Spatiotemporal Variation of Vegetation and Its Climatic Response in the Horqin Sandy Land, 1982-2015: Postprint

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Date: 2021-04-23T00:00:00+00:00

Abstract

Based on GIMMS NDVI3g.v1 data from 1982-2015, combined with station meteorological data, and employing methods such as trend analysis, coefficient of variation, Hurst exponent, and partial correlation analysis, this study investigates the spatiotemporal characteristics, climate response, and future trends of vegetation cover in the Horqin Sandy Land. The results indicate: (1) Over the 34-year period, vegetation cover in the Horqin Sandy Land showed a slow increasing trend, with a growth rate of 0.23% per decade. Overall, the vegetation cover changes can be divided into three increasing periods (1982-1999, 2000-2004, and 2008-2012) and three decreasing periods (1999-2000, 2004-2007, and 2012-2015), with the maximum value occurring in 1999 and the minimum value in 2009. (2) The vegetation cover pattern in the Horqin Sandy Land exhibits a distribution characteristic of "high in the north and south, low in the middle." Using the "Xar Moron River-Xinkai River" as a boundary, the vegetation change trend in the northern region is mainly degradation, while in the southern region it is mainly improvement. (3) The coefficient of variation in the Horqin Sandy Land is high in the west and low in the east, with significant regional differences. Areas with low fluctuation are mainly distributed in the northern high-altitude regions (accounting for 5.52%), where the vegetation type is primarily coniferous and broadleaf mixed forest. (4) The same-direction characteristic of vegetation change in the Horqin Sandy Land is stronger than the reverse-direction characteristic, with areas of continuous degradation and continuous improvement accounting for 61.48% and 37.03%, respectively. Precipitation is the main factor influencing vegetation change in the study area.

Full Text

Spatiotemporal Variation of Vegetation in the Horqin Sandy Land and Its Response to Climate Change from 1982-2015

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Abstract

Based on GIMMS NDVI3g.v1 data and meteorological station data from 1982 to 2015, this study employs trend analysis, variation coefficient, Hurst index, and partial correlation analysis to investigate the spatiotemporal characteristics, climatic responses, and future trends of vegetation cover in the Horqin Sandy Land. The results indicate: (1) Vegetation cover exhibited a slow increasing trend of 0.23% per decade, with the overall change pattern divisible into "three ascendings" (1982-1999, 2000-2007, 2008-2012) and "three descendings" (1999-2000, 2004-2008, 2012-2015). The maximum value occurred in 1999 and the minimum in 2009. (2) The spatial distribution of vegetation cover showed a "high in the north and south, low in the middle" pattern. Using the "Xar Moron River-Xinkai River" as a boundary, the northern region experienced primarily degradation trends, while the southern region showed improvement. (3) The coefficient of variation displayed a "high in the west, low in the east" pattern with significant regional differences. Low-fluctuation areas were mainly distributed in the northern high-altitude regions (5.52% of the total area), dominated by coniferous and broadleaf mixed forests. (4) Hurst index analysis revealed that vegetation change persistence was stronger than anti-persistence, with continuous degradation and continuous improvement areas accounting for 61.48% and 37.03%, respectively. (5) Precipitation was the dominant factor influencing vegetation variation in the study area.

Keywords: Horqin Sandy Land; NDVI3g.v1; spatiotemporal variation; climate response; Hurst index; partial correlation analysis

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1. Introduction

Desertification represents one of the most critical ecological, social, and economic issues in northern China. Sandy lands are recognized as among the most sensitive regions responding to global change, where land desertification and deteriorating ecological environments pose severe threats to ecological security and sustainable socioeconomic development. The Horqin Sandy Land, historically a lush grassland with abundant water and vegetation, has gradually evolved into China' s largest desertified area due to climate change and human activities, becoming a major source region for sandstorms in northern China.

Vegetation serves as a crucial indicator of ecosystem trajectory. Terrestrial vegetation plays vital roles in water conservation and soil retention, forming the foundation of ecosystem existence. Therefore, studying vegetation dynamics in ecologically fragile zones is essential for vegetation management in desertified regions. Vegetation indices are important metrics for assessing surface vegetation conditions and indicating ecological changes. Among various vegetation indices, the Normalized Difference Vegetation Index (NDVI) is the most widely applied, as it can objectively reflect surface vegetation cover conditions and monitor large-scale, long-term vegetation changes.

Previous studies have analyzed vegetation cover changes in the Horqin Sandy Land using different NDVI products. For instance, Huang et al. used SPOT VEGETATION NDVI data to reveal an overall increasing vegetation trend with substantial magnitude. Ma et al. employed MODIS NDVI data to analyze qualitative and quantitative relationships between climate and vegetation, finding that vegetation conditions gradually deteriorated from east to west, with vegetation showing improvement trends and precipitation exhibiting slight increases while temperature trends remained unclear. Wang et al. developed the WaVEM eco-hydrological model to study vegetation response patterns under climate change, identifying precipitation interannual variability as the primary driver of vegetation change. Short-term droughts caused sharp vegetation declines, while vegetation recovered rapidly after drought cessation; however, consecutive multi-year droughts led to significant vegetation degradation. Wei et al. analyzed MODIS surface reflectance products and found that vegetation growth was better in the east than west and better in the south than north, with limited spatiotemporal variability. Li et al. used MODIS NDVI data to show that vegetation in the Horqin region increased overall at a rate of 0.23% per year.

However, research on long-term vegetation cover changes and climate responses in the Horqin Sandy Land remains insufficient. Most studies have focused solely on grassland, leading to fragmented understanding. Additionally, previous climate response analyses typically employed pairwise correlation between climate variables and surface cover variables, neglecting the interactions among climate variables. Multivariate correlation analysis better reveals land-atmosphere interaction mechanisms. Therefore, this study utilizes the latest long-term GIMMS NDVI3g.v1 data, combined with temperature and precipitation data, and employs trend analysis, variation coefficient, Hurst index, and partial correlation analysis to comprehensively analyze spatiotemporal characteristics, trend features, land-atmosphere coupling, sustainability, and future change trends of various vegetation types (sandy land, grassland, forest, and shrub) in the Horqin Sandy Land. This research aims to reveal vegetation cover change patterns and climate impacts on vegetation growth in arid and semi-arid regions under global change, providing theoretical foundations for desertification trend assessment and prevention efforts.

1.1 Study Area The Horqin Sandy Land is located in the transitional zone between the Inner Mongolia Plateau and the Northeast Plain, geographically positioned between 41°41 -46°05 N and 117°49 -123°42 E. It extends from the Qilaotu Mountains of the Yanshan system in the west to the western Songnen Plain in the east, bordered by the Nuluerhu Mountains to the south and the Greater Khingan Mountains to the north, covering a total area of 12.51$×10^{4}$ km^2. The terrain slopes from west to east with elevations ranging from 120–800 m. The region experiences a temperate semi-arid continental monsoon climate with annual mean temperatures of 5.4–6.8°C, annual precipitation of 343–451 mm, and annual wind speeds of 3.4–4.4 $\mathrm{m} \cdot \mathrm{s}^{-1}$. The dominant soil type is aeolian sandy soil, followed by meadow soil and chestnut soil. The native vegetation consists of sparse forests dominated by *Ulmus pumila* and *Quercus mongolica*, though most natural vegetation has degraded to psammophytic vegetation and temperate desert steppe due to human disturbance and desertification. Located in the farming-pastoral ecotone of northern China, the Horqin Sandy Land has a fragile ecological environment, and frequent wind-sand disasters combined with irrational human activities have made it one of the most typical desertified regions in northern China.

1.2 Data Sources **Remote Sensing Data:** The GIMMS NDVI3g.v1 dataset was obtained from NASA' s Goddard Space Flight Center, spanning 1982–2015 with a spatial resolution of 0.083°$×$0.083° and a temporal resolution of 15 days. This dataset underwent rigorous radiometric correction, geometric correction, cloud removal, and bad line elimination, ensuring data quality. Compared with other NDVI datasets, it offers longer time series, higher accuracy, and smaller errors, demonstrating excellent applicability in global and regional vegetation change studies. This study employed the Maximum Value Composite (MVC) method to effectively eliminate cloud, atmospheric, and solar zenith angle effects, and further applied MVC to obtain annual maximum NDVI (NDVI).

Land Cover Data: The vegetation type map was obtained from the Earth System Science Data Sharing Platform (Globalland30 at https://www.webmap.cn/commres.do?method=globeIndex) at a scale of 1:1,000,000.

Meteorological Data: Annual average temperature and precipitation data from meteorological stations were obtained from the China Meteorological Data Sharing Network (http://data.cma.cn). Using ArcGIS©, 100 km kriging interpolation was applied to these station data to generate annual average temperature and precipitation distributions at 0.083° resolution for the Horqin Sandy Land from 1982–2015.

1.3 Methods **1.3.1 Trend Analysis:** The unary linear regression trend analysis method simulates the change trend of each pixel, reflecting the spatial characteristics of NDVI trends over different periods. Using data from all years avoids randomness and contingency in results, providing more accurate reflection of vegetation growth conditions and change trends. The slope is calculated as:

$$\theta_{slope} = \frac{n \times \sum_{i=1}^{n} i \times NDVI_{max_i} - \sum_{i=1}^{n} i \sum_{i=1}^{n} NDVI_{max_i}}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where θ_{slope} is the regression equation slope for the pixel; n is the monitoring period; $NDVI_{max_i}$ is the annual maximum NDVI value for year i. When $\theta_{slope} > 0$, vegetation index increases over time, indicating increasing vegetation cover; conversely, it indicates decreasing trends.

1.3.2 Variation Coefficient: The variation coefficient measures the relative variability of geographic data. This study uses it to analyze vegetation change stability:

$$C_v = \frac{\sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (NDVI_{max_i} - \overline{NDVI_{max}})^2}}{\overline{NDVI_{max}}}$$

where C_v is the variation coefficient of NDVI ; n is the monitoring period; $NDVI_{max_i}$ is the annual maximum NDVI for year i; $\overline{NDVI_{max}}$ is the mean NDVI . Larger C_v values indicate greater fluctuation, while smaller values indicate more stable conditions.

1.3.3 Hurst Index: The Hurst index quantitatively describes long-term dependence in time series data, effectively predicting future development trends relative to past patterns. For a given time series $\xi(t)$, $t = 1, 2, \dots, n$, the mean sequence is calculated as:

$$\xi(\tau) = \frac{1}{\tau} \sum_{t=1}^{\tau} \xi(t), \quad \tau = 1, 2, \dots, n$$

The cumulative deviation is:

$$X(t, \tau) = \sum_{u=1}^{t} (\xi(u) - \xi(\tau)), \quad t = 1, 2, \dots, \tau$$

The range $R(\tau)$ and standard deviation $S(\tau)$ are:

$$R(\tau) = \max_{1 \le t \le \tau} X(t, \tau) - \min_{1 \le t \le \tau} X(t, \tau)$$

$$S(\tau) = \sqrt{\frac{1}{\tau}\sum_{t=1}^{\tau}(\xi(t) - \xi(\tau))^2}$$

If there exists a relationship $R/S \propto \tau^H$, the time series exhibits Hurst phenomenon, where H is the Hurst index obtained through least squares fitting in a double logarithmic coordinate system.

1.3.4 Partial Correlation Analysis: Partial correlation analysis examines the relationship between two specific variables while controlling for a third variable correlated with both. First, the correlation coefficient between two elements is calculated:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where r_{xy} is the correlation coefficient between variables x and y; n is the sample size; x_i and y_i are annual maximum NDVI, temperature, or precipitation values; $\bar{x}$ and $\bar{y}$ are corresponding temporal means.

The partial correlation coefficient is then calculated as:

$$r_{xy,z} = \frac{r_{xy} - r_{xz}r_{yz}}{\sqrt{(1 - r_{xz}^2)(1 - r_{yz}^2)}}$$

where $r_{xy,z}$ represents the partial correlation between variables x and y with variable z held constant.

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2. Results

2.1 Temporal Variation Characteristics of Vegetation Cover From 1982 to 2015, NDVI in the Horqin Sandy Land showed an overall slow increasing trend of 0.23% per decade [Figure 2: see original paper], consistent with previous research but significantly lower than China' s overall vegetation cover increase of 0.84% per decade. The temporal variation can be divided into "three ascendings" (1982-1999, 2000-2007, 2008-2012) and "three descendings" (1999-2000, 2004-2008, 2012-2015). The maximum value occurred in 1999 and the minimum in 2009. The "three descending" periods corresponded well with concurrent drought events.

2.2 Spatial Variation Characteristics of Vegetation Cover 2.2.1 Spatial Distribution Patterns: Based on NDVI data, the spatial distribution exhibited a "high in north and south, low in middle" pattern [Figure 3: see original paper]. NDVI values ranged between 0.2-0.8, with the mean value of 0.6.

High-value areas (0.6–0.8) accounted for 35.49% of the study area, primarily distributed in northern high-altitude regions with coniferous forests, broadleaf forests, and shrubs, as well as in southern low-elevation flat areas covered by forests and croplands. Medium-cover areas (0.4–0.6) comprised 57.60%, forming large contiguous patches in central and southern regions dominated by grassland and cropland. Low-value areas (0.2–0.4) accounted for 6.91%, concentrated in eastern Ongniud Banner and northwestern Naiman Banner, dominated by desert grassland and bare land.

2.2.2 Spatial Change Trends: Pixel-based trend analysis of NDVI revealed significant spatial heterogeneity [Figure 4: see original paper]. Using the "Xar Moron River–Xinkai River" as a boundary, the northern region, dominated by cropland, grassland, and forest, showed primarily degradation trends, possibly related to recent climate variability (rising temperatures, decreasing summer precipitation) and warming-drying trends. In contrast, the southern region, also containing extensive cropland and grassland, showed improvement trends, significantly influenced by human activities including the Grain for Green Program, grazing bans, the Three-North Shelter Forest Program, and scientific agricultural management. Extremely significant improvement areas accounted for 26.49% of the study area, mainly distributed south of the "Xar Moron River–Xinkai River."

2.2.3 Spatial Variation Stability: The variation coefficient (C_v) ranged from 0.01–0.45, showing a "high in the west, low in the east" pattern with distinct regional differences [Figure 5: see original paper]. Based on C_v magnitude and regional characteristics, five fluctuation levels were defined: low fluctuation (0–0.05), relatively low fluctuation (0.05–0.10), moderate fluctuation (0.10–0.15), relatively high fluctuation (0.15–0.20), and high fluctuation (>0.20). The spatial pattern exhibited "west high, east low, with coexisting high and low fluctuations, predominantly relatively low fluctuation, and obvious regional differences." Relatively low fluctuation areas were most common (55.74%), distributed along both sides of the Xar Moron, Laoha, Xinkai, and Jiaolai Rivers. Moderate fluctuation areas (27.98%) surrounded relatively high fluctuation areas, mainly north of the "Xar Moron River–Xinkai River." High fluctuation areas were least common (3.83%), distributed in central-eastern Bairin Right Banner, southern Naiman Banner, and Kulun Banner, dominated by grassland and cropland.

2.3 Vegetation Response to Climate Change Spatial partial correlation analysis between vegetation growth and climate change revealed that NDVI was positively correlated with precipitation across 91.85% of the study area, with significant ($P<0.05$) and extremely significant ($P<0.01$) positive correlations in 43.69% of the area, mainly in northeastern and southeastern regions [Figure 6: see original paper]. Negative correlations accounted for 8.15%, primarily in southeastern Ongniud Banner and Naiman Banner, with significant negative correlations in only 0.10% of the area.

NDVI correlations with temperature showed a "negative north, positive south" pattern relative to the "Xar Moron River–Xinkai River" boundary [Figure 7: see original paper]. Positive correlations occurred in 56.36% of the area, with significant and extremely significant positive correlations in 4.32%, mainly in Kailu County and Horqin District along the Xiliao and Xinkai Rivers where water resources are abundant. Negative correlations accounted for 43.64%, mostly in the northern region with high evaporation, high annual temperatures, and low precipitation, accelerating surface evapotranspiration.

Pixels influenced solely by precipitation accounted for 24.50%, those influenced solely by temperature for 4.08%, while only 1.24% were simultaneously influenced by both temperature and precipitation, distributed sporadically.

2.4 Future Trends of Vegetation Cover The mean Hurst index for NDVI was 0.65, with 98.11% of pixels showing $H > 0.5$, indicating that vegetation change persistence was stronger than anti-persistence in the Horqin Sandy Land [Figure 8: see original paper]. High Hurst index values ($H > 0.65$) were distributed in southern and northern regions, showing strong consistency between future and past trends. Areas with $0.35 < H \leq 0.65$ were mainly distributed along the Xar Moron and Ulgai Rivers, showing weak persistence or anti-persistence.

Overlay analysis of change trends and Hurst index revealed that continuous degradation, continuous improvement, improvement-to-degradation, and degradation-to-improvement areas accounted for 61.48%, 37.03%, 0.30%, and 1.19%, respectively. Using the "Xar Moron River–Xinkai River" as a boundary, the northern region primarily showed continuous degradation while the southern region showed continuous improvement. The average partial correlation coefficients between NDVI and precipitation and temperature were 0.23 and 0.03, respectively, confirming that precipitation exerts stronger influence than temperature on vegetation cover in the Horqin Sandy Land.

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3. Conclusions

From 1982 to 2015, vegetation cover in the Horqin Sandy Land showed a slow increasing trend of 0.23% per decade, indicating generally favorable vegetation development conditions. The temporal variation pattern featured "three ascendings" (1982–1999, 2000–2007, 2008–2012) and "three descendings" (1999–2000, 2004–2008, 2012–2015), with maximum and minimum values in 1999 and 2009, respectively.

Spatially, vegetation cover exhibited a "high in north and south, low in middle" pattern, with low-value areas (6.91%) concentrated in desert grassland and bare land. Hurst index analysis demonstrated stronger persistence than anti-persistence in vegetation changes. Using the "Xar Moron River–Xinkai River" as a boundary, the northern region experienced continuous degradation while the southern region experienced continuous improvement, with these two categories accounting for 61.48% and 37.03% of the area, respectively.

The variation coefficient ranged from 0.01–0.45, showing a pattern of "high in the west, low in the east, with coexisting fluctuations, predominantly relatively low fluctuation, and significant regional differences." Low-fluctuation areas (5.52%) were mainly distributed in northern high-altitude regions with coniferous and deciduous broadleaf forests.

Precipitation was the primary factor controlling vegetation variation in the study area, with its influence significantly exceeding that of temperature. These findings provide a scientific basis for desertification evolution assessment and prevention efforts in the Horqin Sandy Land.

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