Spatiotemporal Variation Patterns of Vegetation Net Primary Productivity and Its Influencing Factors in Mongolia from 2000 to 2020: Postprint

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Abstract

Mongolia is China' s northern neighbor, and its grassland ecosystem is highly susceptible to influences from both natural and human activities. A univariate linear regression model was employed to analyze the spatiotemporal evolution patterns of vegetation Net Primary Productivity (NPP) in Mongolia from 2000 to 2020; a random forest regression model combined with the Gridded Livestock of the World (GLW) dataset was used to simulate livestock grazing density in Mongolia for the year 2020; and the Geodetector method, incorporating indicators such as annual mean land surface temperature, annual mean precipitation, downward shortwave radiation, soil moisture, NO2 emissions, and the Human Footprint Index, was applied to quantitatively investigate the influencing factors of NPP variation at both national and provincial scales in Mongolia. The results indicate: (1) From 2000 to 2020, NPP in Mongolia exhibited a spatial variation pattern of increase in the east and decrease in the west, and increase in the north and decrease in the south; overall, it showed an increasing trend, primarily characterized by non-significant increases, with non-significant increase areas accounting for 62.539% of Mongolia' s total land area. (2) Single-factor analysis revealed that climatic factors constitute the primary cause of NPP variation in Mongolia, among which downward shortwave radiation and annual mean precipitation exhibited the highest explanatory power, with q-values of 0.615 and 0.602, respectively; however, the interaction effects between the Human Footprint Index, NO2 emissions, and climatic factors were greater than the results from single-factor analysis. (3) Provincial-scale analysis demonstrated that natural factors such as climate and topography remain the main driving forces of NPP variation in eastern and western Mongolia, whereas NPP variation in central Mongolia and the Hangai region is more susceptible to the interactive effects of human activities (such as grazing density and NO2 emissions) and natural factors; these regions are priority areas for future grassland degradation risk

prevention and control efforts. The research findings can provide a scientific basis for the effective management of grassland ecosystems and the formulation of sustainable development strategies in different regions of Mongolia.

Full Text

Spatiotemporal Evolution Characteristics and Influencing Factors of Vegetation Net Primary Productivity in Mongolia from 2000 to 2020

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Abstract: Mongolia, China' s northern neighbor, possesses a grassland ecosystem that is highly vulnerable to natural and anthropogenic influences. This study employs a univariate linear regression model to analyze the spatiotemporal evolution of vegetation net primary productivity (NPP) in Mongolia from 2000 to 2020. A random forest regression model, integrated with the Gridded Livestock of the World (GLW) dataset, is used to simulate livestock grazing density across Mongolia in 2020. The geographic detector method is then applied to quantitatively investigate the driving factors of NPP variation at both national and provincial scales, incorporating indicators such as mean annual land surface temperature, mean annual precipitation, downward shortwave radiation, soil moisture, NO_2 emissions, and the human footprint index. The results reveal that: (1) From 2000 to 2020, Mongolia' s NPP exhibited spatial patterns of increase in the east and north and decrease in the west and south. Overall, NPP showed an increasing trend dominated by nonsignificant increases, which accounted for 62.539% of the country' s land area. (2) Single-factor analysis demonstrates that climatic factors constitute the primary drivers of NPP change in Mongolia, with downward shortwave radiation (q = 0.615) and mean annual precipitation (q = 0.602) exhibiting the strongest explanatory power. However, the interactive effects between the human footprint index or NO_2 emissions and climatic factors surpass the explanatory power of individual factors. (3) At the provincial scale, climate and topography remain the main driving forces of NPP change in Mongolia' s eastern and western regions. In contrast, NPP changes in the central and Khangai regions are more strongly influenced by interactions between human activities (grazing density and NO_2 emissions) and natural factors, making these areas critical for future grassland degradation risk prevention and control. These findings provide scientific evidence for effective grassland ecosystem management and sustainable development strategy formulation across different regions of Mongolia.

Keywords: NPP; spatiotemporal variation; influencing factors; grazing density; Mongolia

Introduction

Grasslands are an indispensable component of terrestrial ecosystems, playing crucial roles in global carbon cycling and climate regulation while also serving as a foundation for socioeconomic development and ecological security in arid regions. However, over the past several decades, intensifying climate anomalies and human activities have subjected grassland ecosystems to unprecedented degradation pressures. Grassland degradation now poses a serious threat to global socioeconomic and ecological security, representing a major environmental challenge. Quantifying spatiotemporal trends in grassland degradation and investigating the impacts of climate change and human activities are therefore essential for grassland ecosystem governance, restoration, and reconstruction.

As the engine and key functional component of terrestrial ecosystems, the physical and functional characteristics of green vegetation—such as vegetation structure, coverage, and productivity—serve as important indicators for assessing vegetation dynamics. According to the United Nations Convention to Combat Desertification, "grassland degradation" refers to the process where climatic or anthropogenic disturbances exceed the regulatory threshold of grassland ecosystems, causing irreversible retrogressive succession. Vegetation net primary productivity (NPP), defined as the total accumulation of organic dry matter by green plants per unit time and area, reflects the ecological status and health of terrestrial ecosystems. Long-term ecosystem dynamic monitoring provides crucial support for regional land-use policy formulation and sustainable management.

Mongolia, China's northern neighbor, possesses a highly fragile grassland ecosystem that is extremely susceptible to natural and human-induced factors. As a typical arid and semi-arid inland country, water availability is the limiting factor for vegetation growth. Under global warming, Mongolia' s average temperature has increased at twice the global average rate. Simultaneously, as a traditional pastoral nation, livestock production is closely linked to both 牧民 livelihoods and grassland ecosystem health. Following the privatization of animal husbandry, Mongolia' s livestock population has surged dramatically to meet economic development goals and market demands for meat products, intensifying grazing pressure and threatening grassland ecosystem health. Additionally, mineral extraction activities and extreme climatic events such as snow disasters have further exacerbated grassland degradation risks. While regional differences in natural conditions and economic development are substantial within Mongolia, existing research has primarily focused on national-scale analyses, leaving the mechanisms of grassland change in different regions poorly understood. This study addresses this gap by quantitatively analyzing NPP variation characteristics using a linear regression model, simulating grazing density using a random forest model, and investigating driving factors at national and provincial scales using geographic detectors. The results provide important references for grassland ecosystem management and sustainable development in Mongolia.

Study Area and Data

Study Area Overview

Mongolia is located in central Asia (87°44 07 –119°54 10 E, 39°17 40 –52°08 55 N), covering approximately 156.641$×10^{4}$ km^2. The country experiences a continental arid and semi-arid climate with extreme seasonal temperature variations. Winters are cold and prolonged, often accompanied by blizzards, while summers are hot and brief. Mean annual land surface temperature ranges from -13.661°C to 15.081°C, exhibiting a spatial pattern of higher temperatures in the south and lower in the north. Mean annual precipitation is approximately 230 mm, concentrated in the 200–300 mm range, with most rainfall occurring from June to August. Under these climatic conditions, vegetation types transition from south to north as desert, grassland, and forest. Grassland is the dominant vegetation type, covering about 80% of the country' s area. Mongolia is administratively divided into the Eastern, Central, Khangai, and Western regions, plus two municipalities [Figure 1: see original paper].

Data Sources

To characterize spatiotemporal NPP patterns and analyze the intensity of natural and anthropogenic influences, this study collected and integrated multiple datasets (Table 1). NPP data were obtained from MODIS products. Climate data including precipitation, temperature, radiation, and soil moisture were sourced from reanalysis datasets and satellite observations. Livestock data were derived from the Gridded Livestock of the World (GLW) dataset and provincial statistical yearbooks. Topographic data came from the Digital Elevation Model (DEM). Human activity indicators included the human footprint index and NO_2 emissions data.

Methods

Trend Analysis

Vegetation dynamic change is the most direct manifestation of grassland degradation and recovery, with vegetation productivity responding accordingly. NPP serves as a crucial indicator of vegetation growth status, directly reflecting grassland dynamics. This study employs a univariate linear regression model to investigate NPP trends at the pixel scale. The slope is calculated as:

$$\text{slope} = \frac{n\sum_{i=1}^{n} i \cdot \text{NPP}_i - \sum_{i=1}^{n} i \sum_{i=1}^{n} \text{NPP}_i}{n\sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where slope represents the trend direction of NPP change, NPP is the NPP value in year i, and n is the number of study years. A positive slope indicates increasing NPP, while a negative slope indicates decreasing NPP.

An F-test is used to assess the significance of the regression, evaluating whether the fitted equation differs significantly from sampling error. A larger F-value indicates a more pronounced temporal trend. The F-statistic is calculated as:

$$F = \frac{U}{Q/(n-2)}$$

where U is the regression sum of squares and Q is the residual sum of squares.

Geographic Detector Analysis

The geographic detector is a statistical tool for analyzing spatial heterogeneity and relationships between variables, comprising factor detection, interaction detection, ecological detection, and risk analysis. This study created a 3 km × 3 km grid across the study area, extracting pixel values at grid centers and removing invalid data points, yielding 12,456 sampling points. To minimize internal variance within each stratum, the natural breaks method was applied to categorize the ten selected driving factors into discrete levels. The factor detection and interaction detection functions were then used to identify dominant factors and their influence intensity on NPP changes.

Factor detection quantifies the spatial heterogeneity influence of independent variables on dependent variables using the q-statistic, where larger q-values indicate stronger explanatory power:

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

where q is the explanatory power (0-1), L is the number of categories, N and N are the total sample size and sample size in category h, and σ^2 and σ ^{2} are the total variance and variance in category h, respectively.

Interaction detection tests whether the interaction between two factors (X_1 and X_2) weakens or enhances their influence on the dependent variable Y, or whether they act independently .

Driver Factor Selection

As a typical arid and semi-arid inland country, water and heat resources are critical constraints on Mongolia' s economy and ecosystem stability. Among radiation factors, downward shortwave radiation (DSR) is essential for plant growth, providing the fundamental energy for photosynthesis, transpiration, and biomass accumulation. However, solar radiation does not always positively affect vegetation productivity. Persistent strong winds reduce photosynthetic efficiency and cause soil coarsening and moisture loss, thereby inhibiting vegetation growth. Human activities, particularly grazing, are decisive for national livelihoods and economic welfare. The dramatic increase in livestock numbers has intensified grazing pressure, posing a severe threat to grassland ecosystem health. Infrastructure development, including transportation networks, has further amplified human disturbance. The human footprint index, integrating land-use intensity, transportation accessibility, nighttime light index, and energy facilities, effectively reflects regional socioeconomic activity intensity. Based on existing research and Mongolia's natural and anthropogenic characteristics, this study selected ten indicators: mean annual land surface temperature, mean annual precipitation, downward shortwave radiation, wind speed, soil moisture, elevation, grazing density, NO_2 emissions, and human footprint index.

Grazing Density Simulation Method

Given that Mongolia only provides provincial-level livestock statistics, quantifying the spatiotemporal distribution of grazing density is necessary for grassland degradation studies. The GLW dataset provides global distribution information for cattle, goats, sheep, and other livestock, representing the most widely used spatial grazing density data. However, it inadequately considers relationships between environmental factors and grazing density, limiting spatial heterogeneity expression. Field investigations confirm that Mongolia' s main livestock species include cattle, goats, sheep, horses, and camels, with distribution primarily determined by pastoral population density and grassland conditions, which correlate with soil moisture, precipitation, and temperature.

This study converted livestock numbers to Tropical Livestock Units (TLU) using the standard conversion: 1 TLU = 250 kg. Based on FAO guidelines, each cattle or horse equals 0.8 TLU, while each goat or sheep equals 0.1 TLU. Using 2020 data for cattle, goats, sheep, and horses as a baseline, combined with pastoral population density, soil moisture, precipitation, and land surface temperature as predictors, a random forest regression model was built on Google Earth Engine to simulate grazing density spatial patterns.

Random forest regression is a machine learning method that constructs multiple decision trees through random sampling and integrates their predictions:

$$\hat{f}_{rf}(x) = \frac{1}{N}\sum_{n=1}^{N} f_n(x)$$

where T represents the original training dataset, (x_1, y_1), (x_2, y_2), ⋯, (x , y) are training samples, each used to construct a regression tree, N is the number of trees, and f (x) is the prediction from the nth tree. The trained model was used to simulate 2000–2020 grazing density distributions, validated against provincial statistical data using coefficient of determination (R^2), mean absolute error (MAE), and root mean square error (RMSE).

Results

Spatiotemporal Dynamics of NPP

From 2000 to 2020, Mongolia' s NPP showed spatial patterns of increase in the east and north and decrease in the west and south [Figure 3: see original paper]. Significantly increasing trends occurred in 24.872% of the country, primarily in forested areas of the Central and Khangai regions and mountainous areas of the Eastern and Western regions. Nonsignificant increases dominated, covering 62.539% of the land area and concentrated in grasslands and sparse shrublands across the Eastern, Central, and Western regions. Significantly decreasing areas accounted for only 0.684%, mainly in industrialized Darkhan-Uul and Khuvsgul provinces. Nonsignificant decreases covered 11.905% of the area, mostly in sparse shrub and grassland regions.

Spatial Distribution of Grazing Density

Random forest results reveal a north-south gradient in grazing density, with higher values in central and northern regions [Figure 4: see original paper]. Southern regions show densities below 5 $TLU \cdot km^{-2}$, indicating low livestock pressure. South Gobi Province, located in the southernmost Gobi region, has the lowest grazing density due to its unique natural environment. Central and northern regions, with abundant water resources and accessible transportation, are high-density zones, such as Arkhangai and Khuvsgul provinces where densities exceed 15 $TLU \cdot km^{-2}$. Model validation against provincial statistics shows strong performance with $R^2 = 0.84$, MAE = 2.31 $TLU \cdot km^{-2}$, and RMSE = 3.12 $TLU \cdot km^{-2}$, demonstrating effective spatial simulation of grazing density.

Identification of Dominant NPP Change Factors

Single-factor analysis reveals that climatic factors are the primary drivers of NPP change in Mongolia [Figure 5: see original paper]. Downward shortwave radiation (q = 0.615) and mean annual precipitation (q = 0.602) exhibit the highest explanatory power, followed by mean annual land surface temperature (q = 0.354) and soil moisture (q = 0.356). Human activity factors show relatively weak individual effects, with human footprint index (q = 0.189) and grazing density (q = 0.168) having lower q-values.

Interaction detection shows that all factor pairs exhibit bivariate enhancement effects on NPP change. The interaction between elevation and precipitation shows the highest q-value (0.708), followed by elevation and temperature (0.599). Interactions between human footprint index and DSR, as well as NO_2 emissions and precipitation, also demonstrate stronger explanatory power than individual factors.

Provincial-Scale Factor Interactions

At the provincial scale, interactions between natural and anthropogenic factors significantly enhance their influence on NPP change. In eastern Mongolia, NPP variation is primarily driven by interactions among climatic factors (precipitation, DSR, temperature) showing nonlinear enhancement. In western regions, NPP change is mainly affected by interactions between elevation and climatic factors, also displaying nonlinear enhancement.

However, central and Khangai regions show distinct patterns where NPP changes are more susceptible to interactions between human activities and natural factors. In central Mongolia, the interaction between NO_2 emissions and climatic factors (precipitation, DSR, wind speed) exerts the strongest negative impact on NPP in Töv, Dundgovi, and Govi-Sümber provinces (q = 0.371). Precipitation provides the most positive contribution to NPP increase in Govi-Sümber (q = 0.368). Grazing density also significantly influences central region NPP changes. In the Khangai region, interactions between human footprint index and precipitation or soil moisture dominate NPP variation in Selenge and Darkhan-Uul provinces with q-values of 0.342 and 0.319, respectively.

These results indicate that NPP changes in Mongolia' s central and Khangai regions result from complex interactions between human activities and natural factors, making them priority areas for grassland degradation prevention and sustainable management strategies.

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