Impacts of Climate Change and Land Use/Cover Change on Vegetation Net Primary Productivity in the Hexi Region (Postprint)

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Abstract

The Hexi region is not only an important priority area for ecological security protection in China, but also a core section of the Silk Road Economic Belt. Conducting assessment of vegetation Net Primary Productivity (NPP) and quantitative analysis of its driving forces in this region holds important theoretical value and practical significance for research on terrestrial ecosystem-atmosphere carbon exchange, the combined effects of climate change and human activities on vegetation, and related studies. Based on MOD17A3 product data, land use/cover data, and meteorological data, and employing R-contribution rate and partial correlation analysis methods, this study analyzed the variation characteristics of vegetation NPP and the impacts of land use/cover change and climate change on NPP in the Hexi region from 2000 to 2020. The results show that: (1) In the Hexi region, the areas of cultivated land, water bodies, and residential construction land showed an overall increasing trend, while the areas of grassland and unused land decreased. Furthermore, the overall dynamic degree of Land Use/Cover Change (LUCC) increased significantly after 2010, with grassland, cultivated land, construction land, and unused land dominating the mutual conversion among land use types. (2) The overall vegetation NPP in the Hexi region exhibited an increasing trend, with change slopes of 0.86 and 1.29 for the periods 2000–2010 and 2010–2020, respectively. Additionally, vegetation NPP displayed obvious regional heterogeneity, decreasing from southeast to northwest. (3) From 2000 to 2020, the impact of LUCC on vegetation NPP in the Hexi region gradually increased, and the contribution rate of climate change to vegetation NPP was generally higher than that of LUCC. However, their roles differed among various land use/cover types: for cultivated land, forest land, and grassland, climate change was the dominant factor affecting vegetation NPP, while for unused land and residential construction land, LUCC gradually became the dominant factor influencing vegetation NPP.

Full Text

Impacts of Climate Change and Land Use/Cover Change on Vegetation Net Primary Productivity in the Hexi Region, Northwest China

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Abstract

The Hexi Region holds a dual significance in China, being both a pivotal area for ecological security and the core of the Silk Road Economic Belt. Assessing the net primary productivity (NPP) of the region and quantitatively analyzing the driving forces behind its dynamics bears immense theoretical importance and practical implications. Based on MOD17A3 products, land use/cover data, and meteorological data, this study scrutinized the evolving characteristics of vegetation NPP and the influences of land use/cover changes and climate fluctuations on NPP in the Hexi Region from 2000 to 2020 using R-contribution rate and partial correlation analysis methods. The results show that: (1) The area of arable land, water bodies, and residential construction land in the Hexi Region showed an overall increasing trend, while grassland and unused land area decreased. The overall dynamic degree of land use/cover change (LUCC) after 2010 increased significantly, with grassland, cropland, construction land, and unused land dominating the mutual conversion of land use types. (2) The overall vegetation NPP in the Hexi Region exhibited an increasing trend, with rates of change of 0.86 and 1.29 for the periods 2000–2010 and 2010–2020, respectively. Significant regional heterogeneity was observed, decreasing from southeast to northwest. (3) The influence of LUCC on NPP gradually increased from 2000 to 2020. While climate change contributed more to NPP than LUCC overall, their respective roles varied among land use/cover types. Specifically, climate change dominated as the influencing factor for NPP on cropland, forest land, and grassland, whereas for unused land and residential construction land, LUCC played a more significant role.

Keywords: Net Primary Productivity; Land Use/Land Cover; Spatio-temporal Variation; Driving Factors; Hexi Region

Introduction

Net Primary Productivity (NPP) represents the portion of organic carbon fixed by vegetation after accounting for respiratory consumption, reflecting the capacity of vegetation to sequester atmospheric CO_2. As a key indicator of ecosystem quality and stability, NPP is crucial for understanding terrestrial ecosystem responses to global change and for balancing the quantity and quality of biological communities. Numerous scholars have explored NPP dynamics from various perspectives. For instance, Li et al. utilized meteorological data from multiple stations to accurately predict NPP levels in western China, while Wang et al. employed MODIS data to examine the developmental trends and spatial patterns of grassland primary productivity in northern Tibet, revealing underlying patterns in this domain.

Both climate change and land use/cover change (LUCC) directly or indirectly affect NPP, with the impact of land use change becoming a critical component of carbon cycle research. Previous studies have investigated how land use changes affect vegetation NPP in specific regions, such as the Three Gorges Reservoir Area and Chengdu, demonstrating that shifts in land use type significantly influence regional vegetation carbon sequestration. However, most research has focused on the economic development aspects of different land use types, with relatively less attention paid to vegetation greening and ecological restoration based on land use type transitions.

In recent years, the Hexi Region has emerged as a primary node of the Silk Road Economic Belt and a key component of China' s western ecological security barrier. While substantial progress has been made in studying the impacts of climate factors (primarily temperature and precipitation), topography, soil type, LUCC, and human activities on NPP, previous studies using overall linear regression methods have failed to adequately consider the nonlinear characteristics of NPP and the collinearity between LUCC and climate factors, resulting in high uncertainty. This study aims to: (1) characterize the spatio-temporal evolution of vegetation NPP in the Hexi Region; (2) quantitatively evaluate the response relationships between NPP and climate factors; and (3) assess the relative contributions of climate change and LUCC to NPP dynamics. The findings will help clarify ecosystem quality and natural productivity in the region, providing a scientific basis for coordinating economic development and environmental protection.

1 Data and Methods

1.1 Study Area

According to the *Gansu Province Yellow River Basin Ecological Protection and Restoration Special Implementation Plan*, the Hexi Region (92°44 –104°14 E, 36°46 –42°49 N) is located in the upper and middle reaches of the Yellow River, forming a narrow corridor connecting with the northeastern Tibetan Plateau. The region extends from the Gansu-Ningxia border in the east to the Gansu-

Xinjiang border in the west, borders Qinghai Province to the south, and extends to Inner Mongolia and Mongolia to the north [Figure 1: see original paper]. Spanning approximately 1,000 km east-west and 200–300 km north-south, the region covers a total area of 27.81$\times10^{4}$ km^2.

The Hexi Region comprises five key ecological implementation zones: the Qilian Mountain water source conservation capacity enhancement zone, the Yellow River tributary water source conservation capacity enhancement zone, the northern sand prevention belt windbreak and sand fixation capacity enhancement zone, the Yellow River basin mining area ecological environment comprehensive management zone, and scattered biodiversity conservation zones within the Gansu Yellow River basin. The region' s geography is characterized by a wider west and narrower east, with dramatic diurnal temperature variations. The Shiyang, Heihe, and Shule Rivers originate from Qilian Mountain ice and snow meltwater, providing abundant freshwater resources for local residents and oasis agriculture. Due to its unique geographical location and fragile ecological environment, the Hexi Region constitutes a critical priority area for ecological security in China and an essential component of the national "Three Zones and Four Belts" and Gansu Province' s "Four Screens and One Corridor" strategic frameworks.

1.2 Data Sources

1.2.1 Vegetation Data This study utilized the Terra MODIS NPP product (MOD17A3 HGF V6) from NASA' s dataset collection, available at https://ladsweb.modaps.eosdis.nasa.gov/. The dataset offers a high spatial resolution of 500 m and annual temporal resolution. By integrating the BIOME-BGC model, light use efficiency model, and related technologies, MOD17A3 provides robust support for vegetation growth assessment, biomass evaluation, and environmental change studies worldwide. Using Python programming language, we performed comprehensive preprocessing on the Hexi Region NPP data, including mosaicking, clipping, reprojection, and removal of invalid values (fill values outside the valid range of -3000–32700), to obtain valid annual NPP data for the study area.

1.2.2 Land Use/Land Cover Data The land use/cover data were obtained from the Chinese Land Use Status Remote Sensing Monitoring Dataset at the National Tibetan Plateau Scientific Data Center (http://data.tpdc.ac.cn). This dataset, supported by the National Science and Technology Support Plan and the Chinese Academy of Sciences Knowledge Innovation Project, provides comprehensive seasonal land use information across Chinese provinces. Based on Landsat TM/ETM+ remote sensing imagery processed through professional technical methods, the dataset achieves 30 m spatial resolution and includes 6 primary categories and 25 secondary categories. For this study, we selected land use data for three periods.

1.2.3 Meteorological and Other Data Meteorological data included monthly mean temperature and precipitation datasets (2000-2020) from the National Tibetan Plateau Scientific Data Center (http://data.tpdc.ac.cn) with 1 km spatial resolution. This dataset integrates high-precision climate information from the Climatic Research Unit (CRU) and WorldClim, collected using the Delta spatial downscaling method. Additionally, Digital Elevation Model (DEM) data were obtained from the USGS website (https://earthexplorer.usgs.gov/) at 30 m spatial resolution to accurately reflect topographic characteristics.

1.3 Methods

1.3.1 Land Use/Cover Change Analysis Land use/cover change analysis involves measuring key parameters to understand regional land use patterns. The single land use dynamic degree measures the change rate of specific land use categories, while the comprehensive land use dynamic degree reveals overall regional development trends, enabling better prediction of future changes.

The single land use dynamic degree is calculated as:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\%$$

where K represents the change degree of a single land use type during a specific period; U_a is the initial area of the land use type; U_b is the final area; and T is the study period. K reflects the annual change rate of the specific land use type' s total area.

The comprehensive land use dynamic degree is calculated as:

$$LC = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |LU_{i-j}|}{\sum_{i=1}^{n} LU_i} \times \frac{1}{T} \times 100\%$$

where LC indicates the overall land use change trend; LU_i represents the total area of land use type i; $|LU_{i-j}|$ is the absolute area converted from type i to type j; and T is the study period. When calculated annually, LC represents the annual change rate of comprehensive land use during the study period.

The contribution rate method, proposed by Hicke et al., calculates the influence and contribution rate of different land use types on total NPP. If S_i, S_j, NPP_i, and NPP_j represent the area and unit area NPP at times t_i and t_j, respectively, the total NPP change (ΔNPP_T) can be expressed as:

$$\Delta NPP_T = NPP_j \times S_j - NPP_i \times S_i$$

This can be decomposed as:

$$\Delta NPP_T = \Delta NPP_{climate} + \Delta NPP_{landuse} + \Delta NPP_{interaction}$$

where $\Delta NPP_{climate}$ represents the impact of climate change, $\Delta NPP_{landuse}$ represents the impact of land use change, and the interaction term represents their combined effect. Excluding the interaction term, the contribution rates of climate variables (R_C) and land use change (R_L) to total NPP change are:

$$R_C = \frac{\Delta NPP_{climate}}{NPP_i \times S_i + \Delta NPP_{climate} + \Delta NPP_{landuse}} \times 100\%$$

$$R_L = \frac{\Delta NPP_{landuse}}{NPP_i \times S_i + \Delta NPP_{climate} + \Delta NPP_{landuse}} \times 100\%$$

1.3.2 Trend and Correlation Analysis The Sen' s slope method and Mann-Kendall trend test were employed for trend detection, while partial correlation analysis was used to explore relationships between paired variables while controlling for other factors. Detailed descriptions of these methods are provided in relevant literature.

2 Results

2.1 Spatiotemporal Distribution and Trends of Vegetation NPP

From 2000 to 2020, the interannual variation of vegetation NPP in the Hexi Region showed an overall upward trend with continuously increasing growth rates [Figure 2: see original paper]. The multi-year average NPP ranged from 55.74 to 61.06 g $C \cdot m^{-2} \cdot a^{-1}$, with the lowest value (43.01 g $C \cdot m^{-2} \cdot a^{-1}$) occurring in 2000 and the highest (73.85 g $C \cdot m^{-2} \cdot a^{-1}$) in 2020, indicating significant interannual variation. The overall positive trend demonstrates that vegetation in the Hexi Region is improving.

The spatial distribution of average NPP exhibited significant heterogeneity, decreasing from southeast to northwest [Figure 3: see original paper]. At the prefecture level, Linxia Hui Autonomous Prefecture showed the highest average NPP (232.59 g $C \cdot m^{-2} \cdot a^{-1}$) due to favorable vegetation conditions, though its small land area resulted in lower total NPP. Jiayuguan City exhibited the lowest average NPP (7.07 g $C \cdot m^{-2} \cdot a^{-1}$), with 96.77% of its area having NPP below 100 g $C \cdot m^{-2} \cdot a^{-1}$, attributable to the predominance of barren grassland, sandy land, and bare soil. Other cities showed moderate NPP values, with Wuwei and Lanzhou exhibiting relatively higher NPP in some areas due to forest coverage.

Areas with NPP $<$ 100 g $C \cdot m^{-2} \cdot a^{-1}$ accounted for 76.53% of the region, primarily distributed west of Jiayuguan and in the Badain Jaran and Tengger Deserts. Areas with NPP between 100-200 g $C \cdot m^{-2} \cdot a^{-1}$ comprised 12.36%, located in the western Loess Plateau. Areas with NPP $>$ 400 g $C \cdot m^{-2} \cdot a^{-1}$ represented only 0.34%, concentrated in the southern Qilian Mountains.

The NPP trend also varied spatially, with 88.70% of the region remaining stable, primarily in areas with NPP $<$ 100 g $C \cdot m^{-2} \cdot a^{-1}$. Increasing trends occupied

9.36% of the area, mainly in central regions, while decreasing trends accounted for 1.94%, primarily in southern Wuwei. From 2010 to 2020, the area with increasing trends expanded to the southeast, rising to 13.43% of the region, while decreasing trends diminished to 2.47%, scattered across Wuwei, Baiyin, and Lanzhou.

2.2 Impact of Climate Change on Vegetation NPP

In China' s arid and semi-arid regions, temperature and precipitation play crucial roles in vegetation improvement. Analysis of correlations between NPP and these climate variables revealed that precipitation showed stronger correlations with NPP than temperature did [Figure 5: see original paper]. From 2000 to 2020, the correlation coefficients between precipitation and NPP were significantly higher than those between temperature and NPP. The correlation with precipitation showed a slight decrease from 2000–2010 to 2010–2020, while the correlation with temperature increased.

Overall, NPP was more significantly correlated with precipitation than with temperature. When soil moisture is depleted, enhanced vegetation transpiration combined with warming exacerbates water loss, inhibiting plant growth and photosynthesis and reducing the total organic matter fixed by net photosynthesis. The positive correlation between NPP and precipitation was strongest in Zhangye, Baiyin, and Wuwei, while negative correlations were limited to scattered areas. Temperature increases can stress surface vegetation, but in arid regions, moderate warming may reduce evapotranspiration and increase photosynthetic efficiency, benefiting biomass accumulation.

2.3 Spatiotemporal Evolution of Land Use/Land Cover

The southeastern Hexi Region is dominated by grassland, with sparse distribution of cropland and forest land. Central areas have concentrated cropland distribution, while the northwest is primarily unused land with scattered grassland patches. Forest and water areas are relatively small, with forests concentrated in Wuwei and water bodies mainly in Jiuquan. Residential construction land is minimal and scattered throughout the region.

The primary land use types are unused land, grassland, and cropland. Unused land (including barren grassland, saline-alkali land, marshland, sandy land, bare soil, and bare rock) decreased continuously during the study period, dropping to 82.20% of the region by 2020. Grassland area also decreased, while cropland area increased by 0.37%. Residential construction land area increased by 0.18% compared to 2010.

From 2000 to 2020, human activities such as land reclamation, sand fixation, and urban expansion reduced unused land by 1,687.76 km^2. Cropland showed the largest net increase (1,022.93 km^2) with a growth rate of 3.41%, while residential construction land increased by 562.12 km^2 (0.49%). The growth rate of cropland slowed after 2010, possibly due to ecological restoration programs converting some farmland back to forest and grassland.

Land use conversions were dominated by transitions among cropland, grassland, and unused land [Figure 7: see original paper]. In 2000–2010, the total converted area was 720.15 km^2, with unused land contributing the largest 转出量. Conversions were primarily from unused land and grassland to cropland, and from grassland to residential construction land. In 2010–2020, conversions decreased overall, with cropland and grassland dominating the transitions. Most converted area shifted from cropland to grassland, reflecting the implementation of the Grain-for-Green program.

2.4 Impact of Land Use Change on Vegetation NPP

Changes in land use type, structure, and spatial configuration affect NPP through conversion processes and functional transformations. From 2000 to 2020, the average annual NPP of all land use types increased, with forest land showing the highest NPP and most significant growth . Since 2010, residential construction land showed decreased average NPP, while other land use types continued to increase, likely due to effective watershed management projects such as ecological water allocation in the Heihe River basin and environmental remediation in the Shiyang River basin.

The impact of land use change on NPP was most pronounced for grassland and forest land due to their large areas. The growth rate of cropland NPP decreased significantly after 2010 compared to 2000–2010. The area with NPP $\geq$ 400 g $C \cdot m^{-2} \cdot a^{-1}$ increased markedly, rising to 1.98% of the region and concentrated in the southern Hexi Region, demonstrating the effectiveness of government ecological policies including wetland protection in Zhangye, afforestation and sand fixation in Jinchang, and soil erosion control in Wuwei. The area with NPP between 200–400 g $C \cdot m^{-2} \cdot a^{-1}$ also expanded significantly, increasing by 4.64 percentage points.

3 Discussion

3.1 Influence of Climate Factors on NPP Variation

Temperature and precipitation are two critical factors affecting vegetation NPP. According to the IPCC Fifth Assessment Report, climate change shows significant positive correlation with the carbon cycle, though this relationship varies regionally. The Hexi Region' s complex climate types and vegetation species result in inconsistent temperature and precipitation effects on NPP across different areas [Figure 8: see original paper].

Areas where NPP correlated positively with temperature accounted for 85.44%, concentrated in central Hexi including the middle and lower reaches of the Heihe and Shule Rivers. Negative correlations (14.56%) were found in the southeast. Positive correlations with precipitation covered 96.07% of the region, with the strongest correlations in Zhangye, Baiyin, and Wuwei. Negative precipitation correlations (3.93%) were scattered in the southeast.

The contribution rate of climate change to NPP increased compared to 2000-2010, while the contribution rate of LUCC also rose, reflecting significant area increases during the same period. The contribution rate of residential construction land increased markedly, corresponding with its area expansion. The contribution rates of all land use types to NPP increased compared to 2000-2010, particularly for grassland and residential areas, benefiting from government measures such as wetland protection, forest management, and grassland grazing management.

3.2 NPP Impacts Across Different Land Use Types

The influence of various land use types on total vegetation NPP was generally smaller than that of climate change, primarily due to vegetation physiological characteristics. However, LUCC did affect NPP, with its influence on NPP in unused land and residential construction land gradually increasing. Ecological protection projects such as Grain-for-Green, water source conservation, and afforestation enhanced vegetation coverage across most of the Hexi Region, highlighting vegetation' s carbon sequestration and oxygen release functions. Conversely, rapid urbanization driven by economic development reduced vegetation coverage in some areas, decreasing carbon sequestration benefits.

NPP positively correlated with precipitation across central and southeastern Hexi, with correlations strengthening in parts of Lanzhou. Negative correlations were scattered in small southeastern areas. The influence factor for NPP on cropland, forest land, and grassland was dominated by climate change, while for unused land and residential construction land, LUCC became increasingly important.

4 Conclusions

Based on MOD17A3 products, land use/cover data, and meteorological data, this study analyzed the spatiotemporal distribution characteristics and dynamic changes of vegetation NPP in the Hexi Region from 2000 to 2020, and examined its responses to climate change and LUCC. The main conclusions are:

(1) Vegetation NPP in the Hexi Region showed an overall increasing trend from 2000 to 2020, with the growth rate accelerating over time. The trend decreased gradually from southeast to northwest. The multi-year average NPP ranged from 55.74 to 61.06 g $C \cdot m^{-2} \cdot a^{-1}$, with significant interannual variation. The lowest value (43.01 g $C \cdot m^{-2} \cdot a^{-1}$) occurred in 2000, while the highest (73.85 g $C \cdot m^{-2} \cdot a^{-1}$) occurred in 2020.

(2) Precipitation showed stronger correlations with NPP than temperature did. Temperature correlations with NPP were both positive and negative,

while precipitation correlations were predominantly positive. The influence factor for NPP on cropland, forest land, and grassland was dominated by climate change, whereas for unused land and residential construction land, LUCC played an increasingly important role.

(3) Cropland, grassland, and unused land were the most common land use types in the Hexi Region. From 2000 to 2020, the area of cropland, water bodies, and residential construction land increased, while grassland and unused land decreased. Transitions among cropland, grassland, and unused land dominated LUCC patterns. The 转出量 of cropland and residential construction land was far less than their 转入量, while grassland transition areas decreased in both periods, and unused land 转出量 far exceeded its 转入量.

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