Spatiotemporal Variation and Driving Factors of Grassland Vegetation Cover in Ningxia Based on Geodetector: Postprint

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Abstract

Using the NDVI time series dataset from SPOT/VEGETATION for the period 2000–2019 as the data source, this study employs the annual mean method, Theil-Sen Median slope analysis, and Mann-Kendall test methods to investigate the spatiotemporal distribution and variation characteristics of grassland vegetation cover in Ningxia, and utilizes the Hurst exponent method to analyze the sustainability characteristics and future development trends of grassland vegetation cover. Simultaneously, based on the geographical detector model, the influences of 13 factors including mean precipitation, elevation, and gross domestic product (GDP) on its spatiotemporal distribution were quantified. The results indicate that: (1) During 2000–2019, the annual mean NDVI of grassland vegetation in Ningxia exhibited a fluctuating increasing trend, with a growth rate of 0.005 a-1, and significant regional variability in fluctuations; spatially, it displayed a distribution pattern of high values in the south and low values in the north, with areas of extremely high and high vegetation cover concentrated in the Liupan Mountain region of Guyuan City and along the Yellow River irrigation zones; (2) Over the 20-year period, the status of vegetation cover improved significantly, with an overall positive trend; however, 59.341% of grasslands may still face potential risks of continuous degradation or a shift from improvement to degradation in the future; (3) The environmental factor to which grassland vegetation distribution responded most sensitively was precipitation, and the interaction with the strongest overall explanatory power was that between climate and soil; the primary manifestation of interactions among factors influencing grassland vegetation distribution and variation characteristics was mutual enhancement or nonlinear enhancement relationships, and no independent relationships existed among the factors.

Full Text

Analysis of Spatiotemporal Variation Characteristics and Driving Factors of Grassland Vegetation Cover in Ningxia Based on Geographical Detectors

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Abstract

This study examines the spatiotemporal variation characteristics of grassland vegetation cover at the regional scale and analyzes its driving factors using the SPOT/VEGETATION NDVI time series dataset from 2000 to 2019. The annual mean method, Theil-Sen Median trend analysis, and Mann-Kendall test were employed to investigate the spatiotemporal distribution and change patterns of grassland vegetation cover in Ningxia. Additionally, the Hurst index method was used to analyze the sustainability characteristics and future development trends of grassland vegetation cover. Simultaneously, geographical detectors were applied to quantify the influence of 13 factors—including average precipitation, altitude, and gross domestic product—on the spatiotemporal distribution of vegetation cover. The results demonstrate that from 2000 to 2019, the average annual NDVI of grassland vegetation in Ningxia exhibited a fluctuating increasing trend with a growth rate of $0.005 \cdot a^{-1}$, though regional fluctuations varied considerably. Spatially, vegetation cover displayed a distribution pattern of high values in the south and low values in the north, with extremely high and high vegetation cover areas concentrated in the Liupan Mountain region of Guyuan City and along the Yellow River irrigation zones. Over the 20-year period, grassland vegetation conditions improved significantly, with an overall positive trend; however, 59.341% of grasslands may face potential risks of continuous degradation or transition from improvement to degradation in the future. Precipitation emerged as the most sensitive environmental factor influencing grassland vegetation distribution response, while climate and soil factors demonstrated the strongest interactive explanatory power overall. The interactions among factors affecting grassland vegetation distribution and change characteristics primarily manifested as mutual enhancement or nonlinear enhancement relationships, with no independent relationships observed between factors.

Keywords: NDVI; trend analysis; spatiotemporal variation; driving factor; grassland; Ningxia

1 Introduction

Grasslands represent a land type dominated by herbaceous vegetation, situated between desert and forest ecosystems, and constitute one of the most widely distributed vegetation types globally, covering approximately 40% of terrestrial ecosystems. They play crucial roles in protecting species abundance, maintaining livestock balance, regulating water cycles, and mitigating climate change. Previous studies have identified significant drivers of vegetation cover change in Ningxia. For instance, research on forest-grass vegetation coverage in the Hetao Irrigation District revealed that regional water content is the primary driver affecting forest and grassland growth conditions. Li et al. found that climate is the dominant factor influencing vegetation cover change in Ningxia, while Lin et al. demonstrated that precipitation, soil type, vegetation type, and GDP are the main drivers of vegetation cover change in the Helan Mountains. The Normalized Difference Vegetation Index (NDVI) is closely correlated with leaf area index (LAI), net primary production (NPP), and fraction of absorbed photosynthetically active radiation (FAPAR), enabling accurate and rapid assessment of vegetation growth conditions. Meteorological, surface, and human activity factors exert significant influences on grassland vegetation, and vegetation in arid and semi-arid regions is particularly vulnerable to damage that is difficult to reverse.

Current research on vegetation cover change in Ningxia encompasses various land types including forestland, grassland, wetland, cropland, and others. However, because grassland is difficult to isolate from other land types, studies focusing specifically on the spatiotemporal dynamics and driving forces of grassland vegetation cover are lacking. This research employs annual mean analysis, Theil-Sen Median trend analysis, Kendall test, and the Hurst index method to investigate the spatiotemporal distribution, change characteristics, sustainability features, and future development trends of grassland vegetation cover in Ningxia. Furthermore, geographical detectors are utilized to analyze the driving factors of grassland vegetation cover change, providing scientific references and decision-making support for developing effective grassland protection and restoration strategies and achieving sustainable grassland ecosystem management in Ningxia.

2 Study Area and Methods

2.1 Study Area Overview

Ningxia is located in northwestern China (104°17 –107°39 E, 35°14 –39°23 N), bordered by the Tengger Desert, Ulan Buh Desert, and Mu Us Sandy Land to the west, north, and east, respectively, and connected to the Loess Plateau in the south. The terrain is higher in the south and lower in the north, with complex landforms. The highest point is Aobao Geda (Ebo Geda, Maji Ridge) at 3,556 m. The region has a temperate continental arid and semi-arid climate characterized by drought, low precipitation, strong evaporation, high winds, abundant sand, cooler temperatures in the south and warmer in the north, and higher humidity in the south and drier conditions in the north. Annual precipitation ranges from 150 mm to 700 mm, with annual temperatures between 5–10°C, making it a typical ecologically fragile zone in China. Natural vegetation types mainly include grassland, forest, and shrubland. Due to variations in climate and hydrothermal conditions from south to north, Ningxia's grasslands form diverse types, sequentially classified from south to north as: mountain meadow, temperate meadow steppe, temperate typical steppe, temperate desert steppe, temperate desert, and temperate desertified steppe.

According to the 2019 Ningxia forest and grassland resources monitoring results, temperate desert steppe accounts for 62.113% of total grassland area, and temperate typical steppe accounts for 25.193%, representing the two dominant grassland types. As the main component of Ningxia's ecosystem, grasslands provide essential ecological functions such as windbreak and sand fixation, soil and water conservation, and play a vital role in maintaining regional ecological balance and promoting economic development.

2.2 Data Sources and Processing

Data sources and preprocessing methods are summarized in Table 1. When constructing the geographical detector model, each factor data required preprocessing: geomorphology and soil data were discretized according to primary categories (geomorphological types and soil orders, respectively); other factors were normalized. NDVI was used as the dependent variable (Y), and the 13 factor datasets were used as independent variables (X).

2.3 Methods

2.3.1 Temporal and Spatial Pattern Analysis Annual NDVI values were calculated to analyze interannual variation patterns; pixel-by-pixel annual NDVI means were computed to examine spatial distribution characteristics and their variations over the 20-year period.

2.3.2 Spatial Variability Analysis The coefficient of variation (Cv) was used to reflect the fluctuation degree of grassland vegetation cover change, calculated as:

$$C_v = \frac{\sigma}{\overline{NDVI}}$$

where σ is the standard deviation and $\overline{NDVI}$ is the mean NDVI value.

2.3.3 Theil-Sen Median Trend Analysis and Mann-Kendall Test The Theil-Sen Median method calculates the median slope to represent the change rate and trend:

$$S = \text{Median}\left\{\frac{NDVI_j - NDVI_i}{j - i}\right\}, \quad i = 1, 2, \ldots, n-1; \quad j = i+1, \ldots, n$$

where $NDVI_i$ and $NDVI_j$ represent NDVI values at times i and j, respectively. A positive slope S indicates an increasing trend, while a negative slope indicates a decreasing trend.

The Mann-Kendall test, widely used in hydrological and climate trend assessment, considers data distribution and automatically handles outliers. It was employed to test the significance of pixel-level change trends. The calculation formula refers to established literature.

2.3.4 Future Evolution Trend Analysis The Hurst index method predicts future evolution trends based on NDVI time series data. The rescaled range (R/S) analysis calculates the Hurst exponent (H). When $0.5 < H < 1$, the time series exhibits long-term memory, meaning future trends will continue past patterns; when $0 < H < 0.5$, the series shows anti-persistence, indicating future trends will reverse past patterns.

2.3.5 Driving Force Analysis of Grassland NDVI Change Thirteen factors (Table 2) were selected to analyze potential driving forces of NDVI change in Ningxia grasslands using the geographical detector model. ArcGIS 10.8 software was used to associate influencing factors with spatial locations and analyze NDVI variation.

Factor Detection: Measures the spatial differentiation of NDVI and the explanatory power of factors (q-value):

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N\sigma^2}$$

where L is the number of strata of variable Y (NDVI) or X (influencing factor); $h = 1, 2, \ldots, L$; σ_h^2 is the variance of stratum h; σ^2 is the total variance of Y in the study area; N_h is the number of units in stratum h; and N is the total number of units. The q-value ranges [0,1], with higher values indicating stronger explanatory power of X over Y.

Interaction Detection: Identifies interaction types between factors (Table 3).

Ecological Detection: Uses F-statistics to test whether the influence of different factors on NDVI spatial distribution has significant differences:

$$F = \frac{N_{X1}(N_{X2} - 1)SSW_{X1}}{N_{X2}(N_{X1} - 1)SSW_{X2}}$$

where SSW_{X1} and SSW_{X2} are the sums of within-layer variances for factors $X1$ and $X2$, respectively; N_{X1} and N_{X2} are their sample sizes.

Risk Detection: Identifies suitable ranges or types of factors for vegetation cover using t-statistics:

$$t = \frac{\bar{Y}_h - \bar{Y}_k}{\sqrt{\frac{\sigma_h^2}{n_h} + \frac{\sigma_k^2}{n_k}}}$$

where $\bar{Y}_h$ and $\bar{Y}_k$ are means of subregions h and k; n_h and n_k are sample sizes; and σ_h^2 and σ_k^2 are variances. The statistic follows a Student's t-distribution.

3 Results

3.1 Temporal Variation Characteristics of Grassland NDVI

At the annual timescale, NDVI values showed an increasing trend from 2000 to 2019, with a growth rate of $0.005 \cdot a^{-1}$ (Figure 2). The mean NDVI value was 0.243, with a maximum of 0.281, indicating overall improvement in grassland vegetation conditions.

[Figure 2: see original paper]

3.2 Spatial Distribution Pattern of Grassland NDVI

Pixel-by-pixel calculation of average NDVI values over 20 years revealed distinct spatial patterns. Using the natural breaks classification method, grassland vegetation status was categorized into five levels: extremely low (NDVI $\leq$ 0.190), low (0.190 $<$ NDVI $\leq$ 0.338), medium (0.338 $<$ NDVI $\leq$ 0.459), high (0.459 $<$ NDVI $\leq$ 0.584), and extremely high (NDVI $>$ 0.584). The spatial distribution showed a clear pattern of high values in the south and low values in the north (Figure 3). Extremely low vegetation cover occupied 7,071.725 km^2 (34.397%), distributed in the northwestern desert margin areas including Huinong District, Dawukou, Zhongning County, Qingtongxia, and Shapotou. Low vegetation cover accounted for 7,845.092 km^2 (38.157%) in central-eastern arid regions. Medium vegetation cover comprised 3,355.033 km^2 (16.318%) in Haiyuan County and Helan County. High vegetation cover occupied 1,688.375 km^2 (8.212%), while extremely high vegetation cover comprised 599.619 km^2 (2.916%), concentrated in the Liupan Mountains and Yellow River irrigation zones.

[Figure 3: see original paper]

3.3 Spatial Variability Analysis

The coefficient of variation (Cv) was calculated pixel-by-pixel for 2000–2019 NDVI data. Results showed that Ningxia grassland NDVI changes exhibited low to medium fluctuation patterns, with significant regional differences (Figure 4). Low fluctuation areas (Cv $\leq$ 0.161) covered 7,538.200 km^2 (36.665%), while medium fluctuation areas (0.161 $<$ Cv $\leq$ 0.204) covered 5,501.385 km^2 (26.758%). High and extremely high fluctuation areas were primarily distributed in central arid zones, desert regions, and the Helan Mountain area, closely related to annual precipitation variability.

[Figure 4: see original paper]

3.4 Spatiotemporal Change Trends

Combining Theil-Sen Median slope analysis with Mann-Kendall significance testing, grassland NDVI change trends were classified into five categories: significant improvement, slight improvement, stable, slight degradation, and significant degradation. Results indicated that grassland vegetation cover improved significantly, with degradation areas being relatively small (Figure 5). Significant improvement covered 13,734.576 km^2 (66.803%), slight improvement covered 5,116.118 km^2 (24.884%), stable areas comprised 84.041 km^2 (0.409%), slight degradation occupied 50.047 km^2 (0.243%), and significant degradation covered 1575.062 km^2 (7.661%).

[Figure 5: see original paper]

3.5 Spatial Transfer Matrix

A spatial transfer matrix of grassland vegetation cover was constructed using ArcGIS (Table 4). Results show that from 2000 to 2019, extremely low vegetation cover decreased substantially, with clear conversion from lower to higher vegetation cover levels, indicating significant grassland vegetation growth and successful ecological restoration.

3.6 Future Evolution Trends

3.6.1 Spatial Sustainability Analysis The mean Hurst index for Ningxia grassland was 0.431, indicating anti-persistence in the time series. Areas with H $>$ 0.5 (8,884.793 km^2, 43.214%) exhibited persistent characteristics, while areas with H $<$ 0.5 (11,675.051 km^2, 56.786%) showed anti-persistent characteristics, suggesting future trends may reverse past patterns.

3.6.2 Spatial Change Trend and Future Development Overlay analysis of change trends and sustainability characteristics revealed four future development directions (Figure 6): benign direction (40.255% of grassland area), malignant direction (59.341%), stable/uncertain (0.404%). Benign development areas are mainly distributed in Yuanzhou District, Pengyang County, Jingyuan County, Longde County, Xiji County, and parts of Yanchi and Tongxin counties. Malignant development areas are concentrated in Xingqing District, Huinong District, Yongning County, and central arid regions.

[Figure 6: see original paper]

3.7 Driving Factor Analysis

3.7.1 Factor Detection Analysis Geographical detector analysis of NDVI spatial differentiation showed varying explanatory power among factors (Table 6). Annual precipitation (X_1) had the highest q-value (0.804), followed by humidity index (X_2, 0.800) and dryness index (X_3, 0.794). Climate factors (precipitation, humidity, dryness, temperature, accumulated temperature) all exceeded 80% explanatory power, representing dominant factors. Soil type, geomorphology, slope, and aspect also showed strong influence (>60%), while population density had minimal significant effect.

3.7.2 Interaction Detection Analysis Most factor interactions exhibited mutual or nonlinear enhancement, with combined q-values exceeding individual factor q-values (Figure 7). The top five interactions involved soil type combined with climate factors (precipitation, temperature) and human activity factors (population density). Although human activity factors alone had low explanatory power, their interactions with environmental factors were strong, indicating indirect but important influences on vegetation spatial patterns.

[Figure 7: see original paper]

3.7.3 Ecological Detection Analysis Ecological detection revealed significant differences between most factor pairs (Figure 8), particularly between precipitation/humidity and other factors, confirming climate as the dominant influence.

[Figure 8: see original paper]

3.7.4 Risk Detection Analysis Risk detection identified optimal ranges for vegetation cover (Table 7). Climate factors: annual precipitation of 545–623 mm and temperature of 2.8–3.7°C supported best vegetation conditions. Surface factors: elevation of 2,303–2,502 m, semi-hydromorphic soils, and medium-relief mountains with slopes of 24–28° showed optimal vegetation. Human activity factors: population density of 62–72 people/km^2 (relatively low disturbance) correlated with better vegetation.

4 Discussion

4.1 Spatiotemporal Variation Characteristics of Grassland NDVI in Ningxia

From 2000 to 2019, Ningxia grassland NDVI showed a fluctuating upward trend with significant spatial heterogeneity. The spatial distribution pattern of high values in the south and low values in the north aligns with regional climate gradients. Low and extremely low fluctuation areas are distributed in southern mountainous regions with relatively abundant precipitation and along the Yellow River irrigation zones, while medium-high fluctuation areas are found in central arid zones and desert regions, closely related to annual precipitation variability.

Although significant degradation currently accounts for only 0.243% of grassland area, future trend analysis indicates that 59.341% of grasslands face potential risks of continuous degradation or reversal from improvement to degradation. This sensitivity to climate change is particularly pronounced in arid and semi-arid regions where vegetation growth is primarily climate-limited. Warm-humid conditions favor vegetation growth, while grassland restoration is influenced by both meteorological conditions and ecological protection policies.

Since the early 2000s, China has implemented ecological restoration measures in the Loess Plateau, including grazing bans and conversion of cropland to forest/grassland, which have effectively promoted vegetation recovery. Ningxia's comprehensive grazing prohibition policies have led to stable grassland communities and noticeable ecological improvement. However, future efforts should strengthen long-term grassland protection and restoration projects, continue grazing bans and restoration policies, establish robust regulatory systems, optimize livestock structures, and control grazing capacity. Enhanced monitoring of precipitation and temperature dynamics is essential for timely assessment of climate change impacts on grassland vegetation.

4.2 Response of Driving Factors to Grassland NDVI Spatial Distribution

Ningxia's location at the intersection of the Yellow River, Tengger Desert, Loess Plateau, and Mongolian Plateau creates a complex environment where meteorological, surface, and human factors jointly influence grassland vegetation. Climate factors, particularly precipitation, demonstrate decisive influence on grassland vegetation growth in semi-arid regions. This study confirms that annual precipitation, humidity index, dryness index, temperature, and accumulated temperature all exceed 80% explanatory power, with precipitation being the primary driver of spatial differentiation in grassland vegetation cover.

Soil-climate interactions show particularly strong effects. Ningxia's soil organic matter decreases from south to north, with a clear pattern of loam soils in the south and sandy soils in the north. Semi-hydromorphic soils (including meadow soil, black soil, fluvo-aquic soil, and irrigated warped soil) developed under relatively humid forest-steppe conditions prove more suitable for vegetation growth than arid soils. Risk detection analysis confirms that these soils, combined with elevations of 2,303–2,502 m and slopes of 24–28°, provide optimal conditions for grassland vegetation.

While human activity factors alone show low explanatory power, their interactions with environmental factors are substantial, indicating indirect but significant influences on vegetation spatial patterns. However, this study did not consider factors such as management regimes, livestock structure and density, grazing intensity, grassland fires, or rodent/insect disasters, which warrant inclusion in future research to deepen understanding of grassland vegetation change mechanisms.

5 Conclusion

This study utilized SPOT/VEGETATION NDVI data and meteorological data, employing annual mean analysis, Theil-Sen Median trend analysis, Kendall test, and geographical detector models to analyze spatiotemporal variation characteristics and driving factors of grassland vegetation cover in Ningxia. The main conclusions are:

1) From 2000 to 2019, grassland vegetation cover in Ningxia showed a fluctuating upward trend with overall significant improvement. Spatially, vegetation cover exhibited a high-south, low-north distribution pattern, with high-cover areas concentrated in the Liupan Mountains of Guyuan City and along the Yellow River irrigation zones. Spatial variation was dominated by low to medium fluctuation patterns with significant regional differences.
2) Grassland vegetation cover improved significantly during 2000–2019, but future trend predictions indicate poor sustainability, with 59.341% of grasslands facing potential risks of continuous degradation or reversal from improvement to degradation.
3) The spatial distribution of grassland vegetation cover is jointly affected by meteorological, surface, and human activity factors, with meteorological factors having the greatest impact. Annual precipitation exerts the strongest influence on vegetation cover spatial differentiation.
4) Interactions among factors affecting grassland vegetation distribution and change characteristics primarily manifest as mutual enhancement or nonlinear enhancement relationships, with no independent relationships observed. Climate and soil factors show the strongest interactive explanatory power.

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