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ORIGINAL ARTICLE

Vegetation dynamics and factor analysis in arid and semi-arid Inner Mongolia

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Abstract Arid and semi-arid regions are highly sensitive to environmental extremes, directly affecting the economic structures and development of human societies. Climate change and human activities are the major factors of vegetation changes in these regions. This study analyzes the roles of these factors of vegetation changes within forest, grassland and desert biomes across Inner Mongolia autonomous region (IM) in China and forecasts the future vegetation dynamics in this region. Based on data from 49 meteorological stations from 1961 to 2012 and the SPOT VEG Normalized Difference Vegetation Index (NDVI) satellite data from 1998 to 2012, we analyze the vegetation coverage patterns, variations and its associating dynamic responses to climate change using the methods of Maximum Value Composition, correlation analysis, fluctuation analysis and the Hurst index. The results show that NDVI patterns in IM were determined by geographical longitude and latitude. The central and eastern portion of IM encompasses a wide area with high vegetation coverage, particularly in Hulun Buir and Xilin Gol. Over the past 15 years, the NDVI has declined in the central portion of Xilin Gol, while vegetation recovery from past degradation was evident in the desert and forest regions. Our results also demonstrate that precipitation was the major driver of vegetation growth other than temperature. However, most of the vegetation in this region is likely to show strong, sustainable growth in the future.

Keywords Inner Mongolia · Vegetation index · Climate change · Ecological restoration

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Introduction

According to the IPCC 5th Assessment Report (AR5), the Earth as a whole has experienced a warming trend of 0.85 (0.65–1.06) °C from 1880 to 2012 (IPCC5 2013). Land-cover and land-use changes interact closely with climate-related changes (Pielke et al. 2002). In particular, global warming caused extreme climate events can damage water and carbon balances (MacKay et al. 2012), cause tree mortality (Allen et al. 2010) and decrease the net primary productivity of the terrestrial system (Melillo et al. 1993; Zhao and Running 2010), especially in the arid and semi-arid regions. Decadal-scale climate anomalies and land-surface degradation have been observed worldwide, including in Northern China, India, West Asia, Africa and Australia (Hendrix and Glaser 2007; John et al. 2005; O'Brien et al. 2004; Thomas 2008; Zhai and Pan 2003).

Dry lands play an important role at the global scale because they support more than 2 billion people and provide critical ecosystem goods and services worldwide (James et al. 2013). Inner Mongolia in northern China is a typical northern-hemisphere arid and semi-arid region experienced a warming trend of 0.52 °C per decade over the last three decades (Bao et al. 2012; Wang and Zhou 2012). This region is an arid/semi-arid inland plateau with a unique, low-density nomadic culture and frequent natural disasters, such as snowstorms, dust storms, desertification and soil erosion, which threaten the survival of pastoralists and their herds (Chen and Tang 2005). According to Olson et al.'s (2001) ecological global terrestrial ecological regionalization, IM could be divided into forest, grassland and dessert. The desert steppe was dominated by *Stipa glareosa* and *S. klemenzii*. The dominant species in the typical steppe were *S. grandis*, *S. krylovii*, and *Artemisia frigida*, whereas in the meadow steppe *S. Baicalensis*, *Leymus chinensis* and *Filifolium sibiricum* were the dominant species (Kang et al. 2013). Since 1998, to slow land degradation and soil erosion and to improve environmental quality, Chinese government has implemented several ecological restoration projects, including the Beijing–Tianjin Sandstorm Source Area Comprehensive Control program (BTSSCC), the Grain for Green project (GFG) and Three-North Protective Forest Program (TNPFP). It is therefore critically important to accurately evaluate the changes in vegetation coverage and to explore how the vegetation of this region has responded to climate change and human activities during the past few decades using the existing databases.

Few studies have taken a combined view of the natural and human impact in IM. Mu et al. (2013) has utilized MODIS-NDVI data to monitor the changes in vegetation and reported a recovery trend from 2000 to 2010 as a combined effect of precipitation and temperature. John et al. (2009) thought that the socio-economic growth has increased the area of grassland and barren land (0.47 and 0.27 million km^2, respectively), and cropland and urban land have also increased (to 0.15 million km^2 and 2,197 km^2, respectively) (John et al. 2009). However, few studies have considered the changes in vegetation in the context of both climate change and human activity (Mu et al. 2013; Ren et al. 2012; Wang et al. 2008; Zhang and Xu 2011). In particular, most reports have focused on regional case studies with datasets that cover short time scales (e.g., the Mu Us sandy land, the Xilin Gol League, the Horqin sandy land and the Hulun Buir sandy land) (Meng et al. 2012; Yang et al. 2011; Zhang et al. 2011; Zhao et al. 2008).

In the present study, the first focus was on the vegetation pattern and variation in the IM, and then the impact of long-term climate parameters and human activities on vegetation coverage was explored. Furthermore, the future dynamics of the spatial vegetation patterns to develop a strong foundation for rational government decision making was predicted.

Materials and methods

Study area

The Inner Mongolia Autonomous Region (97°12′–126°04′E, 37°24′–53°23′N, zonal average elevation of 1,000 m) is the third largest province in China (Fig. 1). This region is characterized by ample mineral resources and a unique natural landscape. The steppe vegetation forms part of the great Euro-Asian grassland, and the region features a transitional climate between the humid monsoon region and the inland arid area stretching from east to west (Sun et al. 2010). During the study period, the average annual temperature ranged from −1 to 10 °C, and the average precipitation is from 50 to 450 mm. As one of the most important agricultural and animal husbandry production regions in China, the intense human activity and

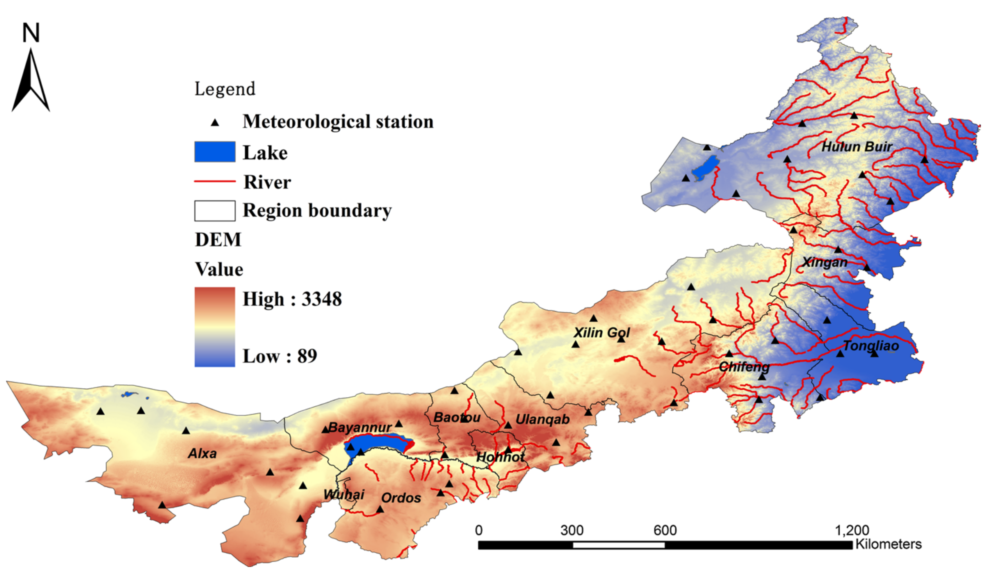

Fig. 1 Location of Inner Mongolia and the distribution of meteorological stations (*black solid triangles* represent all observatory stations) and Digital Elevation Model (DEM) data within the study area

overgrazing of the fragile ecosystem in recent years have made IM a highly sensitive area (Sun and Wang 2008).

Data resources

An NDVI dataset known as Système Probatoire d'Observation de la Terre (SPOT VGT-S10) was downloaded from a French website (http://free.vgt.vito.be/home.php/). SPOT/VEG NDVI, produced by the VEGETATION program, is a synthesis product (S10) with 1 km spatial resolution from 1998 to 2012 by MVC (Maximum Value Composite) (Holben 1986). As by better atmospheric correction, spatial resolution distortion at off-nadir angles, improved navigation and radiometric sensitivity, the VEGETATION instrument has several advantages compared to AVHRR and plays a good performance in the Inner Mongolia region (Gobron et al. 2000; Miao et al. 2013). Meteorological data from 1961 to 2012 were obtained from 49 stations across the Inner Mongolia region through the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/); it is a distributed operational system (distributed in physical existence and unified in logics) constituted jointly by national and provincial level data service (Zheng et al. 2004). To obtain a different view of the biological response to climate, Olson's global terrestrial ecological regionalization scheme was also applied (Olson et al. 2001). Ecological restoration area (i.e., the planted area of the GFG project) was collected from the 1998–2011 Chinese Statistical Yearbooks. A digital elevation model (DEM) was downloaded from an international scientific data service platform (http://datamirror.csdb.cn/).

Methods

MVC NDVI analysis

The Max NDVI algorithm (Maximum Value Composite method) calculating the NDVI was used to eliminate the influence of atmospheric conditions, such as volcanic aerosols, high insolation, low water vapor and near-nadir viewing, from each pixel (Holben 1986). The parameter of interest was the highest NDVI value in each year, which was computed using the formula given below (Holben 1986). The temporal trends in MVC NDVI were then equated to the temporal trends in green biomass (Evans and Geerken 2004). MVC NDVI was calculated based on the ten-day SPOT NDVI data using the Interactive Data Language (IDL) environment:

$$MVC_{NDVI,i} = \max_{j=1,36} I_{NDVI,ij} \quad (1)$$

where $I_{NDVI,ij}$ is the semi-monthly value in year i, j is the individual 10-day period (1–36) and $MVC_{NDVI,i}$ is the annual maximum NDVI in year i.

Correlation analysis

The Pearson correlation coefficient is an index to measure the linear relationship between two random variables. Positive and negative correlation (r_{XY}) indicates a positive and a negative trend, respectively (Lee Rodgers and Nicewander 1988). The empirical relation to calculate the correlation coefficient is shown in Eq. (2),

$$r_{XY} = \frac{\sum_{i=1}^{N}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{N}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{N}(Y_i - \bar{Y})^2}} \quad (2)$$

where, $\bar{X}$, $\bar{Y}$ are the average values of the two series, N is the total number, i is the serial number.

Fluctuation analysis

Standard deviation is a widely applied method of obtaining the fluctuation (Gupta 1952). A low standard deviation indicates that NDVI value of each pixel is close to the mean value, whereas high standard deviation indicates that it disperses over a large range of value in the time series (Mu et al. 2013). The standard deviation is calculated based on Eq. (3) mentioned below,

$$S = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - \bar{X})^2} \quad (3)$$

where, S is the standard deviation, $\bar{X}$ is the average value, i is the serial number. The larger the S value, the larger the fluctuation of vegetation.

Hurst index prediction

Rescaled range analysis (R/S) is an effective method to predict and quantify the dynamics of future time series. This method was developed by the hydrographer H.E. Hurst in 1951. The Hurst index is used to evaluate whether the long-term variation of a time series is continuous or random. This index quantifies the relative tendency of a time series either to regress strongly to the mean or to cluster in a preferential direction (He et al. 2011). According to Li et al. (2013), the following steps are used to calculate the Hurst index:

First, divide the time-series data $\{\delta(t)\}$ ($\tau = 1, 2, \ldots n$) into subseries $\delta(t)$.

$$\langle\delta\rangle_\tau = \frac{1}{\tau}\sum_{t=1}^{\tau}\delta(t), \ \tau = 1, 2, \ldots n. \quad (4)$$

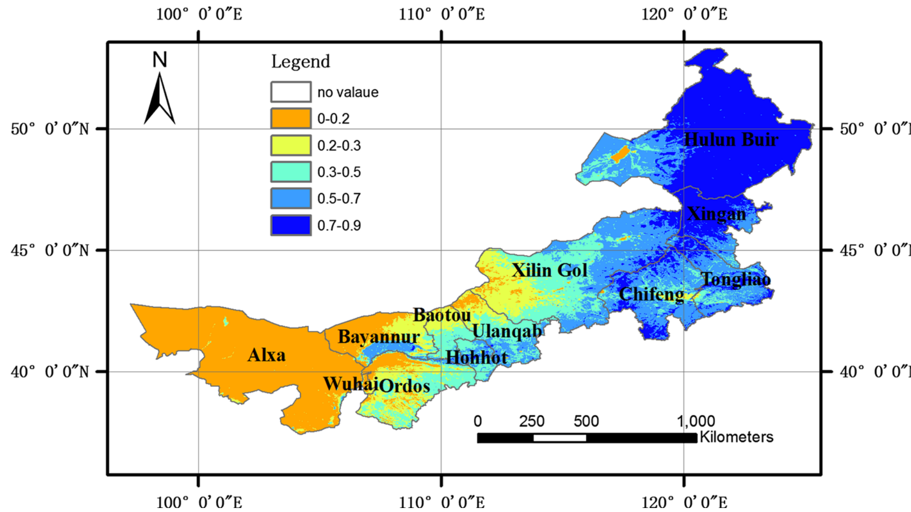

Fig. 2 Spatial distribution of NDVI in IM from 1998 to 2012

Then, calculate the cumulative deviation.

$$X(t,\tau) = \sum_{u=1}^{t} (\delta(u) - \langle\delta\rangle_\tau), 1 \le t \le \tau \quad (5)$$

$$R(\tau) = \max_{1 \le t \le \tau} X(t,\tau) - \min_{1 \le t \le \tau} X(t,\tau), \quad \tau = 1,2\ldots,n \quad (6)$$

Next, create the standard deviation sequence:

$$S(\tau) = \left[\frac{1}{\tau}\sum_{t=1}^{\tau} (\delta(t) - \langle\delta\rangle_\tau)^2\right]^{\frac{1}{2}}, \ \tau = 1,2,\ldots n \quad (7)$$

Finally,

$$R(\tau)/S(\tau) \cong R/S\infty(c\tau)^H \quad (8)$$

When the Hurst index (0–1) equals 0.5, the time series is stochastic without consistency. A value greater than 0.5 indicates the long-term future sustainability of the time series, with greater values indicating greater consistency. A value less than 0.5 indicates the anti-consistency (future anti-trend) of the time series, with lower values corresponding to greater sustainability of the anti-consistency (He et al. 2011; Hurst 1951; Mu et al. 2013).

Results

Spatial pattern and temporal variation of vegetation

Figure 2 shows the general average vegetation NDVI in Inner Mongolia from 1998 to 2012. The magnitude of NDVI clearly declines from the northeast (NDVI value 0.5–0.9) to the southwest (NDVI value 0–0.3). According to Olson's ecological zones, the eastern portion of IM is covered by dense forest, whereas the middle and western portions are covered by grassland and desert vegetation, respectively (Olson et al. 2001). The Hulun Buir prairie and the Xilin Gol League in the northeast part have dense vegetation coverage (NDVI value 0.3–0.9), whereas desert regions, such as Alxa and Bayannur in the southwest part, have sparse vegetation coverage (NDVI value 0–0.3).

The spatial pattern of the vegetation is decided by the original geographic features. The relationships between elevation (extracted from the DEM map), longitude and latitude and NDVI from 1998 to 2012 are shown in Fig. 3. According to Fig. 3a, NDVI is negatively correlated with altitude ($R = -0.57$, $P < 0.01$), indicating that most of the vegetation is located on the plains rather than in high-altitude mountain regions. NDVI is significantly positively correlated with longitude ($R = 0.80$, $P < 0.01$) and latitude ($R = 0.62$, $P < 0.01$) (Fig. 3b, c), increased from west to east (100°–124°E) and from south to north (39°–50°N), respectively. The magnitude of NDVI increases with longitude and latitude which means the vegetation NDVI has a broad altitudinal and latitudinal distribution.

As shown in Fig. 3d, the annual NDVI shows a slight increase from 1998 to 2012, with peak values of approximately 0.41 and 0.52. The maximum values appear in 2003 and 2008, whereas the minimum values appear in 2001, 2007 and 2009. Across the entire NDVI time series, the periods 2001–2003 and 2009–2012 exhibit strong recovery trends, whereas the period 1998–2001 shows a continuous significant decreasing trend from 0.48 to 0.41 due to the severe drought (Li et al. 2010). From 2003 to 2009, NDVI has declined from 0.48 to 0.43 at a rate of 0.71 % per year, although a fluctuation is evident in 2008.

Spatial variation and fluctuation of vegetation coverage

Figure 4 indicates the annual spatial variation and fluctuation of vegetation NDVI from 1998 to 2012, and Fig. 4a shows that 80 % of IM has become greener over the past 15 years, with significant spatial differences, in accordance with a global trend toward increasing greenness in semi-arid areas from 1981 to 2007 (Fensholt et al. 2012). NDVI

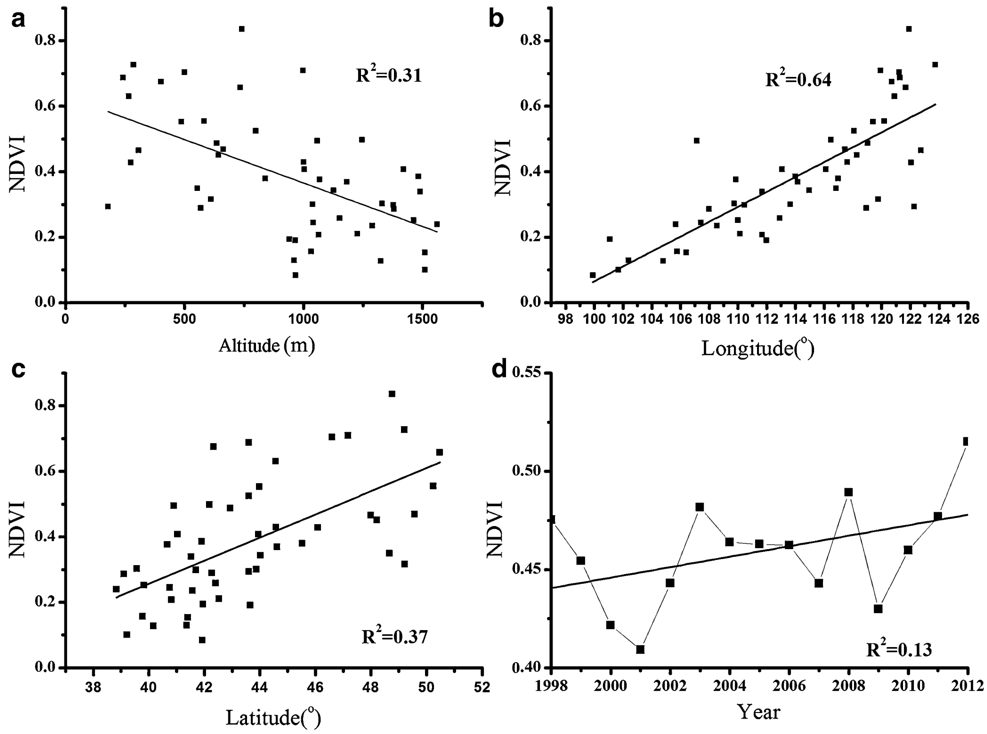

Fig. 3 Relationship between NDVI with DEM (**a**), longitude (**b**), latitude (**c**) and variation of annual NDVI during 1998–2012 (**d**); the *black solid line* indicates the fitting curve

has progressively declined in the central IM of Xilin Gol and Ulanqab, whereas the eastern and western portions of the region have become increasingly greener. In Fig. 4b, the strength of the fluctuation is indicated by a color scale varying from 0 to 0.42 (with larger values corresponding to greater fluctuation) (Mu et al. 2013). Large fluctuations appear in the central portion of IM (Xilin Gol, Chifeng, Tongliao, Hohhot, Ulanqab and Batou), where the decreasing trend is evident. Therefore, it was concluded that the vegetation in the Xilin Gol area has declined, with wide variation in recent years. Meanwhile, NDVI in Hulun buir is increased with very high fluctuations; desert NDVI in the Alxa is enhanced in a relatively low rate. This result could be evidenced and explained by Yang's research in Xilin Gol, ecological development has been accompanied by a shift from a regional ecological surplus to an ecological deficit due to excessive consumption of local resources and huge demand for livestock production, eventually leading to land degradation and overgrazing in this area (Yang et al. 2011).

The response of vegetation to climate variability and human activities

Climate changes in IM

According to the meteorological station data, the zonal average temperature of IM has increased linearly by 0.48 °C per decade from 1961 to 2012. The mean temperature over the past 52 years was 4.25 °C, with lowest and highest temperatures of 2.4 and 6.2 °C, respectively. From 1961 to 1969, a decreasing trend of approximately 1.5 °C per decade occurred (Fig. 5). Then, however, the mean temperature has increased at a rate of 0.57 °C per decade which is much higher than the global warming trend. The mean temperature in IM shows a declining trend from south to north and from west to east. Within IM, the warmest and coldest meteorological stations are Guai Zi (9.4 °C) and Tu Li River (−4.3 °C) station, respectively, with a mean temperature difference of 13.7 °C between the two stations. Before 1974, precipitation declined with small fluctuations (9.6 mm per decade). Precipitation then increased rapidly from 1975 to 1998 (30.7 mm per decade). During 1999–2012, precipitation increased slightly, from 241.5 to 381.3 mm. The spatial distribution of overall precipitation shows that the northeastern portion of IM receives more rainfall than the southwestern portion which did not show here, with a mean annual rainfall of 280 mm. The wettest and driest regions of IM are located in Xiao Ergou (479 mm) and E Jinaqi (34 mm) station, respectively.

The response of vegetation to climate

Through comparison of views on the meteorological data and the NDVI time series, the authors concluded the

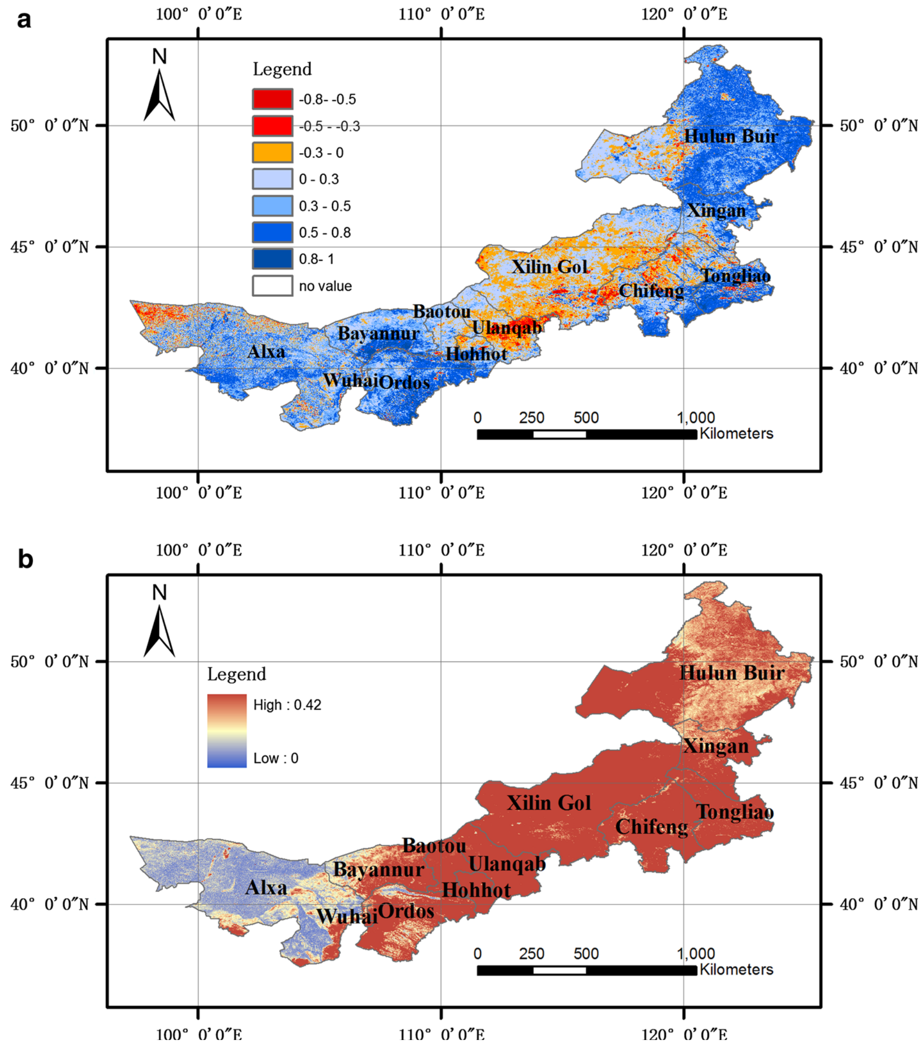

Fig. 4 Annual spatial variation (a) and fluctuation (b) of NDVI from 1998 to 2012

temporal trend of grassland, forest and desert biomes under the climatic factors over the last 15 years. The NDVI time series in Fig. 6 show vegetation recovery in the forest and desert biomes and a declining trend in grasslands. The grassland NDVI decreased from 0.51 in 1998 to 0.43 in 2012, showing a strong positive correlation with precipitation ($R = 0.80$, $P < 0.01$) and no correlation with temperature ($R = -0.11$, $P = 0.69$). The forest NDVI has increased substantially ($R = 0.56$, $P < 0.1$) and shows positive correlations with precipitation ($R = 0.61$, $P < 0.1$) and temperature ($R = 0.61$, $P < 0.1$). The desert NDVI shows no apparent trend and is significantly strong correlated with precipitation ($R = 0.89$, $P < 0.01$) and not correlated with temperature ($R = 0.08$, $P = 0.77$). These differences among biomes suggest that the impact of climate on vegetation is highly biome specific. Among the three biomes, the desert biome shows the closest relationship with precipitation. The forest, grassland and desert NDVI values respond much more weakly to temperature than to precipitation, indicating that precipitation is the main driving factor, especially in the desert region.

Future vegetation dynamics

The Hurst index is a purely mathematical method that provides statistical predictions concerning future trend. Based on the Hurst index, the authors simulated the trend of the spatial structure of the vegetation NDVI (Fig. 7), the average Hurst index based on the SPOT time series from 1998 to 2012 is 0.621, indicating that most of the vegetation coverage has shown a positive trend over the past 15 years. The blue-colored regions are the most sustainable areas (approximately 88 % of the region), and the low sustainability area is 60.7 %. The anti-sustainable areas are shown in red and yellow and account for 12 % of the area. Here, low sustainability refers to the combined effect of human activities and climate-related changes, whereas high sustainability refers to the individual impacts of human activities or climate-related changes (He et al. 2011).

Figures 4a and 7 compared the past vegetation trend with the future vegetation trend in the corresponding region of IM to capture the vegetation coverage features. Figure 4a shows an increasing trend on both portions of the IM region during the past 15 years, whereas the Hurst index values shown in Fig. 7 predict a positive recovery trend across most of the region. It suggests that the forested areas in the eastern portion of IM (Hulun Buir, Xingan) and the desert areas in the western portion (Alxa, Bayannur and Ordos) will show a sustainable trend. While in certain degraded areas, such as Xilin Gol, Ulanqab and Chi Feng, are expected to recover (Figs. 4b, 7). The grassland areas in Xilin Gol show anti-degradation in the future, with weak anti-consistency. Thus, this highly sustainable vegetation recovery trend can be expected to expand throughout most of IM. Government decision corresponds closely to our finding of anti-sustainable development in this region. The Hurst index results can be tested based on the official ecological projects in Inner Mongolia completed in 2012, as well as the newest environmental policies for 2013–2022 that have already been published (e.g., the second phase of BTSSCC).

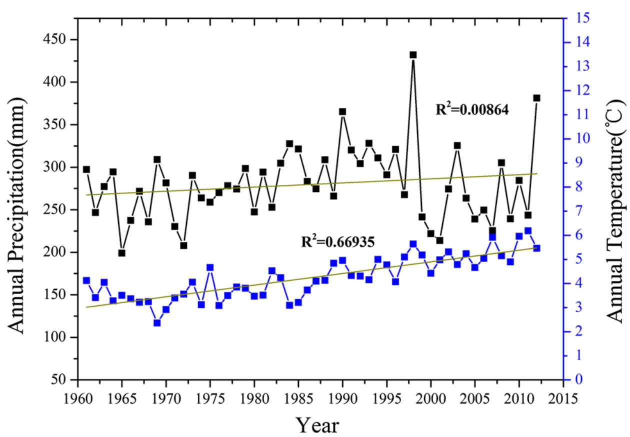

Fig. 5 Time series of annual precipitation and temperature from 1961 to 2012

Discussions

Most researchers believe that climate change is the main cause of changes in vegetation coverage in arid and semi-arid regions. For example, Anyamba and Tucker (2005) indicated that vegetation changes in the Sahel are closely related to precipitation, while temperature is the main factor driving overall vegetation recovery in northern Europe (Karlsen et al. 2008). In the present study in Inner Mongolia, the authors have estimated historical vegetation dynamics and climate changes using simple statistical analyzes. Results show that precipitation rather than temperature may be the predominant factor affecting the vegetation in IM, especially in the desert region, it suggested that the response of vegetation to precipitation differs by both biome type and its amounts in IM. In the future climate scenario analysis, the precipitation simulation in

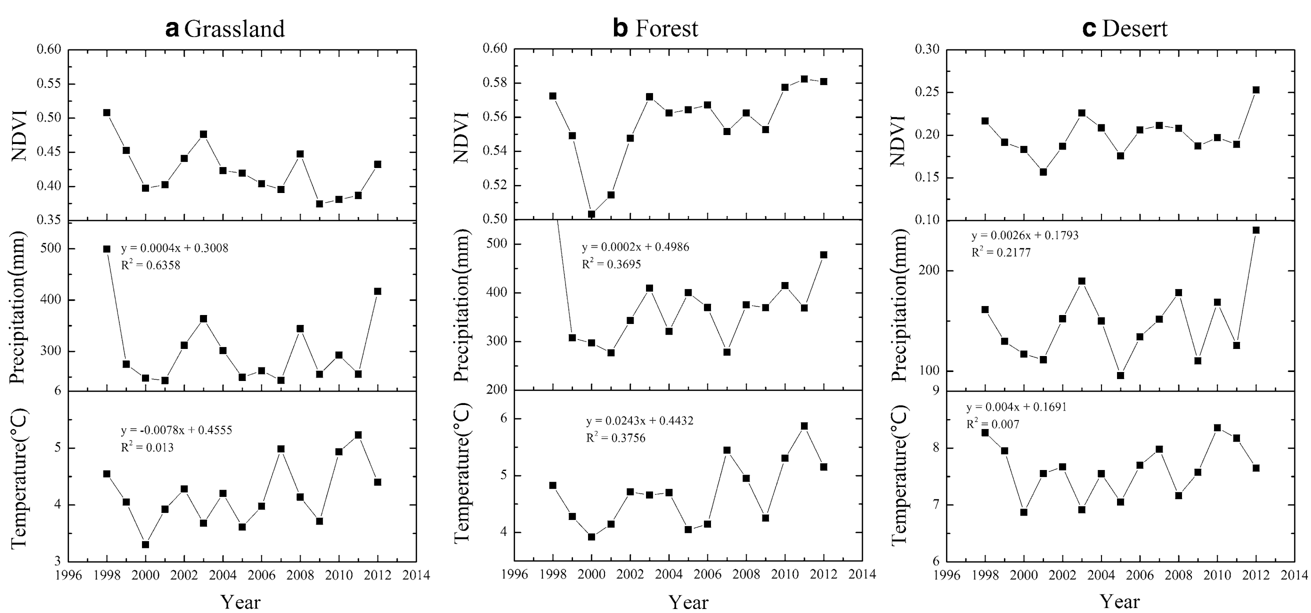

Fig. 6 Changes of NDVI, precipitation and temperature in different ecological zones [grassland (**a**), forest (**b**) and desert (**c**)] from 1998 to 2012

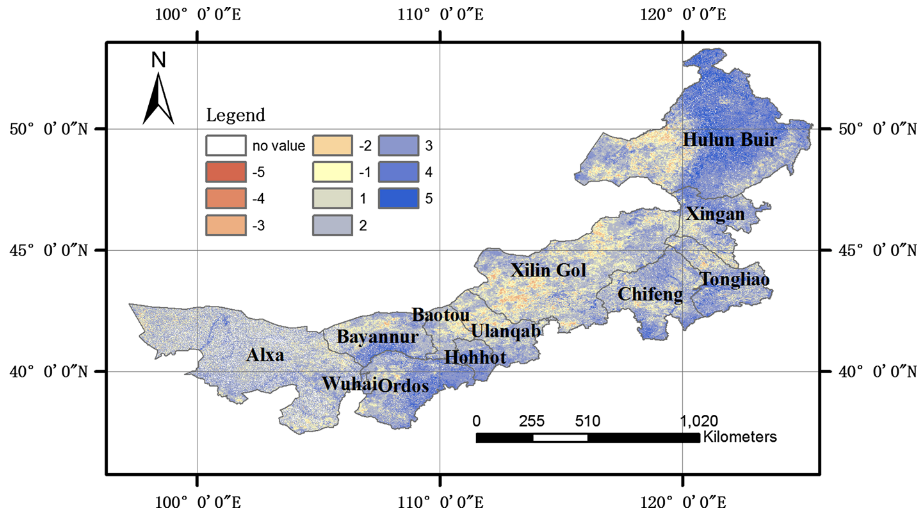

Fig. 7 The simulated trend of the spatial structure of the Hurst Exponent. The value can be divided into the 11 following intervals: $-5(0 \leq H \leq 0.20)$, $-4(0.20 \leq H \leq 0.25)$, $-3(0.25 \leq H \leq 0.35)$, $-2(0.35 \leq H \leq 0.45)$, $-1(0.45 \leq H < 0.50)$, $1(0.50 < H \leq 0.55)$, $2(0.55 \leq H \leq 0.65)$, $3(0.65 \leq H \leq 0.75)$, $4(0.75 \leq H \leq 0.85)$, and $5(0.85 \leq H \leq 1.00)$

the arid and semi-arid regions is of particular importance.

Apart from the aforementioned natural drivers, human modifications could potentially play an important role in regional ecosystem changes. However, these effects are difficult to quantify in spatial patterns as most studies are qualitative research. Several ecological projects have been implemented in Inner Mongolia and have largely improved the vegetation quality and coverage (Liu et al. 2008). Among these project (BTSSCC, GFG and TNPFP), according to the Chinese Statistical Yearbooks, the total area under the GFG project in IM increased from 4.48×10^5 hm^2 in 1998 to 7.35×10^5 hm^2 in 2012 (92.7×10^5 hm^2 in total from 1998 to 2012), the size of the project peaked from 2002 to 2010 (with 9.23×10^5 and 9.12×10^5 hm^2). The combined effect from climatic factors and ecological restoration projects may improve the environmental conditions for plant growth in Inner Mongolia in the future as shown by the Hurst index. At the local scale, farmers' decisions could largely determine the vegetation variation (Meng et al. 2012).

Conclusions

This work provides a better understanding of climate change in the past five decades and the vegetation NDVI trends from 1998 to 2012 in the Inner Mongolia, and attempts to predict the development of the vegetation in this region. Generally speaking, by analyzing the 49 meteorological stations in IM, there shows a warming trend from 1961 to 2012, although the meteorological data show no apparent changes in precipitation statistically. On the other hand, the pattern of grassland and forest biomes is driven by terrain and adequate temperature and precipitation conditions; NDVI is significantly positively correlated with longitude and latitude and it declines from the northeast to the southwest. Precipitation is the main climatic driver factor in IM, among the three biomes; the desert biome shows the closest relationship with precipitation. Analyzing the long time series of SPOT VEG, our results also indicate that vegetation recovery has occurred over the past 15 years (1998–2012), deteriorated vegetation areas are located in Xilin Gol. The vegetation in IM is predicted to show a strong recovery trend in the near future due to the combined influence of climate change and human activities. Overall, vegetation coverage increases in IM is identified likely largely due to the Chinese grassland ecological policy implemented in recent years. In the future, our potential research aims to apply more accurate remote-sensing phenology and situ data on the IM to more accurate estimation of the vegetation dynamics.

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