Spatiotemporal Patterns and Driving Forces of NEP in the Loess Plateau, 2000–2020: Postprint

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Abstract

The Loess Plateau is an important ecological barrier in China. Against the backdrop of global change, the carbon budget balance of the Loess Plateau has attracted considerable attention. Based on MOD17A3HGF data, this study analyzes the carbon source/sink characteristics of the Loess Plateau from 2000 to 2020 using methods including the GSMSR model, trend analysis, difference analysis, and Geographical Detector, revealing the spatiotemporal patterns of Net Ecosystem Productivity (NEP) and its driving factors in this region during 2000–2020. Simultaneously, the study area was divided into western, central, and eastern sub-regions along the longitudinal direction to compare the differences in driving factors among different regions. The results show: (1) Over the past 20 years, 49.69% of the Loess Plateau area has transitioned from a carbon source to a carbon sink; NEP shows a fluctuating upward trend over time, being higher in the southeast than in the northwest, with a multi-year average value of 12 g C · m-2 · a-1. (2) Moisture conditions are the primary natural factor influencing the spatial distribution of NEP, while land use type is the primary anthropogenic factor affecting the spatial distribution of NEP; the interaction between different factors generally has a greater impact on NEP than individual factors. (3) The driving factors of NEP in the western, central, and eastern sub-regions exhibit distinct spatial differentiation characteristics; the central and western regions are more influenced by climate, primarily moisture conditions such as precipitation and humidity; the eastern region is comprehensively affected by factors including topography, climate, and human activities, among which anthropogenic disturbance represented by land use type is the strongest.

Full Text

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Abstract

The Loess Plateau is an important ecological barrier in China. In the context of global change, the carbon balance of the Loess Plateau has attracted considerable attention. Based on MOD17A3HGF data, this study analyzed the spatiotemporal patterns and driving factors of net ecosystem productivity (NEP) in the Loess Plateau from 2000 to 2020 using the geostatistical model of soil respiration (GSMSR), trend analysis, difference analysis, and Geodetector. The study area was divided longitudinally into western, central, and eastern subregions to compare differences in driving factors across regions. The results showed that: (1) 49.69% of the region shifted from carbon source to carbon sink over the 21-year period. NEP exhibited a fluctuating upward trend over time, with values higher in the southeast than in the northwest, and a multi-year average of 12 g $C \cdot m^{-2}$. (2) Moisture conditions were the primary natural factor affecting the spatial distribution of NEP, while land use type was the main anthropogenic factor. The interaction between different factors generally had a greater influence on NEP than any single factor alone. (3) The driving factors of NEP in the three subregions showed clear spatial differentiation. The central and western regions were more influenced by climate, particularly moisture-related variables such as precipitation and humidity. The eastern region was affected by a combination of topography, climate, and human activities, with anthropogenic disturbance—represented by land use type—being the most significant factor.

Keywords: trend analysis; Geodetector; net ecosystem productivity; spatiotemporal patterns; Loess Plateau

Introduction

Vegetation is a crucial component of terrestrial ecosystems and plays a vital role in regulating carbon balance. Enhancing vegetation carbon sink function is an effective approach to mitigating rising atmospheric CO_2 concentrations and global warming, and represents a key factor in achieving carbon neutrality goals. Net ecosystem productivity (NEP) describes the net carbon exchange between terrestrial ecosystems and the atmosphere, and is an important indicator for assessing ecosystem carbon source/sink status. Previous studies have demonstrated that terrestrial ecosystems exhibit significant carbon sink characteristics, though the spatial distribution of carbon sinks varies considerably and is susceptible to changes in external conditions. Determining regional ecosystem carbon sink changes and their driving mechanisms remains challenging, making regional NEP estimation and analysis of its spatiotemporal patterns and driving factors a hot topic in global change research.

The Loess Plateau is characterized by complex terrain and variable climate, playing an important role in China's ecological protection and socio-economic development. Long-term intensive human activity has caused severe vegetation degradation and soil erosion, making it a typical ecologically fragile region in China. However, since the implementation of the "Grain for Green" program, vegetation cover has increased and the ecological environment has improved significantly. While numerous studies have used normalized difference vegetation index, net primary productivity (NPP), vegetation coverage, and other indicators for regional ecological monitoring and assessment, few have investigated the driving factors of vegetation carbon source/sink spatiotemporal distribution. Existing studies also suffer from several limitations: (1) relatively few driving factors are selected, limiting explanatory power for spatial patterns; (2) studies have only analyzed correlations with driving factors without quantifying their contributions; (3) research has focused on single-factor effects while neglecting synergistic interactions between factors; and (4) studies have emphasized the Loess Plateau as a whole while paying insufficient attention to internal differences—necessitating more in-depth research.

To address these issues, this study divided the research area into three subregions from west to east based on large provincial administrative units to explore internal differences. NEP was estimated using the GSMSR model, and Theil-Sen Median trend analysis and Mann-Kendall significance testing were employed to investigate spatiotemporal changes. Finally, Geodetector was used to screen and analyze driving factors affecting NEP within the study area and quantitatively assess their influence levels and interactions. This research aims to explore the spatiotemporal evolution characteristics of NEP in the Loess Plateau, reveal the effectiveness of ecological construction improvements from 2000 to 2020, and provide a scientific basis and decision-making reference for sustainable development and ecological protection in the region.

1.1 Study Area Overview

The Loess Plateau is located in the middle and upper reaches of the Yellow River (33°43 ~41°16 N, 100°54 ~114°33 E), in a transitional zone from coastal to inland areas and from plains to plateaus. Annual precipitation increases from northwest to southeast, ranging from 200–750 mm and concentrated in specific months. Evaporation generally exceeds precipitation. The annual average temperature is 14.3°C. The region's landforms can be classified into plateau gullies, hill gullies, mountains, loess gullies, and valley plains. The study area was divided longitudinally into western, central, and eastern parts. The western region lies in an arid and semi-arid zone, covering all of Ningxia and parts of Qinghai and Gansu, with elevations mostly between 2000–3000 m. The central region comprises the Guanzhong Plain and Northern Shaanxi Plateau, with latitudinal zonality in precipitation distribution—semi-humid in the south and semi-arid in the north. The eastern region covers all of Shanxi and parts of Henan, with complex topography dominated by mountains and hills, and a mainly semi-humid climate, representing the most precipitation-rich area of the Loess Plateau [Figure 1: see original paper].

1.2 Data Sources

This study collected NEP and environmental factor data for the research area. The spatial reference for all datasets was set to CGCS2000_3_{{{Degree}}*{{GK}}*}{{{CM}}_{{105E}}}, with spatial resolution resampled in ArcGIS 10.8. Data sources are detailed in .

1.3 Research Methods

1.3.1 NEP Estimation NEP represents the net absorption or storage of carbon in ecosystem carbon cycles and has been widely used to estimate terrestrial ecosystem carbon sources and sinks. When NEP > 0, the carbon fixed by vegetation exceeds that emitted by soil microbial respiration, and the ecosystem functions as a carbon sink. When NEP < 0, the carbon fixed by vegetation is less than that emitted by microbial respiration, and the ecosystem functions as a carbon source. NEP is defined as the difference between annual net primary productivity (NPP) and annual soil heterotrophic respiration (Rh). Rh is determined through a fitting equation between Rh and soil respiration (Rs). Rh is sensitive to precipitation, temperature, and soil organic carbon density (SOC) and is proportional to Rs. Based on multi-year records from Chuai et al., a linear fitting equation between Rh and Rs suitable for China was calculated:

$$NEP = NPP - Rh$$

$$Rh = 0.4679 \times Rs + 114.42$$

Monthly soil respiration (Rs_{month}) can be calculated using the GSMSR model, which has proven reliable for simulating Rs across China:

$$Rs_{\text{month}} = 0.588 + 0.118 \times SOC + 2.972 \times P + 5.657 \times T + 1.83 \times e^{-0.006 \times (P-2)}$$

where P is monthly precipitation (mm) and T is monthly average temperature (°C). Annual soil respiration is the sum of monthly values:

$$Rs_{\text{annual}} = \sum_{i=1}^{12} Rs_{\text{month}}$$

1.3.2 Trend Analysis Theil-Sen median trend analysis is a robust non-parametric method for trend detection with high computational efficiency that has been widely applied in previous studies. The expression is:

$$\beta = \text{Median}\left(\frac{NEP_j - NEP_i}{j - i}\right), \quad \forall i < j$$

where β represents the trend of the NEP time series, NEP_i and NEP_j are values for years i and j, and n is the study period length. If $\beta > 0$, NEP shows an upward trend; if $\beta < 0$, it shows a downward trend.

The Mann-Kendall trend test is a rank-based non-parametric test used to assess trend significance. It does not require normalized distribution and is robust against outliers. Significance levels are categorized in .

1.3.3 Difference Analysis Difference analysis was performed by calculating pixel-by-pixel differences between NEP values from 2000 and 2020 to obtain the magnitude of change:

$$D_{ij} = NEP_{ij}^{2020} - NEP_{ij}^{2000}$$

where D_{ij} is the difference value for the pixel in row i, column j, NEP_{ij}^{2020} is the 2020 value, and NEP_{ij}^{2000} is the 2000 value. Statistical results are shown in .

1.3.4 Geodetector Geodetector is a spatial statistical method that reveals spatial heterogeneity and quantifies the influence of driving factors on response variables through four modules. This study employed factor detection and interaction detection. The factor detector uses the q statistic to measure explanatory power, with larger q values indicating stronger influence on NEP spatial distribution:

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

where $h = 1, \ldots, L$ are strata of the factor, N_h and N are unit numbers within stratum h and the entire region, and σ_h^2 and σ^2 are variances of stratum h and the whole region, respectively.

The interaction detector compares q statistics of individual and combined factors to determine whether interactions enhance, weaken, or are independent. Interaction types are detailed in .

2 Results

2.1 Temporal Variation Characteristics of NEP

The multi-year average NEP of the Loess Plateau from 2000 to 2020 was 12.00 $\mathrm{g\ C \cdot m^{-2} \cdot yr^{-1}}$, with a minimum of -88.80 $\mathrm{g\ C \cdot m^{-2} \cdot yr^{-1}}$ and a maximum of 44.91 $\mathrm{g\ C \cdot m^{-2} \cdot yr^{-1}}$. Among the three internal regions, the central region had the highest average at 10.09 $\mathrm{g\ C \cdot m^{-2} \cdot yr^{-1}}$, the western region the lowest at -7.46 $\mathrm{g\ C \cdot m^{-2} \cdot yr^{-1}}$, and the eastern region intermediate at 6.69 $\mathrm{g\ C \cdot m^{-2} \cdot yr^{-1}}$. NEP showed clear interannual variation with an overall change rate of 7.07 $\mathrm{g\ C \cdot m^{-2} \cdot yr^{-1}}$. The central region exhibited the highest increase rate at 8.99 $\mathrm{g\ C \cdot m^{-2} \cdot yr^{-1}}$, while the western and eastern regions also showed upward trends at 6.17 and 6.69 $\mathrm{g\ C \cdot m^{-2} \cdot yr^{-1}}$, respectively. Notably, 49.69% of the region experienced conversion from carbon source to carbon sink characteristics.

2.2 Carbon Source/Sink Characteristics Based on NEP

From 2000 to 2020, areas with carbon source characteristics accounted for 21.20% of the Loess Plateau ecosystem, mainly distributed in the northwest region, Guanzhong Plain, and Fen River Valley. Carbon sink areas comprised 78.80% of the region, primarily located in the Lvliang Mountains and southeastern areas. The area that shifted from carbon source to sink characteristics accounted for 49.69% of the total region [Figure 3: see original paper].

2.3 NEP Trend and Difference Analysis

During 2000–2020, 85.01% of the Loess Plateau showed an upward NEP trend, with 55.17% being extremely significant, distributed widely across the study area. Only 0.96% showed a downward trend, located mainly in large and medium-sized cities [Figure 4: see original paper]. Within subregions, the central region had the largest proportion of upward-trending area at 94.83%, with 86.07% being extremely significant—the most pronounced increase in the study area. The western region had 80.67% upward-trending area, with 50.18% extremely significant. The eastern region had 76.65% upward-trending area, with 42.24% extremely significant, but had a higher proportion of relatively stable areas compared to the central and western regions.

Overall, the region exhibited a northwest carbon source vs. southeast carbon sink pattern. From 2000 to 2020, 22.46% of the Loess Plateau showed conversion from carbon source to sink characteristics, mainly distributed in the northwestern margins and major cities [Figure 4: see original paper]. Areas with the most significant differences were concentrated at provincial capitals and other central cities, showing diffusion patterns from the Gansu-Shaanxi border to surrounding areas. The proportion of areas with differences of 0–300 $\mathrm{g\ C \cdot m^{-2}}$ was highest in the western region (98.44%), while the central region had 96.79% and the eastern region 4.33%. In summary, NEP in the Loess Plateau showed predominantly upward trends during the study period, with the central region showing the highest proportion and magnitude of increase, followed by the western region. The eastern region had relatively more stable areas [TABLE:3, TABLE:4].

2.4 Driving Factor Analysis

2.4.1 Factor Detection Potential driving factors for NEP in the Loess Plateau and subregions were analyzed using the factor detector. To facilitate analysis, factors were sorted by q values and those with cumulative contributions exceeding a threshold were selected for subsequent interaction detection. Factor detection revealed that precipitation had the strongest explanatory power for NEP spatial distribution, followed by relative humidity ($q = 0.31$). Evaporation, land use type, soil type, and sunshine hours had moderate influence ($q > 0.1$). While multiple factors demonstrated influence, anthropogenic interference, represented by land use type, had the most pronounced comprehensive impact. Spatially, driving factors showed clear heterogeneity in their influence across regions [Figure 5: see original paper].

2.4.2 Interaction Detection Interaction detection was used to explore synergistic contributions of different driving factors. Results showed that interactions between any two factors had greater influence on NEP than individual factors alone, exhibiting double-factor enhancement or nonlinear enhancement effects. In the study area, interactions between precipitation and other factors yielded the highest q values, indicating precipitation as the dominant factor influencing NEP. Interaction q values were generally higher in central and western regions, with water condition factors (precipitation, evaporation) showing the strongest interactions. In the eastern region, interaction q values were relatively lower, with land use type showing the strongest interactions with other factors [Figure 6: see original paper].

3 Discussion

3.1 Study Area Division

Numerous studies have addressed vegetation restoration across the entire Loess Plateau, but few have examined internal differences within the plateau. Given the complexity of the natural environment, scholars have often focused on geomorphological zoning, such as Wang et al.'s division into five geomorphological regions based on the "Comprehensive Management Plan for the Loess Plateau Region (2010–2030)" to reveal vegetation coverage differences. However, recent ecological restoration measures in the Loess Plateau have been predominantly implemented within administrative units. Therefore, this study argues that analyzing differences between administrative divisions, with emphasis on human activities, is more relevant. The study area was divided into western, central, and eastern subregions by longitude using large provincial administrative units (data deficiency in Inner Mongolia's portion of the Loess Plateau led to its exclusion). Although not covering the complete Loess Plateau region, this approach encompasses most of the area while highlighting both natural precipitation gradients and anthropogenic differences resulting from administrative management, thereby better reflecting the effectiveness of ecological governance projects.

3.2 Uncertainty of NEP Estimation

The accuracy of NEP estimation results was indirectly evaluated by comparing them with other scholars' findings. The spatial distribution and magnitude of NEP, as well as the distribution and transformation patterns of carbon source/sink areas, showed high consistency with the results of Chuai et al. and Zhang et al., indicating that the NEP estimation in this study possesses high credibility.

3.3 Spatiotemporal Changes in NEP

During the study period, NEP in the Loess Plateau showed an upward trend, with the ecological environment gradually improving from northwest to southeast—consistent with previous research findings. Internally, the central region exhibited the greatest change rate, with the most significant increases occurring between the Guanzhong Plain and Northern Shaanxi Plateau. Before ecological governance, this area was dominated by slope farmland and suffered from China's most severe soil erosion. Implementation of the Grain for Green program has gradually increased carbon storage and habitat quality. Although northern Yulin showed some improvement after 2010, it remains a carbon source, likely due to its location on the Northern Shaanxi Plateau near the Mu Us Desert, with arid climate and poor soil conditions unfavorable for vegetation restoration. The eastern region also showed substantial NEP increases, mainly in mountain and hill areas suffering from severe water erosion, where the relatively humid climate favors vegetation recovery. The western region had relatively smaller NEP increases, primarily at the Gansu-Shaanxi border, as most of this area lies on the Longzhong Plateau with low precipitation, making ecological restoration difficult. Areas near Shaanxi have better climate conditions and hill-dominated terrain, resulting in more obvious NEP increases. In summary, slope farmland conversion to forest and grassland over the past two decades has significantly increased vegetation cover and enhanced ecological carbon sink function in the Loess Plateau.

3.4 Analysis of NEP Driving Factors

The spatial differentiation of NEP in the region results from combined natural environmental and human activity factors. Previous studies have verified that temperature and precipitation affect NEP at various spatiotemporal scales. This can be attributed to: (1) temperature and precipitation being key factors in Rh estimation that influence Rh magnitude, and (2) temperature and precipitation representing hydrothermal conditions that affect plant growth and consequently NEP. Analysis of the Loess Plateau from 2000 to 2020 showed that annual average temperature increased by 0.42°C and annual precipitation increased by 91 mm, creating more suitable conditions for vegetation growth. Prior research indicates that in arid and semi-arid regions, moisture conditions are often critical for vegetation restoration, a finding consistent with our results. Factor detection showed that moisture control factors (precipitation, evaporation, relative humidity) are the main natural drivers of NEP distribution. Interaction detection further revealed that combined factors had significantly higher explanatory power than single factors, confirming that NEP distribution is primarily controlled by moisture conditions.

Regarding human activities, land use type is an important driving factor affecting NEP in the Loess Plateau. Previous studies have shown that human-driven land use and cover change have profoundly altered natural ecosystem structure and function, affecting not only landscapes but also surface ecosystem carbon fluxes. Land use type influences NEP through: (1) differing natural attributes and ecological structures among land use types, with forests having the strongest carbon sink capacity, and (2) transitions between land use types inevitably causing NEP changes. The spatial heterogeneity of driving factors among the three subregions was significant. In the central and western regions, with relatively less human disturbance, interactions between moisture control factors and other factors determined NEP patterns. In the eastern region, human activities had stronger influence, and interactions between land use type and other factors better explained NEP distribution.

3.5 Limitations and Prospects

Vegetation carbon fixation and soil respiration are extremely complex physiological and ecological processes, and model-based estimations inherently contain uncertainties. Moreover, carbon sink capacity is a long-term dynamic process, with longer time series generally yielding more reliable assessments. Limited by data availability, this study only examined the period 2000–2020, which somewhat restricts in-depth analysis of NEP and its driving factors. Therefore, future research plans include assessing carbon sink capacity over longer time scales with finer temporal resolution (monthly and quarterly) and higher-precision NEP estimation models to examine carbon sink changes under different driving factors, providing more accurate and detailed scientific support for regional ecological restoration.

4 Conclusions

Based on the GSMSR estimation model and remote sensing data, this study analyzed spatiotemporal patterns and driving forces of NEP in the Loess Plateau from 2000 to 2020. The main conclusions are:

1) From 2000 to 2020, NEP in the study area showed an upward trend, gradually increasing from northwest to southeast. Significant differences existed between regions, with the most pronounced increases in mountainous and hilly areas, particularly at the Shaanxi-Gansu border. Nearly half of the

region shifted from carbon source to carbon sink characteristics.

2) Precipitation was the dominant natural factor influencing NEP spatial distribution patterns. Improving moisture conditions is key to further enhancing NEP in the Loess Plateau. Land use type was the dominant anthropogenic factor affecting spatial differentiation. Compared with single factors, interactions between natural and anthropogenic factors generally enhanced the influence on NEP spatial distribution.

3) The three subregions exhibited strong spatial heterogeneity in NEP driving factors. In the central and western regions, natural environmental factors—primarily climate—had greater influence. In the eastern region, NEP was affected by a combination of climate, topography, and human activity interference, with anthropogenic disturbance being predominant.

In summary, vegetation restoration in the Loess Plateau has significantly increased the area functioning as a carbon sink, though clear spatial heterogeneity exists. NEP spatial distribution patterns are influenced by numerous factors, among which precipitation and land use type are particularly important.

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