Spatiotemporal Dynamics of Vegetation Cover in Hulunbuir (2000-2022) and Its Response to Climatic Factors (Postprint)

Authors: Zou Xiang, Zhang Yuting, Xu Lu

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Abstract

Studies on the spatiotemporal variation characteristics of vegetation cover in Hulunbuir can provide insights for formulating precise vegetation restoration and ecological environmental protection policies, which is beneficial to the ecological civilization construction in Hulunbuir. Using methods such as Mann-Kendall trend analysis, Hurst index, linear regression, and partial correlation, based on monthly maximum value composited remote sensing data combined with temperature and precipitation datasets, this study quantitatively analyzes the dynamic distribution characteristics and future trends of vegetation in Hulunbuir from 2000 to 2022, and discusses the response of vegetation cover to climatic factors. The results show that: (1) Vegetation cover in Hulunbuir increased at a rate of $0.0021 \cdot a^{-1}$. During the entire study period, two changes in trend characteristics occurred, namely that the annual mean Normalized Difference Vegetation Index (NDVI) exhibited a stable increasing trend ($0.00007 \cdot a^{-1}$) from 2000 to 2010 and a significant increasing trend ($0.0031 \cdot a^{-1}$) from 2010 to 2022, reflecting that vegetation cover is influenced not only by climatic factors but also to a large extent by ecological protection policies. (2) Seasonally, the change rate was highest in spring ($0.0031 \cdot a^{-1}$), followed by winter ($0.0021 \cdot a^{-1}$) and summer ($0.0019 \cdot a^{-1}$), and lowest in autumn ($0.0014 \cdot a^{-1}$); spatially, the annual mean NDVI decreased from the central Greater Khingan Mountains region to the eastern hills and western grasslands. (3) The sensitivity of annual mean NDVI to climate change varied spatially and temporally, manifesting as greater sensitivity to precipitation spatially, mainly concentrated in the western grassland areas, while being more sensitive to temperature in terms of interannual variation. Vegetation cover in Hulunbuir showed an overall favorable trend, but local degradation has also emerged. Forest vegetation in the Greater Khingan Mountains region may face degradation risks in the future.

Full Text

Spatio-temporal Dynamics of Vegetation Cover in Hulun Buir and Its Response to Climatic Factors (2000–2022)

ZOU Xiang, ZHANG Yuting, XU Lu

School of Geography, Geomatics and Planning, Jiangsu Normal University, Xuzhou 221116, Jiangsu, China

Abstract

Investigating the spatiotemporal variation characteristics of vegetation cover in Hulun Buir provides valuable insights for developing targeted vegetation restoration and ecological environmental protection policies, thereby facilitating ecological civilization construction in the region. Using Sen' s slope estimator, Mann-Kendall trend analysis, the Hurst index, linear regression, and partial correlation analysis, this study quantitatively examines the dynamic distribution characteristics and future trends of vegetation in Hulun Buir from 2000 to 2022 based on monthly maximum-value-composited MODIS NDVI data combined with temperature and precipitation datasets. The results reveal that vegetation cover in Hulun Buir increased at a rate of $0.0021 \cdot a^{-1}$ during the study period. Two distinct trend phases were identified: a stable period from 2000 to 2010 ($0.00007 \cdot a^{-1}$) and a significant increasing phase from 2010 to 2022 ($0.0031 \cdot a^{-1}$), indicating that vegetation dynamics are influenced not only by climatic factors but also significantly by ecological protection policies. Seasonally, the change rates followed the order of spring ($0.0031 \cdot a^{-1}$) > winter ($0.0021 \cdot a^{-1}$) > summer ($0.0019 \cdot a^{-1}$) > autumn ($0.0014 \cdot a^{-1}$). Spatially, annual mean NDVI decreased gradually from the central Greater Khingan Mountains toward the eastern hills and western grasslands. The sensitivity of vegetation cover to climate change varied across space and time, showing greater responsiveness to precipitation in the western grassland regions spatially, while exhibiting higher sensitivity to temperature in interannual variations. Although vegetation cover in Hulun Buir demonstrates an overall improving trend, localized degradation has emerged, and forest vegetation in the Greater Khingan Mountains may face future degradation risks.

Keywords: NDVI; vegetation cover; sustainable development; Hurst index; Hulun Buir

1. Introduction

Vegetation plays a pivotal role in ecosystems as primary producers and serves as a key indicator for evaluating regional ecological environmental changes. As the medium through which soil, atmosphere, and water interact, vegetation tightly couples these spheres in nature. Consequently, investigating vegetation dynamics across different spatiotemporal scales holds significant importance for informing sustainable ecosystem development. Vegetation growth is closely related to natural conditions and human production activities, including climate, hydrology, terrain, and urban construction. Among these factors, temperature and precipitation play critical roles in plant growth and development. Climate change alters plant growth environments, thereby affecting vegetation species composition, distribution, and community structure. Human activities can modify vegetation cover trends and exert profound impacts on global ecological environments. Unreasonable anthropogenic activities such as deforestation, excessive cultivation and grazing, and land-use conversion lead to significant vegetation cover decline, while afforestation, returning farmland to forest, and improved agricultural irrigation techniques can enhance vegetation cover. Therefore, systematically and quantitatively studying the impacts of climate change and social factors on vegetation spatiotemporal variation is crucial for providing references for regional or global ecological environmental sustainability.

Benefiting from advances in satellite remote sensing monitoring technology, the Normalized Difference Vegetation Index (NDVI) has been widely applied to assess vegetation cover dynamics. NDVI is closely related to photosynthetically active radiation absorbed by photosynthetic tissues and can serve as an evaluation indicator of vegetation response to climate change, where NDVI increase or decrease indicates vegetation cover enhancement or degradation. Currently, widely used NDVI data products include NOAA/AVHRR, SPOT VGT, and MODIS. Among these, MODIS NDVI has attracted considerable attention from researchers due to its complete time series. Previous studies using NDVI to evaluate vegetation changes in northern China have achieved remarkable results. Research indicates that summer precipitation is the primary factor affecting grassland vegetation growth in northern China, and hydrothermal variations caused by temperature and precipitation remain key factors influencing vegetation cover changes. However, some studies suggest that temperature has a more significant impact on vegetation growth than precipitation. Through correlation analysis between NDVI and climate factors in Northeast China, researchers have found that vegetation cover is positively correlated with temperature and precipitation but negatively correlated with sunshine intensity, with precipitation being the most important factor. Therefore, meteorological factors constitute important influences on vegetation growth in northern China.

Located in a high-latitude inland arid region of China, Hulun Buir has experienced significant changes in temperature and precipitation patterns under global warming, leading to reorganization of water cycling processes. Various vegetation types in Hulun Buir, including grasslands and forests, have responded to these climatic drivers to varying degrees. Consequently, assessing the adaptability and response mechanisms of Hulun Buir' s vegetation to climate change holds important significance. This study employs MODIS imagery, temperature, and precipitation data from 2000 to 2022, utilizing major methods for vegetation spatiotemporal change analysis to investigate vegetation distribution patterns, change trends, and relationships with climate factors. This research provides a comprehensive assessment of the ecological environmental status of vegetation in Hulun Buir, enhances understanding of vegetation cover responses to climate change, and offers scientific foundations for vegetation ecological environmental protection, degradation control, and grassland management in the region.

2. Study Area and Data

2.1 Study Area

Hulun Buir is located in northeastern Inner Mongolia, bordering Mongolia and Russia at the intersection of the three countries, and is considered an important ecological barrier in northern China [Figure 1: see original paper]. The region covers approximately 75.97% of Inner Mongolia' s total area, with forest and grassland accounting for of its land area, making it one of the world' s largest natural grassland regions. The overall landform exhibits zonal distribution, comprising the western plateau grasslands, central mountainous forests, and eastern hilly croplands. Hulun Buir belongs to the mid-temperate and cold-temperate climate zones, characterized by a temperate continental climate with long, cold winters, short, warm summers, and pronounced seasonal precipitation distribution. The region features numerous rivers and lakes, including the Argun River and Hulun Lake, which play important regulatory roles in the regional ecological environment. As the forests, grasslands, and meadows in Hulun Buir are situated in mid-to-high latitude temperate zones [Figure 1: see original paper], they respond sensitively to global climate change. Northeast China has been identified as one of the most significant warming regions in China and East Asia under global climate change.

2.2 Data Sources

This study utilized MODIS/MOD13Q1 satellite data with a spatial resolution of 250 m and a temporal resolution of 16 days. The data product was generated using the maximum value composition method and had undergone geometric and radiometric corrections. In this study, if monthly mean values were missing, they were replaced by the mean of neighboring years. Annual mean NDVI was calculated as the average of all monthly values, while seasonal means represented the average of spring (March–May), summer (June–August), autumn (September–November), and winter (December–February) months. Meteorological datasets, including annual precipitation and mean temperature from 2000 to 2022, were obtained from the National Earth System Science Data Center (http://www.geodata.cn). All data products were processed using Python for projection transformation, boundary masking, and resampling to obtain annual mean NDVI, precipitation, temperature, elevation, and population density data at 250 m resolution. Additionally, land-use data for Hulun Buir were downloaded from the Resource and Environmental Data Platform (https://www.resdc.cn) with 1 km spatial resolution.

2.3 Research Methods

This study employed simple linear regression to analyze the spatiotemporal trends of NDVI in Hulun Buir from 2000 to 2022, where the slope value indicates the trend magnitude and sign represents increasing or decreasing vegetation change. The absolute slope value serves as an important indicator for determining the significance of vegetation change. Additionally, the Sen+Mann-Kendall trend analysis, a non-parametric statistical method for detecting trends in time series data, was applied to all raster pixels. This method calculates the median and is robust as it does not require data distribution assumptions and is unaffected by missing values and outliers. Based on slope values, vegetation change was classified into three categories: degradation (Slope $<$ -0.0005), stable (-0.0005 $\leq$ Slope $\leq$ 0.0005), and improvement (Slope $>$ 0.0005). Statistical significance was determined using the Z-value, with $|Z| \geq 1.96$ indicating significance at the 0.05 level. These parameters were used to further classify vegetation cover into five categories: severe degradation, slight degradation, stable, slight improvement, and significant improvement.

The Hurst index was employed to analyze the sustainability characteristics and future trend classification of vegetation cover in Hulun Buir, with detailed methodology available in Zhang et al. Additionally, spatial analysis based on raster pixel values was used to conduct partial correlation analysis between annual NDVI and climate factors. Changes in partial correlation coefficients indicate enhanced or reduced associations between vegetation growth conditions and climate factors.

3. Results and Analysis

3.1 Spatial Pattern of NDVI in Hulun Buir

From 2000 to 2022, annual mean NDVI in Hulun Buir exhibited a decreasing gradient from the central Greater Khingan Mountains toward the eastern hills and western grasslands [Figure 2: see original paper]. Extremely low NDVI values in the southwestern typical steppe pastoral areas (Xin Barag Left Banner, Xin Barag Right Banner, Manzhouli) primarily corresponded to water bodies, including Hulun Lake in the southwest and the Nen River reservoir and Nen River basin in the east. High-value NDVI zones were distributed in north-central Ergun City, central-western Oroqen Autonomous Banner, northwestern Arun Banner, and central-western Zhalantun City. Statistical analysis of raster pixel values revealed that annual mean NDVI ranged from 0.31 to 0.49, with high-value areas accounting for 31.74% of the total region and low-value areas comprising 64.94%. The low NDVI values in western Hulun Buir may be associated with overgrazing, urban expansion, and mining development. Therefore, the impacts of vegetation degradation caused by human activities require urgent attention from relevant authorities.

3.2 Temporal Variation Characteristics of NDVI

Overall, vegetation cover in Hulun Buir showed a fluctuating yet stable increasing trend from 2000 to 2022 (Slope = 0.0021, $R^2 = 0.5341$, $p < 0.01$). Two distinct phases were identified: a stable period from 2000 to 2010 (Slope = 0.00007, $p > 0.05$) and a significant increasing phase from 2010 to 2022 (Slope = 0.0031, $R^2 = 0.4685$, $p < 0.01$), with the latter slope exceeding the overall trend, indicating rapid vegetation cover increase during this period. Mann-Kendall trend analysis further confirmed a significant upward trend after 2010 [Figure 3: see original paper].

Seasonally, vegetation growth rates ranked as spring ($0.0031 \cdot a^{-1}$) > winter ($0.0021 \cdot a^{-1}$) > summer ($0.0019 \cdot a^{-1}$) > autumn ($0.0014 \cdot a^{-1}$). The spring growth rate exceeded the annual mean, indicating that spring vegetation growth is most influenced by external environmental factors. Summer and autumn rates were lower than the annual mean, suggesting relatively weaker external influences. Following the implementation of the "Twelfth Five-Year Plan," China strengthened the transformation and upgrading of livestock structures, and rational livestock development further promoted significant vegetation cover increase. This demonstrates that after vegetation cover reaches saturation, national and governmental interventions become important influencing factors, highlighting the need for timely policy adjustments based on ecological changes.

3.3 Spatial Change Trends of NDVI

Except for central-eastern Oroqen Autonomous Banner, southeastern Morin Dawa Daur Autonomous Banner, most areas of Arun Banner, northeastern Zhalantun City, northern Xin Barag Right Banner, and localized areas of Xin Barag Left Banner where slope values were negative, most regions exhibited positive NDVI change rates [Figure 4: see original paper]. Vegetation improvement areas were dominated by forests and grasslands in temperate monsoon zones with abundant precipitation and thermal conditions. Significant degradation areas coincided with negative slope regions, accounting for 6.12% of total pixels, reflecting impacts of unreasonable human activities on vegetation growth trends. Significant improvement areas comprised 71.47% of total pixels, distributed mainly in central and northern regions including Yakeshi City, Genhe City, Ergun City, and southern Zhalantun City .

The Chinese government implemented the "Returning Grazing to Grassland" policy in 2003, strengthening management of northern grasslands and markedly improving grassland ecology and resources. Additionally, the State Council issued "Opinions on Promoting Sound and Rapid Development of Pastoral Areas" in 2011, establishing an ecological priority development strategy for Hulun Buir and maintaining grassland ecosystem stability—key reasons for the significant vegetation improvement trend. However, vegetation degradation in certain areas appears linked to human activities: point-like grassland degradation in the southwest may relate to coal mining; large-scale degradation in central Oroqen

Autonomous Banner is closely associated with urban expansion; and extensive vegetation degradation in the southeast may result from unreasonable agricultural cultivation. Urban construction land in Hulun Buir increased from 0.407% to 0.484% of total land area, while farmland showed a slight increasing trend, indicating human activities play an important role in vegetation cover change [Figure 5: see original paper].

3.4 Correlation Between NDVI and Climate Factors

The Hurst index for annual mean NDVI in Hulun Buir ranged from 0.24 to 0.71 with a mean value of 0.54, indicating that future vegetation cover will show overall anti-persistence with slight increasing trends likely to reverse. In future trend predictions, pixels showing persistent degradation and persistent improvement accounted for 47.37% and 39.32% of the total area, respectively [Figure 6: see original paper]. Persistent improvement areas were distributed mainly in southwestern grasslands and eastern hilly regions, while persistent degradation areas were concentrated in the central Greater Khingan Mountains forest zone. Areas experiencing severe degradation, including central-eastern Oroqen Autonomous Banner and most of Arun Banner, are projected to improve in the future. These findings suggest that forest vegetation degradation in the Greater Khingan Mountains warrants attention and enhanced management.

Annual precipitation in Hulun Buir ranged from 170.97 mm to 571.40 mm, with a mean of 416.99 mm. Linear regression revealed an increasing trend at 5.7547 $\mathrm{mm \cdot a^{-1}}$. Precipitation exhibited a southwest-east-northeast zonal distribution pattern, influenced by the north-south orientation of the Greater Khingan Mountains, which blocks moisture from reaching western areas, creating a northeast-high, southwest-low pattern. Annual mean temperature ranged from -5.89°C to 3.91°C, with a mean of -0.97°C, showing an increasing trend of 0.0319°C $\cdot\,\mathrm{a^{-1}}$ consistent with global climate change patterns. Low-temperature zones were concentrated in northern Ergun City and Genhe City, while high-temperature areas were distributed in northern Xin Barag Left Banner, Xin Barag Right Banner, and northern Zhalantun and Arun Banners [Figure 7: see original paper].

Partial correlation analysis between annual NDVI and precipitation revealed positive correlations across 70.35% of the study area, with high correlation coefficients (0.22–0.72) concentrated in southwestern grasslands (37.24% of total area), indicating precipitation strongly influences NDVI variation in these regions. The southwestern grasslands feature an east-high, west-low topography, consistently affected by continental air masses and blocked from eastern warm-moist airflow by the Greater Khingan Mountains, resulting in low precipitation. Additionally, evaporation significantly exceeds precipitation in this region, making water availability a key limiting factor for vegetation growth.

Correlation between NDVI and temperature showed positive coefficients across 71.5% of the study area, concentrated in the Greater Khingan Mountains forest zone, coinciding with high NDVI value distributions. Hulun Buir is a typical temperate continental monsoon region where precipitation occurs mainly in summer (60-70% of annual total), with spring and autumn receiving less and winter the least. Favorable hydrothermal conditions during summer months benefit the growth of perennial and xerophytic herbaceous plants, making summer a critical period for vegetation growth.

Correlation analysis between NDVI and extreme climate events showed significant correlations with temperature variables, particularly the strongest correlation with annual minimum temperature ($r = 0.59$, $p < 0.01$), moderate correlation with mean annual temperature ($r = 0.56$, $p < 0.01$), and weakest correlation with annual maximum temperature ($r = 0.41$, $p < 0.05$). However, correlations with precipitation variables were not significant, except for annual mean precipitation ($r = 0.36$, $p < 0.05$), suggesting that temperature, particularly minimum temperature, is the key meteorological factor controlling vegetation cover in high-latitude Hulun Buir, while extreme precipitation events may have limited impact on vegetation development.

4. Conclusion

Hulun Buir serves as an important ecological barrier in northern China, with vegetation cover influenced by multiple factors including natural conditions and human activities, making it a natural laboratory for studying interactions between climate factors and anthropogenic impacts. Using Sen+Mann-Kendall trend analysis, correlation, and partial correlation methods, this study investigated spatiotemporal vegetation cover changes and driving factors in Hulun Buir from 2000 to 2022, yielding the following conclusions:

1. **Spatial characteristics**: Vegetation cover in Hulun Buir decreases gradually from the central region toward the southwest and east, corresponding to the land-use pattern of grassland-forest-cropland from west to east.

2. **Temporal characteristics**: Overall, vegetation cover showed an increasing trend from 2000 to 2022 at a rate of $0.0021 \cdot a^{-1}$. Seasonally, spring exhibited the highest growth rate ($0.0031 \cdot a^{-1}$), followed by winter and summer, with autumn showing the lowest rate ($0.0014 \cdot a^{-1}$). Two distinct phases were identified: a stable fluctuation period (2000–2010, $0.00007 \cdot a^{-1}$) and a significant increase period (2010–2022, $0.0031 \cdot a^{-1}$), demonstrating that national policies have important impacts on vegetation cover after growth saturation.

3. **Spatial change trends**: Most areas showed significant improvement trends, while degradation occurred in southeastern hilly areas of Morin Dawa Daur Autonomous Banner, central urban expansion areas of Oroqen Autonomous Banner, and mineral extraction areas around Manzhouli. Future predictions indicate forest vegetation degradation in the Greater Khingan Mountains and improvement in southwestern grasslands, necessitating tailored ecological protection policies.

4. **Climate response**: Vegetation cover showed significant responses to climate factors. Spatially, vegetation is sensitive to both temperature and precipitation, particularly in southwestern temperate grasslands where precipitation is a key limiting factor. Interannually, vegetation cover is more responsive to temperature, especially annual minimum temperature, while showing no significant response to precipitation extremes.

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Note: Figure translations are in progress. See original paper for figures.