reasons for the trends of vegetation activity.

2. Data and methods

2.1. Study area

The Beijing–Tianjin Sand Source Region (109°30′–119°20′E and 38°50′–46°40′N) is bounded by Damao Banner in Inner Mongolia on the west, Ping Yuan County in Hebei Province on the east, Dai County in Shanxi Province on the sourth and Dong Ujimqin Banner in Inner Mongolia on the north (Fig. 1). There are 75 counties (banners, cities or districts) in the Beijing, Tianjin, Hebei, Shanxi and Inner Mongolia provinces in this region and its total area is 458,000 km^2.

Topography of this area includes plain, mountain, and plateau. The plains are located in the southeast and are part of the plain of the Haihe River; the west, northwest, and north of this area are located in the central Inner Mongolian Plateau, where the landform has a declining slope from west to east; the mountains are in the middle of the plain and plateau and include the northern Taihang and Yanshan Mountains and the southern Greater Hinggan Mountain from southwest to northeast. The Otindag and Horqin Sandy Lands are located in the central and eastern areas. Variations in landform in this area cause climate differences, including two climatic zones (warm temperate zone and temperate zone) and five climatic regions. Specifically, climate from south to north is warm temperate semi-humid, temperate semi-humid, temperate semi-arid, temperate arid and temperate extreme arid. The annual average temperature in this area is from 4 °C to 7.5 °C with a decreasing trend from east to west. Total annual precipitation is 250–470 mm, also with a decreasing trend from east to west (Gao et al., 2008).

To analyze the benefits of the ecological restoration program, Gao et al. (2008) divided the BTSSR into eight sub-areas (the desert grassland sub-area (desert grassland), the typical grassland sub-area (typical grassland), the Otindag sandy land sub-area (Otindag), the southern Greater Hinggan Mountains sub-area (Greater Hinggan), the Horqin sandy land sub-area (Horqin), the agro-grazing ecotone sub-area (agro-grazing ecotone), the northern Shanxi's mountainous sub-area (Northern Shanxi) and the water source protection area in the Yanshan mountainous sub-area (Yanshan)), based on the complex climate, landform, soil and vegetation. In this paper, we adopted the same division of the BTSSR (Fig. 1).

2.2. Dataset

The monthly NDVI data, with a 1-km spatial resolution covering the period from 2000 to 2010, were derived from MODIS from NASA's Earth Observing System. MODIS monthly NDVI data were obtained using the maximum value composite (MVC) method, which minimized cloud contamination, atmospheric effects and solar zenith angle effects (Holben, 1986).

Monthly meteorological data from 28 meteorological stations distributed in the BTSSR (Fig. 1) from 2000 to 2010 were obtained from the Chinese National Meteorological Center. The

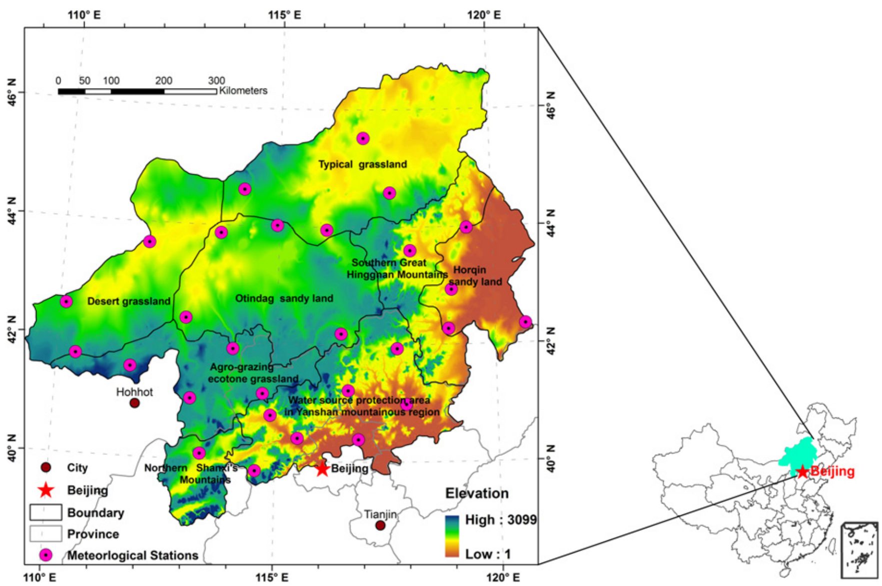

Fig. 1. Location of the study area, China.

data included monthly mean air temperature, monthly total precipitation and monthly solar radiation. We interpolated climate data to grid cells with a resolution of 1 km × 1 km using inverse distance weighted (IDW) interpolation.

Vegetation data were obtained from the 1:1,000,000 vegetation map covering the BTSSR (Editorial Board of Vegetation Map of China, 2001). Vegetation was grouped into the following six types: typical grasslands, meadow steppe, forests, shrubs, cultivation, and deserts. The data were aggregated to grid cells at a 1 km × 1 km resolution, as performed for the NDVI and climate datasets. The distribution of different types of vegetation was shown in Fig. 2.

2.3. Methods

2.3.1. Data preprocessing

The availability of the long-term NDVI data derived from AVHRR, SPOT and MODIS has motivated many scientists to study interannual variations in vegetation activity. Most commonly, these studies examined changes in NDVI (Ma and Frank, 2006; Fensholt et al., 2009), NPP (Nemani et al., 2003), vegetation coverage (Gutman and Ignatov, 1998) or the fraction of photosynthetically active radiation absorbed by vegetation (fPAR) (Donohue et al., 2009). Ground conditions strongly affect NDVI, leading to unstable values that cannot accurately represent vegetation status in desert regions (Fang et al., 2004). Therefore, similar to Myneni et al. (1997), Slayback et al. (2003) and Wang et al. (2011), an NDVI threshold of 0.05 was used to exclude bare and sparsely vegetated area.

The vegetation activity in the BTSSR can be addressed by four variables: mean NDVI ($NDVI_a$), annual-integrated NDVI (AINNDVI), net primary productivity (NPP) and vegetation coverage. $NDVI_a$ is defined as the average NDVI for each monthly NDVI in a year. AINNDVI is defined as the sum of the monthly NDVI values that exceed 0.05 in a year. The CASA (Carnegie-Ames-Stanford Approach) model and dimidiate pixel model were applied to generate NPP (Potter et al., 1993) and vegetation coverage (Gutman and Ignatov, 1998). The NPP was usually estimated based on the CASA model, which was run with the NDVI data, climate data, vegetation type and soil data (Potter et al., 1993). The CASA model has been widely used to obtain NPP in China (Piao et al., 2001; Yuan et al., 2006). Zhu et al. (2005) found that the simulated NPP was consistent with the observed values based on the CASA model in Inner Mongolia ($R^2 = 0.84$, $P < 0.001$, $n = 30$). In this study, we chose the same model and parameter as Zhu used. The monthly NPP was obtained by CASA model and then the annual NPP was generated by the average of NPP for each monthly in a year. The dimidiate pixel model is also widely used to estimate the vegetation coverage (Gutman and Ignatov, 1998). In the dimidiate pixel model, it is assumed that a pixel consists of only two parts vegetation and non-vegetation. The proportion of vegetation in the pixel is the vegetation coverage of this pixel (Jing et al., 2011). In this study, the monthly vegetation coverage was generated by dimidiate pixel model with monthly NDVI. Then the annual vegetation coverage of individual pixel was generated by the average of vegetation coverage for each monthly in a year. Finally, the overall vegetation coverage in area scale was obtained as the average of the annual vegetation coverage for all pixels. The simulated vegetation coverage with dimidiate pixel model was closed to the observed vegetation coverage ($R^2 = 0.815$, $P < 0.001$, $n = 64$). The relative change (increase or decrease) in the rate of vegetation activity during the study period was estimated as follows:

$$\mathrm{RCR} = \frac{\mathrm{slope}}{\mathrm{mean}} \times N \times 100\%$$

where RCR is the relative change rate, slope is the slope of variable (e.g., $NDVI_a$, NPP), mean is the average of the variable over the N years, and N is the length of study period.

2.3.2. Methods for trend analysis

2.3.2.1. Linear regression methods (LRMs). A linear regression method was applied to detect and analyze trends in the time series. The slope of the regression indicated the mean temporal change in the studied variable. Positive slopes indicated increasing trends, while negative slopes indicated decreasing trends (Stow et al., 2003; Ma and Frank, 2006; Piao et al., 2011; Fensholt and Proud, 2012).

2.3.2.2. Sen's slope estimator. In addition to the linear regression analysis, Sen's slope estimator was applied to the BTSSR data. 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 (1968). Sen's slope estimator did not

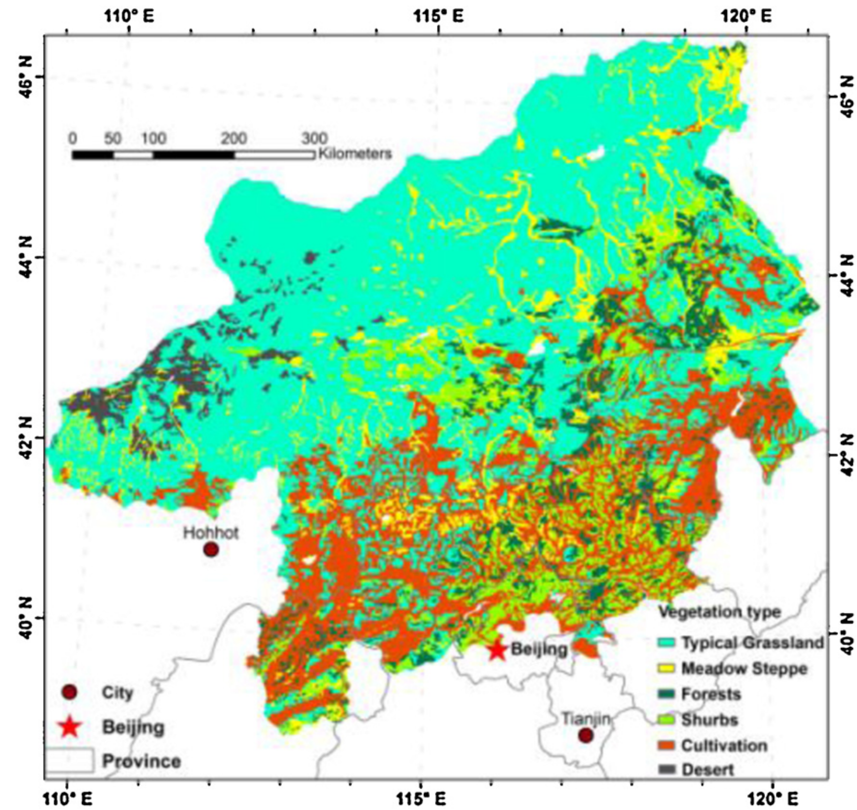

Fig. 2. Vegetation types in the BTSSR.

require the data to be distributed normally. Therefore, it has been gradually applied in vegetation dynamics studies (Fernandes and Leblanc, 2005; Cai, 2008). β, Sen's slope, was computed as follows:

$$\beta = \text{Median}(Q_i) = \text{Median}\left(\frac{x_j - x_i}{j - i}\right) \quad \text{for} \quad i = 1, \cdots, N$$

where x_i and x_j was the value at time i and j ($j > i$), respectively. Median was the median function. The median of these N values of Q_i is β. If N is odd, then β is computed by:

$$\beta = Q_{[(N+1)/2]}$$

If N is even, then β is computed by:

$$\beta = \frac{1}{2}(Q_{[N/2]} + Q_{[(N+2)/2]})$$

As well as with linear regression method, positive values of β indicated increasing trends, while negative values of β indicated decreasing trends.

3. Results

3.1. Trends of vegetation activity at the annual scale

3.1.1. BTSSR-wide trend analysis

In this section, we discuss the trends of four variables of vegetation activity analyzed using two different trend methods. Fig. 3 illustrates the interannual variations in $NDVI_a$, AINNDVI, NPP and vegetation coverage in the BTSSR during 2000–2010 using LRM. The increasing trend in vegetation activity for the four vegetation variables was observed over the entire study period, demonstrating that the overall state of vegetation in the area increased from 2000 to 2010. Obviously, the four vegetation variables showed that vegetation activities were high in 2003, 2004 and 2008 but low in 2001, 2007 and 2009. Nevertheless, the $NDVI_a$ ($R = 0.16$, $P = 0.65$), AINNDVI ($R = 0.26$, $P = 0.44$), NPP ($R = 0.18$, $P = 0.60$) and vegetation coverage ($R = 0.25$, $P = 0.46$) showed no significant increasing trends. The minimum values in 2007 and 2009 may have contributed to the lack of a significant increasing trend.

Table 1 summarizes the mean values, trends and relative increase rates of the four vegetation variables calculated using two different trend analysis methods. There was almost no difference between LRM and the Sen method for the same vegetation variable. For example, the increase rate of AINNDVI by LRM and the Sen method was 4.27% and 5.25%, with a trend of 0.0121 year^{-1} and 0.0149 year^{-1}, respectively. However, there was slight difference among the four vegetation variables within each method. The increase rates of $NDVI_a$, AINNDVI, NPP and vegetation coverage by LRM were 2.49%, 4.27%, 5.90% and 4.21%, with a trend of 0.00061 year^{-1}, 0.0121 year^{-1}, 1.431 year^{-1} and 0.0013 year^{-1}, respectively. Furthermore, the average increase rates of vegetation activity by LRM and Sen were 4.22% and 4.06%, respectively, implying that vegetation activity increased over the study period in the BTSSR.

3.1.2. Spatial patterns of vegetation change trends at the annual scale

For each pixel, the linear trend and Sen's slope trend of the four vegetation variables over the study period were estimated (Figs. 4 and 5). Similar to the trend of vegetation activity at the whole-area scale, there was little difference in the spatial patterns of the four vegetation variables between the two methods. Although the increasing trend of vegetation activity was not significant at the whole-area scale, we found a high degree of spatial

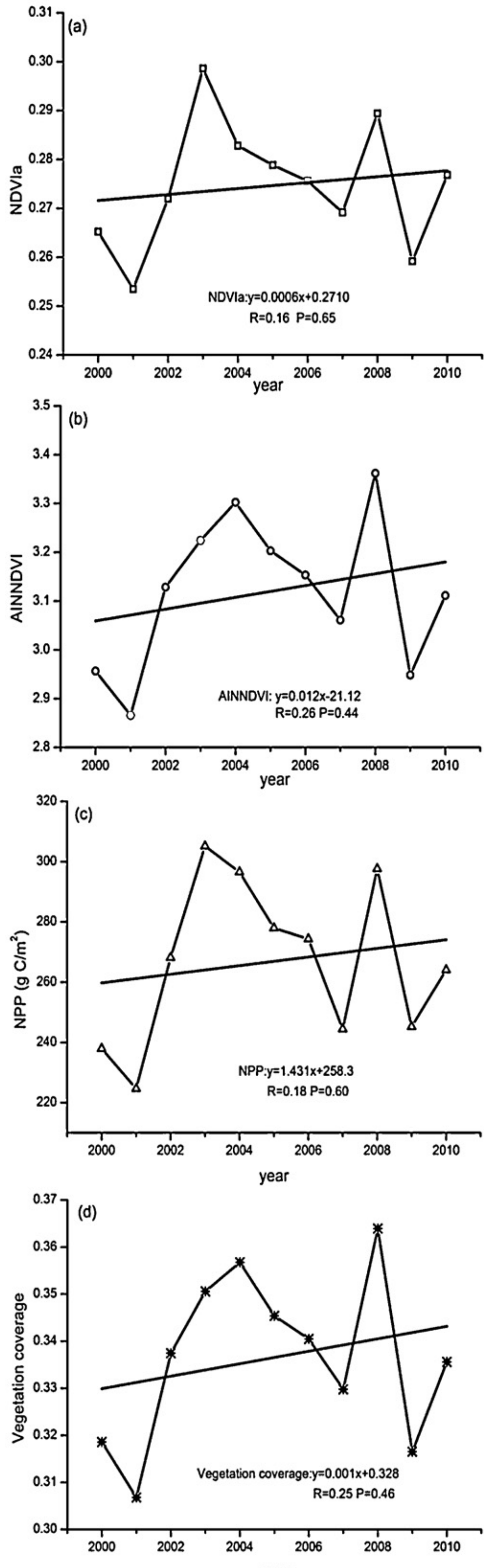

Fig. 3. The trends of four vegetation variables in the BTSSR from 2000 to 2010. (a) $NDVI_a$, (b) AINNDVI, (c) NPP, and (d) vegetation coverage.

heterogeneity. The trends of the four vegetation variables increased in the south (especially in Yanshan and Northern Shanxi), southeast (southern Greater Hinggan and Horqin), northwest (Desert grassland) and north (southwest Typical grassland), while it decreased sharply in the southwest (agro-grazing ecotone), center (southern Otindag) and northeast (northern Greater Hinggan). These decreasing regions were mainly a southwest -to-northeast band within the area (blue box).

Moreover, we summarized the percentage of the four vegetation variables that increased/decreased using the two methods (Table 2). Again, there was almost no difference between the LRM and the Sen method for the same vegetation variable, while there was a slight difference among the four vegetation variables when using one method. Most regions of the BTSSR showed an increasing trend during 2000–2010. For example, the $NDVI_a$ increased over 58.44% of entire area according to the LRM.

3.2. Trends of vegetation activity at the seasonal scale

To analyze the trends of seasonal and monthly vegetation activity in the BTSSR, the time-integrated NDVI and linear regression method (LRM) were selected. The time-integrated NDVI and LRM have advantages in several aspects: (1) the NDVI has been proven to be a proxy for the status of the vegetation activity at the landscape level (Beatriz and María Amparo, 2009); (2) previous studies have indicated that the time-integrated NDVI was highly correlated with vegetation coverage and NPP (e.g., Carlson and Ripley, 1997); (3) the increase rate of AINNDVI is 4.27%, which is lightly larger than the average increase rate 4.22%, and the percentage of AINNDVI increase is 64.33%; (4) the four vegetation variables have the same trend over 11 years and the fluctuations in the trend of vegetation activity appear in the same year; and (5) LRM is the common method used to detect and analyze trends in time series. At the same time, to avoid spurious NDVI trends due to winter snow, we only analyzed seasonal NDVI trends in three seasons (spring, summer and autumn).

3.2.1. Trends in seasonal NDVI

In this section, we discussed the NDVI trends in three seasons: spring (March to May), summer (June to August) and autumn (September to November). NDVI images of spring, summer and autumn were generated separately by computing the sum of respective months. The NDVI trends for all three seasons were positive (Fig. 6a–c), implying that all three seasons contributed to the increased in AINNDVI (Fig. 6d). To recognize the changes in seasonal NDVI, we calculated the annual increasing trends and increasing rates of seasonal NDVI in the study area (Table 3). The largest NDVI increase (R = 0.47, P = 0.15) occurred in the spring, with a magnitude of 7.08% over the 11 years and a trend of 0.00399 $year^{-1}$ (the 11-year averaged NDVI was 0.62). The increase rates for summer (R = 0.13, P = 0.70) and autumn (R = 0.15, P = 0.74) were 3.23% and 2.10% with a trend of 0.00364 $year^{-1}$ and 0.0016 $year^{-1}$, respectively. Despite the NDVI increase in all three seasons, several large fluctuations appeared in the NDVI trends. For example, spring NDVI was large in 2003 and 2009 but small in 2001 and 2006, while autumn NDVI was large in 2004 and 2008 but small in 2002 and 2009. Over the past 11 years, AINNDVI in the study area increased by 0.0121 $year^{-1}$, with a relative annual increase rate of 4.27% (Fig. 6d). Additionally, the summer is the best season for vegetation growth, and thus, the patterns of summer NDVI fluctuation corresponded well with that of AINNDVI. In 2008, summer NDVI was relatively high, coinciding with the peaks of AINNDVI. Similarly, the AINNDVI minima of 2001, 2007 and 2009 correspond with the minima of summer NDVI over these years. However, the larger autumn NDVI in 2004 may result in the relatively high value for AINNDVI in 2004. In summary, the NDVI trends for all three seasons increased, and the largest NDVI increase was in the spring (7.08%), followed by the summer (3.23%) and autumn (2.10%).

Table 1
Mean value, trend and relative increased rate of four vegetation variables by two trend analysis methods.

Method	Mean ± SD	Trend per year (LRM)	Relative increase (LRM) (%)	Trend per year (Sen)	Relative increase (Sen) (%)
$NDVI_a$	0.27 ± 0.012	0.00061	2.49	0.00061	2.49
AINNDVI	3.12 ± 0.146	0.0121	4.27	0.0149	5.25
NPP	266.92 ± 25.35	1.431	5.90	0.808	3.33
Vegetation coverage	0.34 ± 0.017	0.0013	4.21	0.0016	5.18
Mean[a]			4.22		4.06

[a] Mean is the average increase rate of four vegetation variables: $NDVI_a$, AINNDVI, NPP and vegetation coverage.

Table 2
Percentage of the four vegetation variables that increased or decreased using the two trend methods.

Variable	Decrease (LRM) (%)	Increase (LRM) (%)	Decrease (Sen) (%)	Increase (Sen) (%)
$NDVI_a$	41.56	58.44	41.78	58.22
AINNDVI	35.67	64.33	36.78	63.22
NPP	41.66	58.34	41.85	58.15
Vegetation coverage	36.48	63.52	37.72	62.28

The total number of pixels is 454,528.

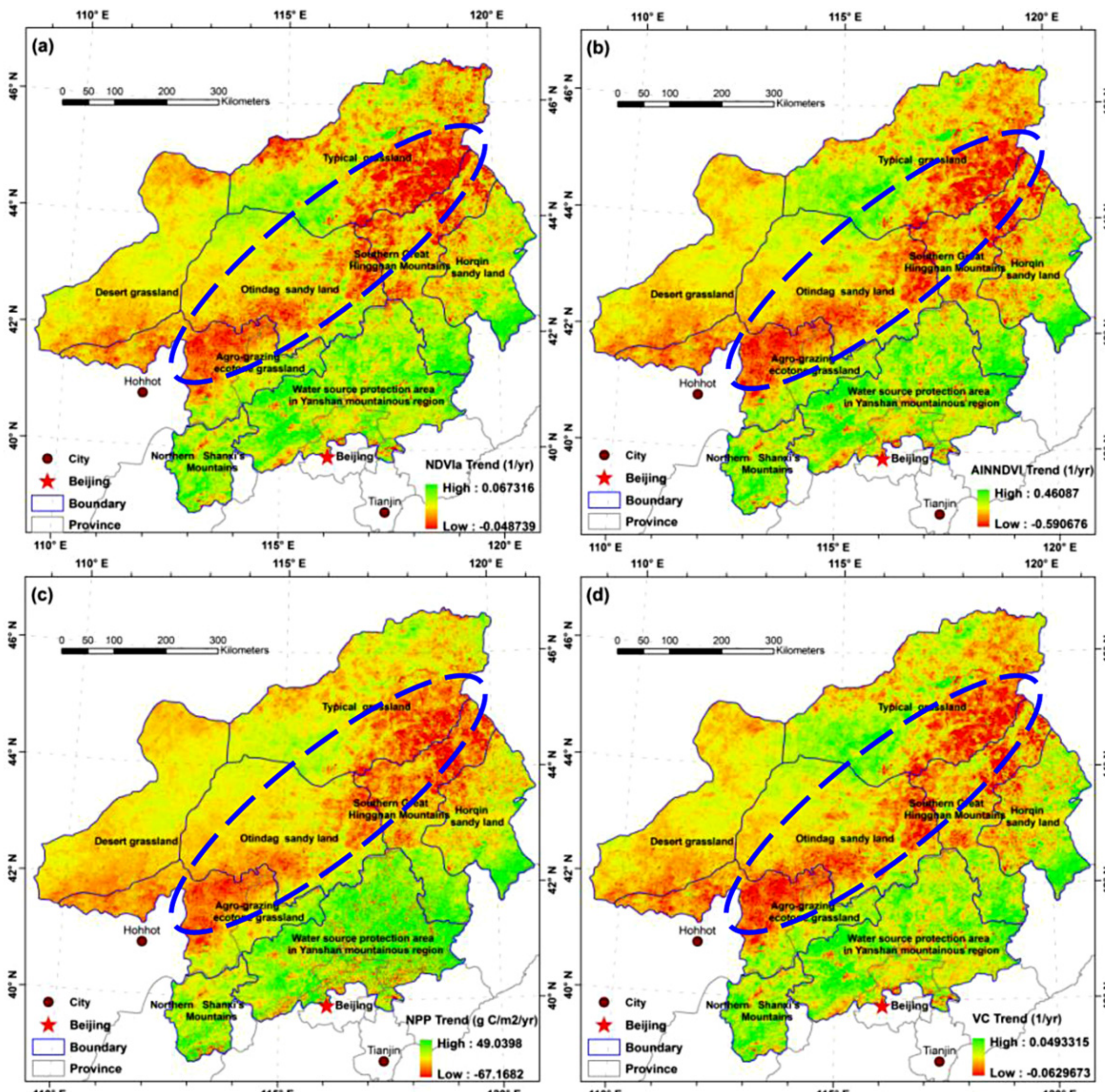

Fig. 4. Spatial patterns of the four vegetation variables in the BTSSR based on LRM during 2000–2010: (a) $NDVI_a$, (b) AINNDVI, (c) NPP (gC/m^2/year), and (d) vegetation coverage. Positive values (green) indicate increasing trends and negative values (red) indicate decreasing trends. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

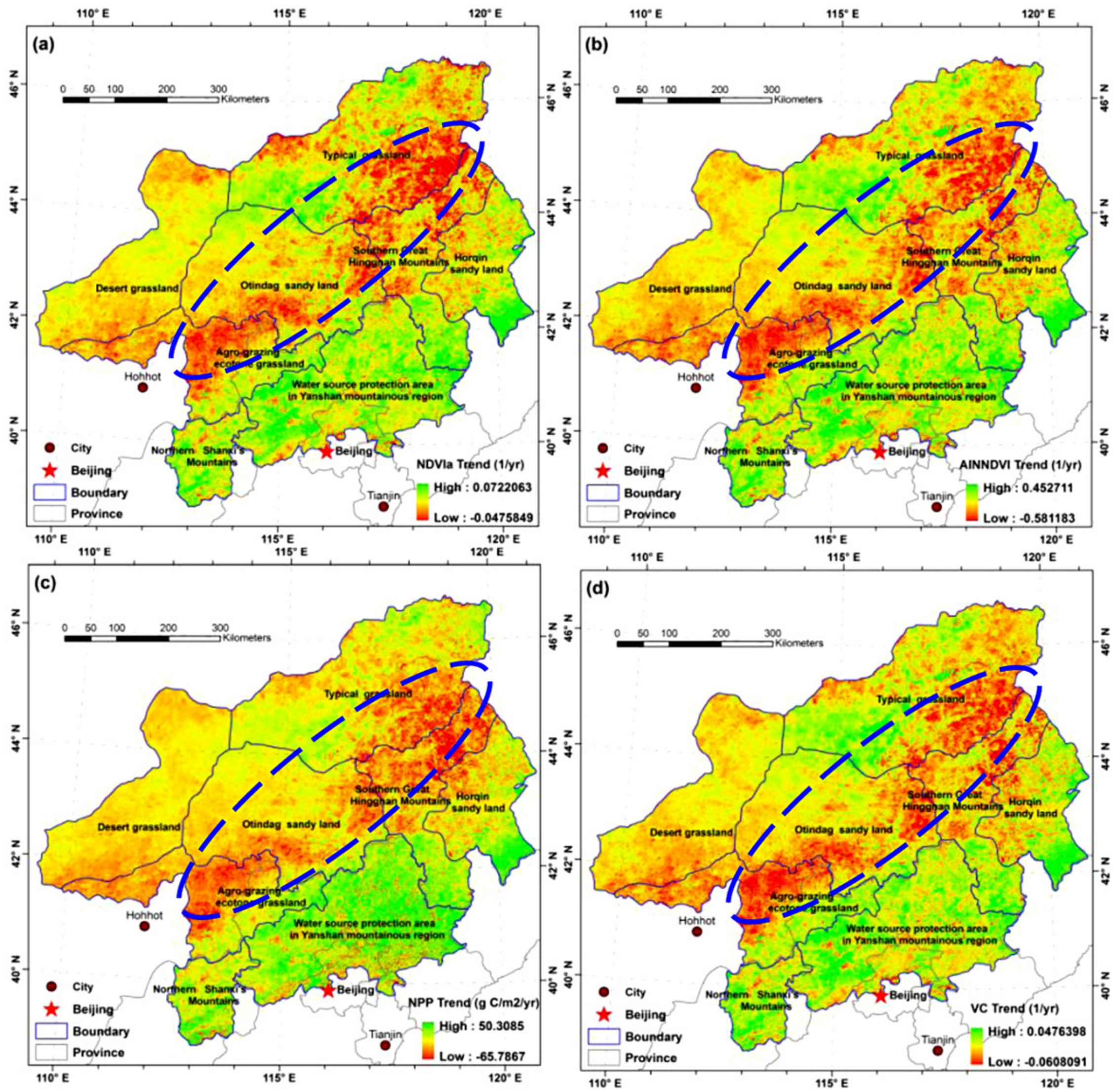

Fig. 5. Spatial patterns of the four vegetation variables in the BTSSR based on the Sen method during 2000–2010: (a) $NDVI_a$, (b) AINNDVI, (c) NPP (gC/m^2/year), (d) vegetation coverage. Positive values (green) indicate increasing trends and negative values (red) indicate decreasing trends. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2.2. Spatial patterns of seasonal NDVI trends

For the period from 2000 to 2010, spatial patterns of trends in seasonal NDVI were shown in Fig. 7. The upper left map in Fig. 7 shows the grid numbers of the slope trend, with the positive values (green) indicating an increasing trend of vegetation activity and the negative values (red) indicating a decreasing trend of vegetation activity. The upper right map in Fig. 7 shows significant increases (green) or decreases (red) in vegetation activity at the 5% significance level over the period 2000–2010. The number of slop trends in Fig. 7 supported the findings in Fig. 6 that the largest NDVI increase was in the spring, followed by the summer and autumn. We found a high degree of spatial heterogeneity that varied seasonally (Fig. 7a–c). In the spring (Fig. 7a), NDVI trends were positive in most areas, especially in Northern Shanxi, southeast of the typical grassland and the southern Horqin sandy, but decreased in the small area of southeast of the typical grassland. Summer NDVI showed a fragmented pattern, increasing in most areas of the desert grassland, southwest of the typical grassland, northern Shanxi, Yanshan, the southern Greater Hinggan and the southern Horqin sandy. However, some regions experienced a decrease in summer NDVI. Similar to the trend of AINNDVI (Fig. 7d), these decreasing regions were mainly a southwest-to-northeast band in the study area (Fig. 7b). The majority of the BTSSR experienced a positive trend of autumn NDVI during 2000–2010 (Fig. 7c). A decrease in autumn NDVI was observed in northern Greater Hinggan and southeast of the typical grassland (located in the eastern part of the BTSSR). The increasing trend of NDVI in the three seasons could contribute to the increase in AINNDVI that occurred in the northern BTSSR (southwest of the typical grassland) and southern BTSSR (especially Yan Shan and Northern Shanxi), while both the decreasing trend of summer NDVI in the southwest (agro-grazing ecotone) and autumn NDVI in the northeast could result in a sharp decreasing trend of AINNDVI (Fig. 7d). To explore the

Table 3
Mean value, trend and relative increase rate of annual and seasonal integrated NDVI.

Season	Mean ± SD	Trend per year	Relative increase (%)
Spring	0.62 ± 0.028	0.00399	7.08
Summer	1.24 ± 0.092	0.00364	3.23
Autumn	0.84 ± 0.046	0.00160	2.10
Annual	3.12 ± 1.205	0.0121	4.27

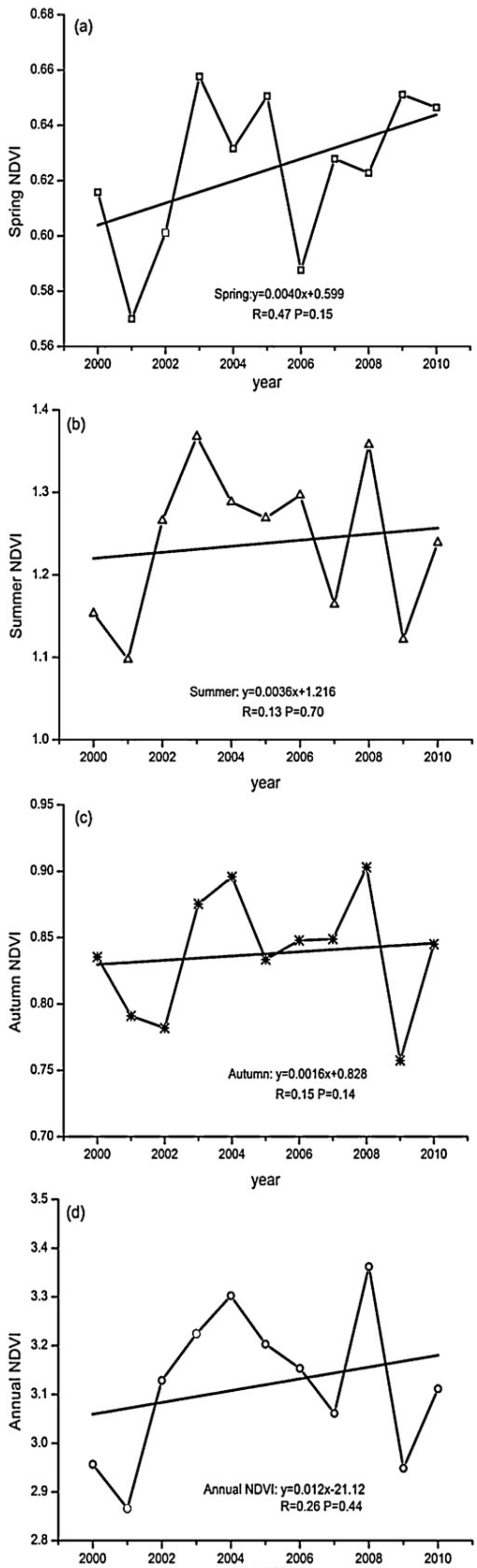

Fig. 6. Interannual variations in (a) spring intergated NDVI, (b) summer intergated NDVI, (c) autumn intergated NDVI and (d) auunal intergated NDVI over the period 2000–2010 in the BTSSR.

trend of seasonal NDVI at the pixel scale, we summarized the percentage of NDVI increase/decrease at the 5% significance levels in the area (Fig. 8a). Over the past 11 years, the area with largest NDVI increase occurred in the spring, while the lowest increase was in the autumn. Statistically, 71.89% of the total study area has increased in NDVI in the spring over the 11 years, of which 14.00% had a significant increase at the 5% level, while in the summer and autumn 57.7% (9.02% at the 5% level) and 54.79% (7.13% at the 5% level) of the total area had increased, respectively. In addition, 64.33% of the total study area has increased, of which 12.38% had a significant increase at the 5% level. This finding indicates that the largest NDVI increase occurred in the spring (71.89% > 64.33%). Fig. 8b provides the percentage of NDVI increases or decreases in magnitude (divided as less than −20%, −20% to −10%, −10% to 0, and so on over the 11 years). For example, the areas with the spring NDVI increase of 10–20% and >20% over the past 11 years were 22.43% and 11.07% of the total study area.

3.3. Trends of vegetation activity at the monthly scale

3.3.1. Monthly trends for the BTSSR-wide analysis

The magnitude of the monthly NDVI and its change over time are important indicators of the contribution of vegetation activity in different months to total annual plant growth (Piao et al., 2003). In the BTSSR, the mean monthly NDVI reached a maximum value in August (Fig. 9). From December to March, the mean monthly NDVI was low. In the past 11 years, the trend of monthly NDVI showed positive values with exceptions in July, August and September, indicating that NDVI increased throughout the 11-year study period. Significant differences were observed from April to October (the growing season). The largest trend was in June (summer), whereas the two smallest decreased trends were observed in July and August (summer). Relatively large NDVI trends were also found in April and May (spring), following that found in June (summer). This finding suggested that plant growth peaked in the middle of the growing season (summer), while the largest NDVI increase occurred in the early growing season.

3.3.2. Monthly trends by vegetation type

Similar to the monthly NDVI and its trend over the past 11 years at the whole area scale, monthly NDVI and its trends showed the largest value in August and June for all vegetation types (Fig. 10). In general, the monthly NDVI was greatest in August and was rather low in January for all the vegetation types. The monthly NDVI trends showed that NDVI had increased in the early growing season (April or May) for all of the vegetation types, which reflected an effect of the extended growing season. It was noteworthy that the NDVI trend in June was large for all vegetation types. Moreover, the monthly NDVI trends showed positive values for all months for cultivation. Furthermore, the trends of monthly NDVI showed positive values except in August and September for forest and shrubs. The trends of monthly NDVI for typical grasslands, meadow steppe, and deserts, had similar magnitudes of the NDVI trend as those of the whole area. Therefore, the trends of monthly NDVI showed positive values, indicating that vegetation activity increased in the BTSSR at the monthly scale.

4. Discussion

4.1. Trends of vegetation activity in the BTSSR

Vegetation activity in most areas of the BTSSR exhibited an overall increase over the past decade, suggesting that the ecological restoration program was effective (Liu et al., 2011; Hua, 2010). Liu

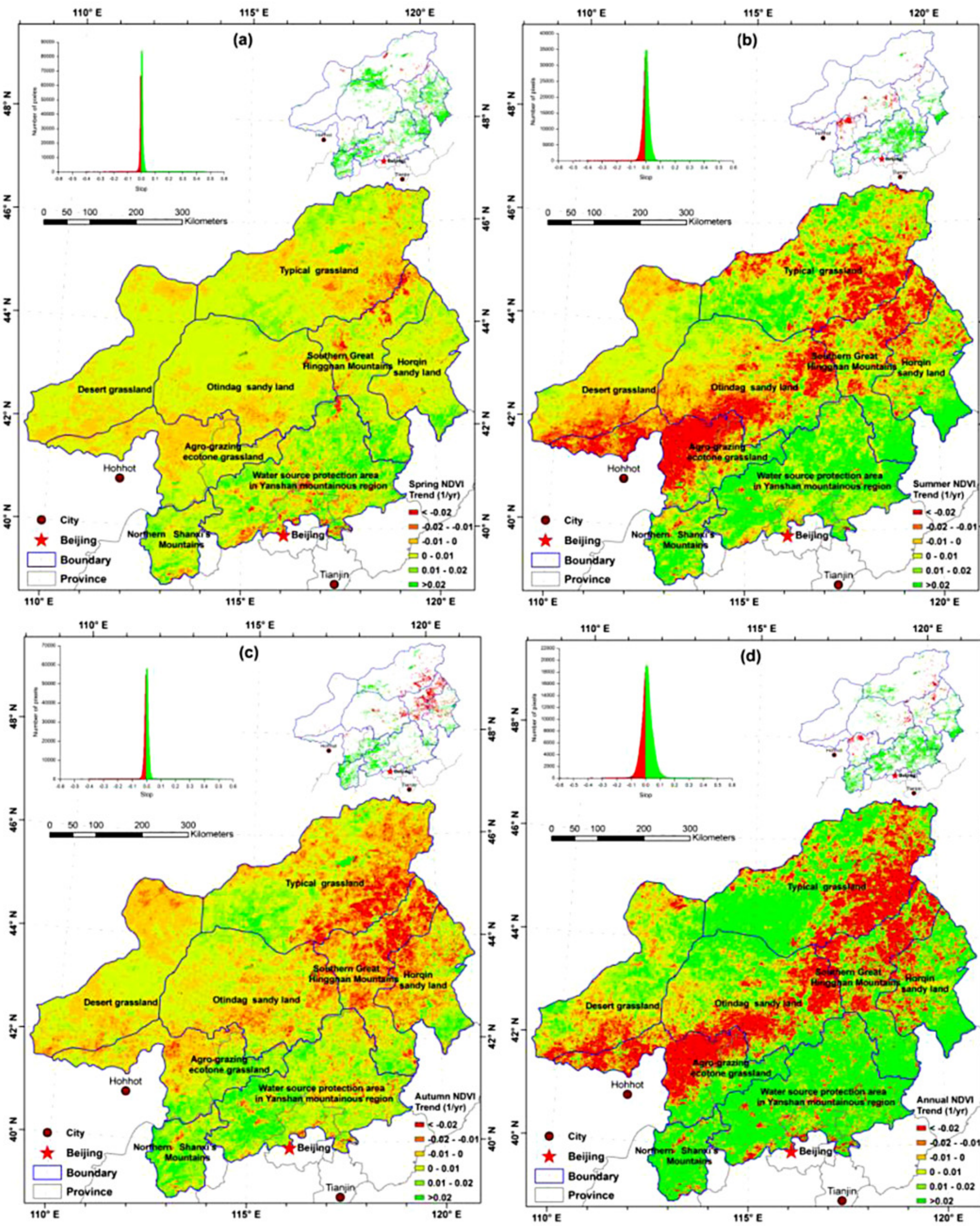

Fig. 7. Spatial patterns of ingergated-NDVI trends for each grid cell for (a) spring (3–5), (b) summer (6–8), (c) autumn (9–11) and (d) year (1–12) over the period 2000–2010 in the BTSSR. The upper left map in this figure shows the grid numbers of the slope trend, with the positive values (green) indicating an increasing trend of vegetation activity and the negative values (red) indicating a decreasing trend. The upper right map in this figure shows significant increases (green) or decreases (red) in vegetation activity at the 5% significance level. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al. (2011) found that NDVI had increased from 2000 to 2008 in the BTSSR based on MODIS NDVI data. By analyzing MODIS NDVI data and detailed field investigation data, Gao et al. (2008) and Shi et al. (2010) documented that vegetation coverage and NPP showed an increasing trend between 2001 and 2005. Moreover, based on NOAA/AVHRR NDVI data with an 8-km spatial resolution, Li and Li, 2010 suggested that the aboveground vegetation biomass showed an increasing trend in the Sunite Left Banner (located in the northern portion of the BTSSR) from 1982 to 2003. Furthermore, the largest increase in NDVI occurred in the spring, which is consistent with the idea that the early advance of spring was a major factor causing the increase in the northern hemisphere's vegetation activity (Zhou et al., 2001; Piao et al., 2003; Fang et al., 2004).

4.2. Impacts of climate change on the vegetation activity

In general, vegetation activity is permanently changing at a variety of spatial and temporal scales due to natural and/or anthropogenic causes (Beatriz and María Amparo, 2009). Variations in vegetation activity have been linked with changes in climate (e.g., Justice and Hiernaux, 1986; Menenti et al., 1993; Piao et al., 2003). The interannual variations of precipitation and AINNDVI were analyzed in the BTSSR during 2000–2010 (Fig. 11). The increased precipitation was parallel with increased AINNDVI. In 2003, 2004 and 2008, the NDVI was relatively high, coinciding with peaks of precipitation. Similarly, the NDVI minima of 2001, 2007 and 2009 correspond with the minima of the precipitation over these years. Hence, the precipitation is the dominated force for the NDVI change

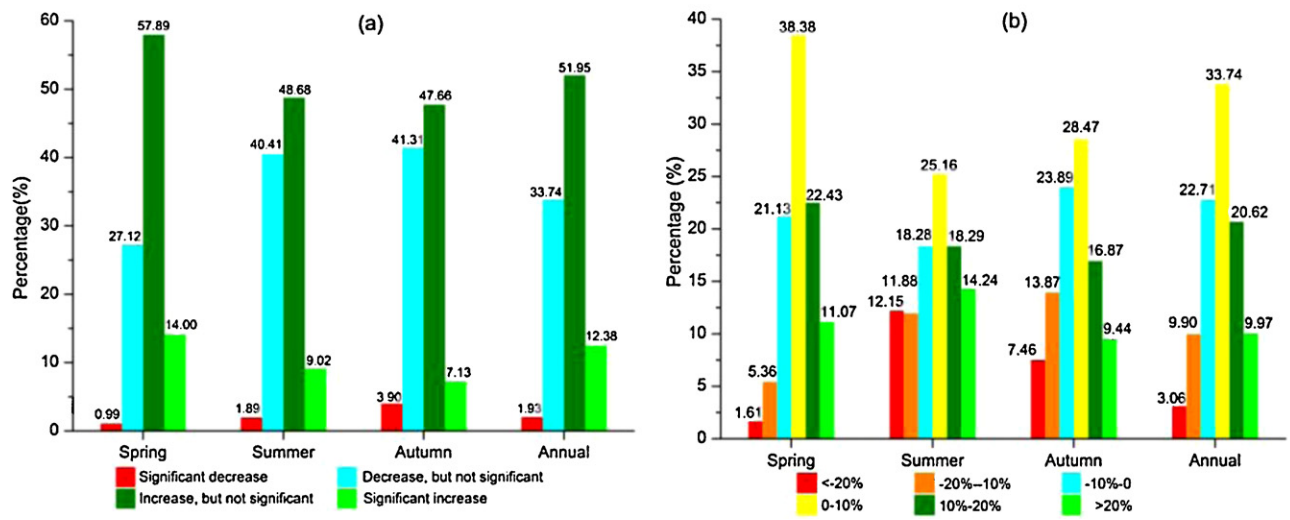

Fig. 8. NDVI increase or decrease on the area for the year and different seasons in the BTSSR. (a) Percentage of NDVI increase/decrease at the 5% significance levels. (b) Percentage of NDVI increase or decrease in magnitude (divided as less than −20%, −20% to −10%, −10% to 0%, and so on).

in the BTSSR. Our finding is consistent with many previous studies, which have indicated that vegetation growth in arid and semi-arid regions is very sensitive to precipitation changes (Du Plessis, 1999; Herrmann et al., 2005). For example, Nicholson et al. (1990) and Herrmann et al. (2005) investigated the relationship between NDVI and precipitation in the African Sahel and found that precipitation was the most important controlling factor of vegetation growth. Moreover, Piao et al. (2003, 2004, 2006) and Zhao et al. (2001) found that NDVI was positively correlated with precipitation in most arid and semi-arid regions. Furthermore, Zhao et al. (2010) found that the 3-month Standardized Precipitation Index (SPI) exhibited the best correlation with the percentage of fractional vegetation coverage in the BTSSR. Therefore, increased or reduced precipitation may lead to an increase or decrease in NDVI in the study area.

There was no significant increasing trend in NDVI. NDVI was small in 2001, 2007 and 2009 (Fig. 3). Northern China experienced intense droughts in 2000, 2001, 2007 and 2009 (He and Lv (2003); Piao et al., 2010; Barriopedor et al., 2012). Drought significantly affects vegetation change (Law et al., 2001; Krishnan et al., 2006), such as limiting the photosynthesis (e.g., Chaves, 1991), altering the vegetation respiration (e.g., Davidson et al., 1998) and changing the vegetation mortality (e.g., Lloret et al., 2004). Previous studies, based on experimental methods (Da Costa et al., 2010), satellite observations (Xu et al., 2011; Zhao and Running, 2010) and carbon process models (Chen et al., 2012; Kljun et al., 2006), have shown that large-scale droughts had reduced vegetation activity. For example, Zhang et al. (2010) found that the drought reduced the vegetation greenness in southwestern North American and Zhao and Running (2010) found that large-scale droughts reduced regional NPP from 2000 to 2009. Moreover, we found that spring NDVI in 2009 was relatively high (Fig. 6a), while summer and autumn NDVI were sharply decreased (Fig. 6b and c). The precipitation in 2009 was lowest from 2000 to 2010 (Fig. 11). Summer is the optimal season for vegetation growth. Fig. 12 shows the interannual variations of summer precipitation in the BTSSR. Also, the summer precipitation in 2009 decreased sharply. Gao et al. (2012) found that the BTSSR suffered from a 30-year drought in 2009. Furthermore, Barriopedor et al. (2012) analyzed the causes of 2009–2010 drought and its impacts on vegetation in China. They found that NDVI was severely affected by the extreme summer and autumn droughts, especially in northern China (particularly in the BTSSR). Thus, drought may result in a non-significant increasing trend in vegetation activity in the BTSSR.

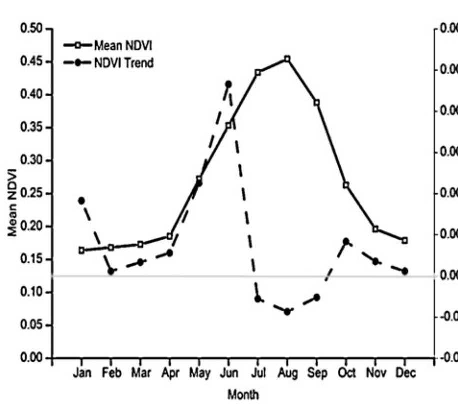

Fig. 9. Eleven-year averaged monthly NDVI and its trend in the BTSSR.

4.3. Impacts of ecological restoration program on the vegetation activity

Climate change is one of the main drivers of the change in vegetation activity in the BTSSR. However, there is no doubt that the ecological restoration program also has a great effect on the vegetation change (Zhang et al., 2000; Vicente-Serrano et al., 2005). To evaluate the impacts of ecological restoration program on vegetation activity, we first analyzed the interannual variations of summer precipitation and summer NDVI. Then we compared the difference of vegetation activity trend between in and outer the ecological restoration program region. Finally, we analyzed the impacts of key measures and policies on vegetation activity.

Summer is the optimal season for vegetation growth. As above mentioned, vegetation growth is very sensitive to precipitation changes. Precipitation in summer showed a decreasing trend in the BTSSR over the period 2000–2010 (Fig. 12). However, there is an increasing trend of summer NDVI in the BTSSR (Fig. 6b). Hence, we speculate that the ecological restoration program is effective on vegetation increase.

To further evaluate the impacts of ecological restoration program on vegetation activity, the comparison of the trend of

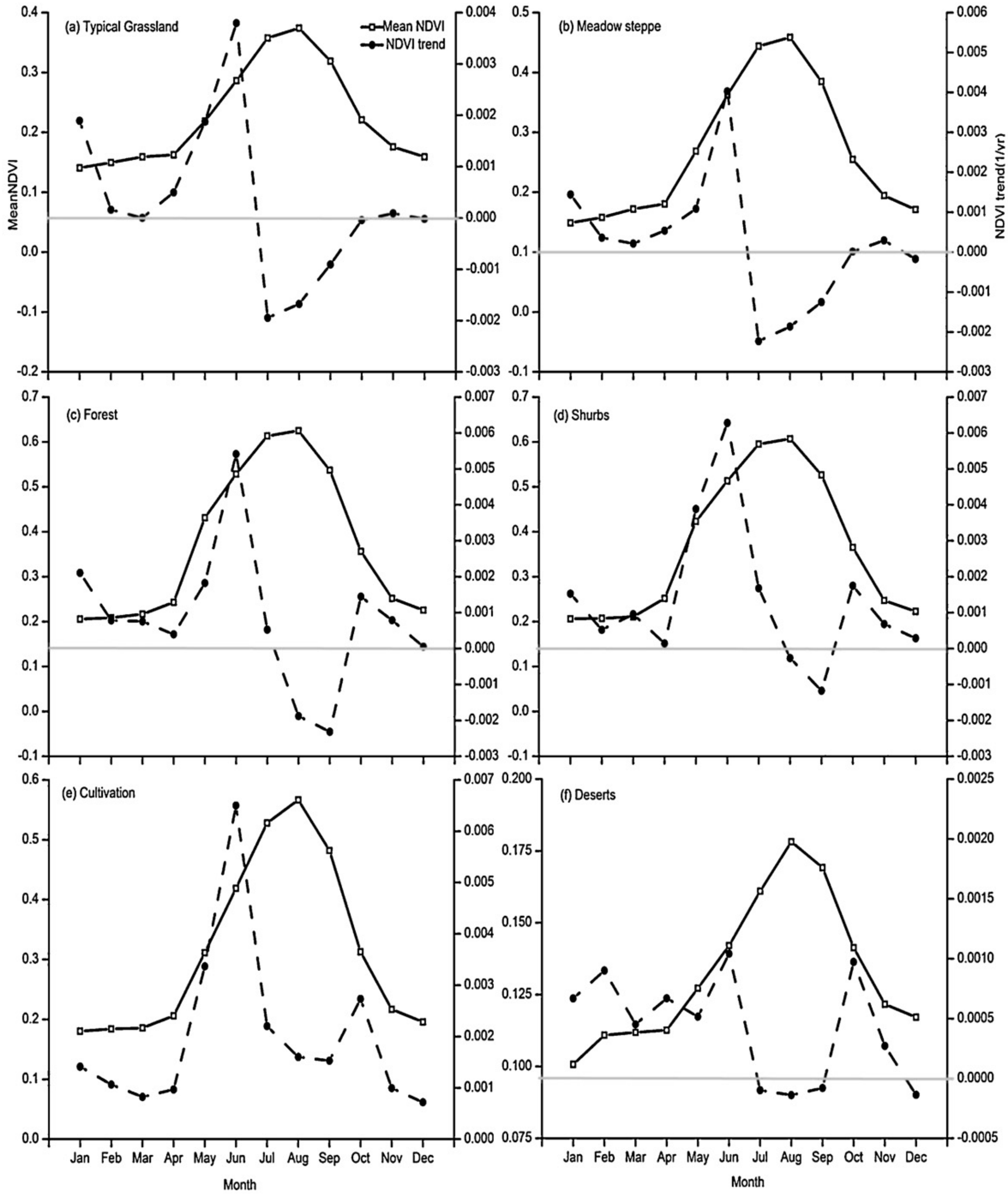

Fig. 10. Variations in averaged monthly NDVI, NDVI trend over the period of 2000–2010 by vegetation type in the BTSSR. (a) Typical grasslands, (b) meadow steppe, (c) forests, (d) shrubs, (e) cultivation and (f) deserts.

vegetation activities in and outer of the ecological restoration program region was analyzed (Fig. 13). The vegetation activity showed a decreasing trend in the most areas of Outer Mongolia (blue box), where the ecological restoration program was not implemented. 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 program is one of main drivers of the increasing trend in vegetation activity in the BTSSR.

Furthermore, the Beijing–Tianjin Sand Source Control Project is a large ecological restoration effort being implemented with key measures and policies, such as enclosure of grassland, conversion of cropland to forest or grassland (i.e., gain for green), reforestation and afforestation by aerial seeding or closing hill, grazing prohibition or rotation or rest. Numerous studies have shown that enclosure of grassland can alter vegetation species composition and improve grassland productivity (Deleglise et al., 2011; Witt et al., 2011; Verdoodt et al., 2009). For example, Jiang and Zhang (2006) found that aboveground biomass increased by 18 times (or 26 times) after 5 years of enclosure of mobile sands (or fixed smooth sands) in Plain Blue Banner, Inner Mongolia, which is located in the center of the BTSSR. Furthermore, grain for green, reforestation and afforestation by aerial seeding or closing hill, can improve vegetation activity (Zhang et al., 2001). For instance, based on field observation data, Zhao et al. (2011) found that aboveground

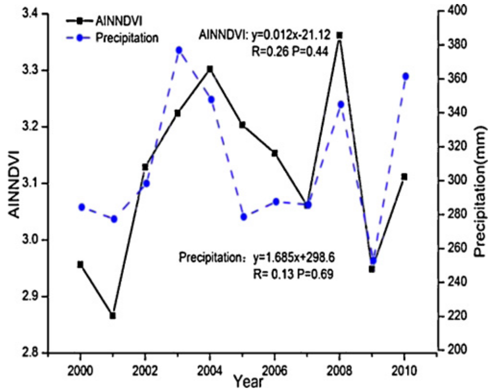

Fig. 11. Interannual variations of precipitation and AINNDVI in the BTSSR during 2000–2010.

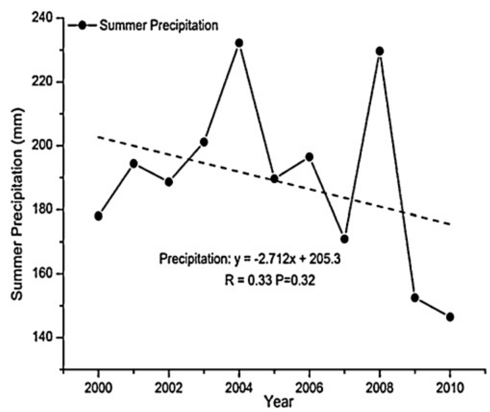

Fig. 12. Interannual variations of summer precipitation in the BTSSR during 2000–2010.

biomass increased significantly due to a project to convert cropland to forest from 2005 to 2010 in Duolun County (located in southern Otindag Sandy land). In summary, the ecological restoration program may have a large effect on the increasing trend of vegetation activity in the BTSSR.

The cause of annual, seasonal and monthly increases in vegetation activity in the BTSSR remains unclear. For example, the advanced growing season may contribute to the increasing spring

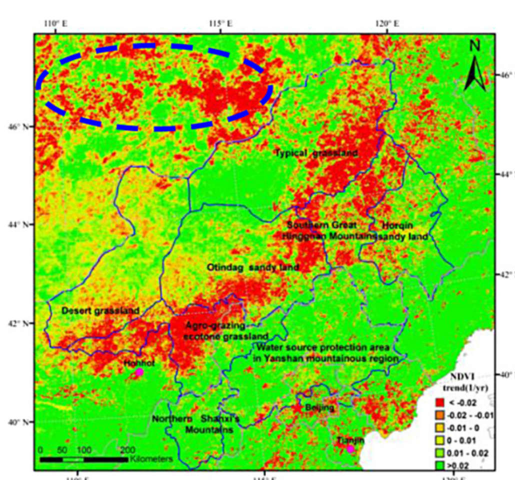

Fig. 13. Comparison of the trend of vegetation activities in and outer of the ecological restoration program region.

NDVI, while reduced precipitation or drought or inappropriate economic growth and land-use may result in a sharp decrease in summer NDVI in the southwest-to-northeast regions of the BTSSR. Moreover, the ecological restoration program may have large effects on the vegetation change. In further studies, the cause of the increasing trend in NDVI in the BTSSR will be analyzed.

5. Conclusions and future directions

The multi-year NDVI dataset from 2000 to 2010 was used to analyze the trends of annual, seasonal and monthly vegetation activities in the BTSSR. The result indicated that annual, seasonal and monthly vegetation activities, as measured by NDVI, NPP and vegetation coverage, increased at the whole area and biome scales, implying that the ecological restoration program was effective in the BTSSR.

(1) The four vegetation variables exhibited an increasing trend over the past 11 years by two different trend analysis methods, indicating that vegetation activity increased in the BTSSR. For example, the AINNDVI showed the largest increase with a magnitude of 4.27% during the 11 years and a trend of 0.0121 $year^{-1}$. Meanwhile, the seasonal-integrated NDVI showed increasing trends in spring, summer and autumn. The largest increase in NDVI was in the spring, with a magnitude of 7.08% over the 11 years and a trend of 0.00399 $year^{-1}$. The increase rates for summer and autumn NDVI were 3.23% and 2.10%, with a trend of 0.00364 $year^{-1}$ and 0.0016 $year^{-1}$, respectively.

(2) Annual and seasonal NDVI show a high degree of spatial heterogeneity. Of the total study area, 64.33% showed an increase over the 11 years, of which 12.38% had a significant increase at the 5% level. The trends of NDVI increased in the south (especially in Yanshan and northern Shanxi), southeast (southern Horqin), northwest (desert grassland) and north (southeast of the typical grassland) but decreased sharply in the southwest (agro-grazing ecotone), center (southern Otindag sandy land) and northeast (northern Greater Hinggan).These decreasing regions were mainly in a southwest -to-northeast band in the study area. Moreover, 71.89% of the total study area had increased over the 11 years in the spring, of which 14.0% had a significant increase at the 5% level, while in the summer and autumn, 57.7% (9.02% at the 5% level) and 54.79% (7.13% at the 5% level) of the total area had increased, respectively.

(3) Although the cause of increasing vegetation activity in the BTSSR remains uncertain, drought may result in a non-significant increasing trend in vegetation activity. However, the ecological restoration program may be one of main drivers of the increasing trend in vegetation activity.

Our approach does not use the concrete and detailed data about climate change and land use change to assess the immediate cause of the observed trend of vegetation activity. It is very difficult to separate the effects of the climate change and human activities on the vegetation activity trend. Thus, there remains a great challenge for further studies on the cause of vegetation activity change in the BTSSR.

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