Postprint: Xinjiang Vegetation NPP and Its Altitudinal Variation in Response to Climate Change

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Abstract

Using MODIS NPP data and meteorological observation data from 2000 to 2017, and employing trend analysis and correlation analysis methods, this study reveals the spatiotemporal evolution pattern of vegetation net primary productivity (NPP) in the Xinjiang region and its elevational differentiation in response to climate change. The results show that: (1) During the 18-year period, the annual average vegetation NPP in Xinjiang was 145.96 g C·m-2, showing an insignificant increase at a rate of 4.422 g C·m-2·(10a)-1; constrained by topography and regional hydrothermal conditions, vegetation NPP exhibited a distribution pattern where northern Xinjiang was superior to southern Xinjiang, and mountainous areas were superior to plains. (2) The mean NPP generally increased first and then decreased with increasing elevation. In the region with elevation <1400 m, vegetation NPP was dominated by an increasing trend, with positive changes concentrated in the northern slopes of the Tianshan Mountains, the southern margin of the Junggar Basin, and the northwestern edge of southern Xinjiang; in the elevation zone of 1400–3800 m, vegetation NPP mainly showed a weak negative growth, with severe NPP degradation in high-altitude mountainous areas such as the Tianshan Mountains and their southern foothills, and parts of the Altai Mountains. (3) Precipitation was the main driving factor for changes in vegetation productivity levels in Xinjiang, but air temperature replaced precipitation as the dominant factor limiting vegetation activity in high-altitude (>3900 m) regions. Across different elevation gradients, vegetation NPP was mainly negatively correlated with air temperature and positively correlated with precipitation, with more prominent gradient differences in the correlations at elevations <1400 m.

Full Text

Altitudinal Differentiation of Vegetation NPP and Its Response to Climate Change in Xinjiang

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Abstract

Using MODIS NPP (Net Primary Production) data and meteorological observations from 2000 to 2017, this study employs trend analysis and correlation analysis to reveal the spatiotemporal evolution patterns of vegetation net primary productivity in Xinjiang and their altitudinal differentiation in response to climate change. The results indicate that: (1) During the study period, vegetation NPP in Xinjiang showed an insignificant increasing trend, with a mean value of 145.96 g $C \cdot m^{-1}$ and a growth rate of 4.422 g $C \cdot m \cdot (10a)^{-1}$. Constrained by topography and regional hydrothermal conditions, vegetation productivity exhibited a distribution pattern of being higher in northern Xinjiang than in southern Xinjiang, and greater in mountainous areas than in plains. (2) Vegetation NPP was dominated by increasing trends at altitudes below 1400 m, with improvement trends concentrated in the northern slope of the Tianshan Mountains, the southern margin of the Junggar Basin, and the northwestern margin of southern Xinjiang. At altitudes between 1400 m and 3800 m, vegetation NPP showed a slight decreasing trend, with productivity decline being particularly prominent in high-altitude mountainous areas such as the Tianshan Mountains and the Altai Mountains. (3) Precipitation is the primary factor driving vegetation productivity changes in Xinjiang. NPP was positively correlated with precipitation across 66.9% of vegetated areas (with 6.6% showing significant correlation), demonstrating that increased precipitation effectively promotes vegetation productivity. At different altitudinal gradients, vegetation NPP was mainly negatively correlated with temperature and positively correlated with precipitation, with both correlations showing more prominent gradient differences at altitudes below 1400 m. However, at high altitudes above 3900 m, temperature replaced precipitation as the dominant factor limiting vegetation activity. Under the general trend of global warming, studying the vertical patterns of vegetation systems and their climate-driven mechanisms in ecologically fragile regions such as Xinjiang is of great significance for improving environmental management and ecological construction capacity.

Keywords: vegetation; net primary production (NPP); climate change; altitudinal differentiation; Xinjiang

1. Introduction

Net Primary Production (NPP) refers to the total amount of organic dry matter fixed by vegetation per unit time and area. As a key indicator of terrestrial ecosystem health, NPP can directly reflect environmental changes and regional carbon budgets. Under the intensifying background of global climate change, vegetation NPP change research has become a core component of international research programs and has received widespread attention at both global and regional scales. With the rapid development of remote sensing technology, numerous scholars have conducted studies on vegetation productivity changes at various spatiotemporal scales using long-term remote sensing data as the primary data source. Existing research mainly focuses on spatiotemporal evolution patterns of vegetation productivity, response relationships between vegetation productivity and climate change, quantitative analysis of driving factors and their influences. Studies have shown that under climate change drivers, global vegetation productivity exhibits an improving trend, but with significant spatial differences. Although the relationship between vegetation and climate is characterized by both driving factor complexity and spatial heterogeneity, precipitation, drought, temperature, and radiation have been confirmed as the main climatic factors limiting vegetation growth. Residual analysis has preliminarily achieved quantitative assessment of climate and anthropogenic impacts on vegetation, with results indicating that urbanization, agricultural development, and ecological construction projects significantly affect vegetation. In addition to climatic and anthropogenic factors, topography can influence vegetation growth and distribution by directly or indirectly affecting spatial differences in hydrothermal conditions and the degree of human disturbance. Research has also shown that climate warming trends have significant elevation sensitivity, and altitudinal gradients can cause changes in hydrothermal combinations and surface temperature within relatively small geographical ranges, thereby leading to vertical differences in vegetation dynamics. Against this background, domestic scholars have successively conducted analyses on vegetation changes and the altitudinal differences in vegetation sensitivity to climate change in regions such as the Nyainqentanglha Mountains, Qinling Mountains, and Tibetan Plateau, confirming that vegetation typically exhibits a unimodal distribution pattern that first increases and then decreases with altitude, and that the effects of temperature and precipitation on vegetation show altitudinal differentiation. Higher altitude vegetation growth is mainly controlled by temperature, while mid- and low-altitude areas are more affected by precipitation.

Xinjiang is a typical inland arid ecologically fragile region in China with diverse landform types, and its vegetation distribution shows obvious vertical zonality. Since the 1980s, the "warming and wetting" trend in Xinjiang's climate has become increasingly prominent, coupled with continuously intensifying human activities, resulting in significant changes in regional vegetation ecosystems and productivity levels. In recent years, research on vegetation productivity evolution patterns and driving factors in Xinjiang has gradually attracted attention.

However, studies on the correlation between vegetation productivity and topographic factors, particularly altitude gradients, in Xinjiang are still lacking. To fill this research gap regarding the vertical differences in vegetation-climate relationships in Xinjiang, this paper uses continuous remote sensing data and meteorological observations from 2000 to 2017 to systematically analyze the patterns and trends of vegetation NPP in Xinjiang, with a focus on exploring the altitudinal gradient differences in its dynamic change characteristics and climate-driven mechanisms, aiming to provide theoretical basis and decision-making references for ecological environment construction and protection in arid and semi-arid regions.

2. Study Area

Xinjiang is located in the northwestern border of China, between 34°25 ~48°10 N and 73°40 ~96°18 E, with a total area of 166$×10^{4}$ km^2. The territory features alternating mountain ranges and basins, forming a unique "three mountains surrounding two basins" geographical structure (Fig. 1). Xinjiang is deep inland, far from the ocean, and surrounded by high mountains, forming a typical temperate continental climate characterized by large temperature variations, low and unevenly distributed precipitation (average annual precipitation around 145 mm), abundant sunshine, and dry climate. These unique topographic and climatic characteristics result in significant horizontal and vertical differences in vegetation distribution, making the ecosystem relatively fragile and sensitive.

3. Data Sources and Processing

Vegetation productivity data were derived from the MOD17A3 product, obtained from the NASA website (https://www.modisland.gsfc.nasa.gov). This dataset has been widely applied in regional and global carbon cycle simulation, ecosystem assessment, and environmental change detection. The data have a spatial resolution of 500 m and a temporal resolution of one year, covering the period 2000–2017. Meteorological data were obtained from the China Meteorological Data Sharing Service Network (https://data.cma.cn), including monthly mean temperature and monthly precipitation data sequences from 34 national benchmark climate stations in Xinjiang from 2000 to 2017. This dataset has undergone strict quality control, with accuracy and completeness meeting research requirements. We used the thin-plate spline function method in ANUSPLIN interpolation software to perform spatial interpolation of meteorological data, using Xinjiang' s 500 m$×$500 m DEM data as covariates to improve interpolation accuracy, obtaining gridded meteorological data with a spatial resolution of 500 m. All experimental data were uniformly processed through projection conversion and clipping using ArcGIS 10.2 to generate annual sequences with consistent spatial and temporal resolution for analysis.

4. Research Methods

4.1 Trend Analysis We used unary linear regression analysis to simulate the trend slope pixel by pixel, revealing the change trend of vegetation NPP in Xinjiang from 2000 to 2017 and its spatial differences. The calculation formula is as follows:

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

where *Slope* is the trend slope; n is the number of years in the study period; and NPP is the NPP value in year i. When Slope > 0, it indicates that vegetation NPP shows an increasing trend; when Slope $= 0$, it indicates no obvious change in vegetation growth status; when Slope < 0, it indicates that vegetation NPP shows a decreasing trend. The larger the absolute value of Slope, the more obvious the change trend of vegetation net primary productivity. The F-test was used to determine the significance level of the change trend.

4.2 Correlation Analysis Pearson correlation analysis was conducted pixel by pixel between the annual NPP sequence and the 同期 temperature and precipitation sequences to evaluate the relative contribution rates of different climate factors to vegetation NPP changes, thereby characterizing the response of vegetation growth to climate change. The calculation formula is as follows:

$$r = \frac{n \times \sum_{i=1}^{n} X_i Y_i - \sum_{i=1}^{n} X_i \sum_{i=1}^{n} Y_i}{\sqrt{[n \times \sum_{i=1}^{n} X_i^2 - (\sum_{i=1}^{n} X_i)^2] \times [n \times \sum_{i=1}^{n} Y_i^2 - (\sum_{i=1}^{n} Y_i)^2]}}$$

where n is the number of years in the study period; X and Y correspond to the two variables in the correlation analysis. The correlation coefficient r ranges from -1 to 1. The larger the absolute value of the correlation coefficient, the higher the correlation between vegetation NPP and climate factor changes; conversely, the smaller the correlation.

5. Results and Analysis

5.1 Spatiotemporal Distribution and Evolution of Vegetation NPP in Xinjiang The spatial distribution of vegetation NPP in Xinjiang from 2000 to 2017 showed significant regional differences, generally characterized by higher values in northern Xinjiang than in southern Xinjiang, and greater values in mountainous areas than in plains. The average NPP values in mountainous areas were generally greater than 200.0 g $C \cdot m^{-1}$, with some areas even exceeding 360.0 g $C \cdot m^{-1}$. Mountainous areas are typically dominated by forest land, and coupled with sufficient moisture conditions, the overall level of vegetation productivity is high. In northern Xinjiang, NPP gradually decreased from west to east. In southern Xinjiang, except for some plain areas, most regions had

NPP values below 90.0 g C·m^{-1}. Overall, vegetation NPP in Xinjiang showed a fluctuating increasing trend from 2000 to 2017, with a linear trend of 4.422 g C·m·(10a)$^{-1}$. Vegetation in 58.2% of the region showed an increasing trend, with 26.4% of the region showing significant changes ($P < 0.05$), indicating that regional vegetation was dominated by productivity increase and improved growth status (Fig. 3). The most significant increasing trends occurred on the northern slope of the Tianshan Mountains, the southern margin of the Junggar Basin, and the northwestern margin of southern Xinjiang, mainly because the northern slope receives more annual precipitation influenced by water vapor from the Atlantic Ocean and Arctic Ocean, which can effectively alleviate soil water deficiency and promote vegetation growth. The distribution characteristics of vegetation NPP differed between mountainous and plain areas, with mountainous areas being the main regions of vegetation improvement trends. Among them, productivity decline was more prominent in local high-altitude mountainous areas such as the Tianshan Mountains and their southern foothills, and parts of the Altai Mountains, with some areas showing significant vegetation productivity degradation (Slope < 0, $P < 0.05$).

5.2 Altitudinal Differentiation of Vegetation NPP in Xinjiang Affected by differences in hydrothermal conditions, vegetation coverage in Xinjiang varied significantly across altitudes (Fig. 4). Altitudes below 1400 m were the main distribution areas of vegetation, with accumulated vegetation area reaching 26.40$×10^{6}$ hm^2. Thereafter, vegetation coverage gradually decreased with increasing altitude. The vertical distribution of vegetation productivity and vegetation coverage was not completely consistent. Vegetation NPP showed a bimodal pattern that first increased and then decreased, with altitude 900 m as the boundary, and the highest productivity levels occurred at altitudes of 1700-1800 m. Analysis suggests that at lower altitudes (<800 m), regional hydrothermal conditions are relatively sufficient and dominated by agricultural vegetation, maintaining relatively high and stable productivity levels. Within the 800-1000 m range, urbanization impacts are intense, causing a significant reduction in NPP. When altitude increases to 1100-1300 m, vegetation types transition to desert grassland and plain grassland. Due to their distribution mainly in piedmont plain zones, orographic rain and snowmelt ensure sufficient soil moisture, vegetation coverage is extensive, and the degree of human disturbance gradually decreases with altitude, leading to increased productivity. When altitude continues to rise, vegetation gradually transitions from plain grassland to mountain grassland, mountain coniferous forest, alpine meadow, and alpine cushion vegetation, with vegetation living space and coverage greatly reduced. Coupled with limitations from hydrothermal conditions, productivity gradually declines.

In terms of change trends (Fig. 5), vegetation NPP basically showed an increasing trend (Slope > 0) at altitudes below 1500 m, with the most prominent increase at altitudes of 200-400 m, followed by the 1100-1300 m range. In the altitude range of 1500-2100 m, decreasing trends dominated (Slope < 0). At altitudes of 2100–3900 m, there was no obvious altitudinal differentiation in change trends. Above 3900 m, the trend shifted from decreasing to increasing, indicating that under warming effects, the ecological environment in high-altitude areas is gradually developing in a direction conducive to vegetation growth. Analysis of the direction and degree of vegetation productivity changes in each vertical zone shows that in the altitude range of 1300–2200 m, vegetation NPP decreased most significantly, with a decrease proportion of 54.8% (30.8% significantly decreased). In contrast, vegetation NPP increases were prominent in altitude zones below 500 m and above 4500 m, with increase proportions of 77.4% (33.8% significantly increased) and 75.4% (30.8% significantly increased), respectively.

5.3 Response of Vegetation NPP to Climate Change and Its Altitudinal Differences Statistics show that during 2000–2017, Xinjiang' s vegetation area exhibited a "warming and wetting" trend consistent with the overall environment (Fig. 6), with temperature and precipitation in the vegetation area increasing at rates of 0.209 °C$\cdot$(10a)$^{-1}$ ($P > 0.05$) and 15.873 mm$\cdot$(10a)$^{-1}$ ($P > 0.05$), respectively. Comparison with annual mean values shows that "cold and wet" years typically corresponded to NPP increases, while "warm and dry" years corresponded to NPP decreases. For example, the substantial precipitation reduction in 2008 directly limited vegetation productivity levels that year, while the temperature decrease in 2005 and the significant moisture increase in 2007 jointly affected NPP changes. The abundant precipitation during 2009–2010 and the continued cooling in 2011 promoted NPP increases in corresponding years, indicating that vegetation response to climate change has a certain time-lag effect.

Temperature variation rates were relatively small at all altitudes ($|\text{Slope}| = 0.021$). Cooling trends were mainly concentrated in the 500–900 m altitude range, while warming trends occurred below 500 m. In the 900–1400 m altitude range, warming was observed, with the greatest warming amplitude above 1400 m. Precipitation showed increasing trends in vertical zones above 2600 m, but the increase was inversely proportional to altitude. Other altitude zones experienced varying degrees of precipitation reduction (Fig. 7).

Correlation analysis shows that precipitation is the main factor affecting vegetation productivity in Xinjiang. Across the entire region, 40.3% of NPP was positively correlated with temperature, with only 6.6% reaching significant positive correlation, mostly distributed in high-altitude mountainous areas with relatively sufficient precipitation, lower temperatures, and heat-dominated vegetation growth. In most areas of northern Xinjiang and southern Xinjiang, due to scarce precipitation and low water availability, temperature increases would enhance soil evaporation and drought, which is not conducive to vegetation growth. Therefore, NPP was negatively correlated with temperature in these areas. Regarding precipitation (Fig. 8), 66.9% of NPP was positively correlated with precipitation (6.6% significantly positively correlated), indicating that for the vast arid region of Xinjiang with high temperatures, low rainfall, and insufficient moisture conditions, increased precipitation can promote vegetation productivity to varying degrees. Overall, with increasing altitude, hydrothermal conditions sequentially showed gradient changes of "cold and dry" (altitude $<$500 m), "warm and dry" (500 m $<$ altitude $<$900 m), "cold and wet" (900 m $<$ altitude $<$1400 m), "warm and wet" (1400 m $<$ altitude $<$2700 m), and "warm and dry" (altitude $>$2700 m).

At different altitudinal gradients, vegetation NPP was mainly negatively correlated with temperature and positively correlated with precipitation (Fig. 9). When altitude was below 1400 m, the correlation between NPP and temperature showed alternating positive and negative patterns with large fluctuations with increasing altitude. In this altitude range, NPP showed strongly fluctuating positive correlations with precipitation. The possible reasons are: in mid- and low-altitude areas, vegetation growth is more sensitive to hydrothermal condition changes and is subject to greater human disturbance, leading to obvious gradient differences in vegetation response to moisture and heat. For example, irrigation and fertilization measures in agricultural areas reduce the correlation between agricultural vegetation productivity and precipitation, causing a significant decrease in the correlation between NPP and precipitation in the 800–1200 m range. When altitude exceeds 1300 m, the positive correlation between NPP and precipitation gradually weakens with increasing altitude, while the negative correlation between NPP and temperature first increases and then decreases. Above 3900 m, the correlation between NPP and precipitation shifts from positive to negative and becomes smaller than the correlation coefficient with temperature, indicating that when temperature is below the optimal temperature for vegetation growth, temperature limitation on photosynthesis will replace precipitation supplementation of soil water deficiency as the dominant factor controlling vegetation growth.

6. Discussion

Topography and landforms and their resulting differences in hydrothermal combination conditions are considered the dominant factors affecting vegetation growth and productivity changes in Xinjiang. The special terrain of western Tianshan Mountains and northern Altai Mountains allows humid airflows from the North Atlantic and Arctic Ocean to converge here, forming abundant cold front rain and orographic rain, and distributing highly productive Tianshan spruce forest communities, which become high-value areas of NPP. The northern slope of the Tianshan Mountains blocks Atlantic water vapor entering through the western gap of the Junggar Basin, forming orographic rain that can provide sufficient water sources for vegetation growth. In contrast, the southern slope is leeward with little rain, high evaporation, and widespread desert areas with sparse vegetation, thus causing spatial distribution and change trend differences of "high in the north and low in the south" and "increasing in the north and decreasing in the south" in vegetation NPP. Low vegetation productivity areas are mainly distributed in ecologically sensitive and fragile zones such as the edges of basins in southern and northern Xinjiang. These areas have high temperatures, little rain, abundant sunshine, severe land desertification, low water conservation function, and relatively harsh vegetation habitats. However, the increase in precipitation in recent years, coupled with the implementation of ecological environmental protection policies such as returning farmland to forest and grassland, has promoted ecological environment improvement and vegetation productivity enhancement in these arid and fragile areas.

The response relationship of NPP being positively correlated with precipitation and negatively correlated with temperature is also consistent with existing research conclusions. Xinjiang' s inland location far from the ocean determines insufficient regional water vapor sources, scarce precipitation, and soil water deficits that weaken the relationship between temperature and vegetation growth, making drought the main limiting factor for ecosystem primary productivity. Increased precipitation can effectively compensate for soil water deficiency in arid and semi-arid areas, reduce surface evapotranspiration, and thereby enhance vegetation photosynthetic efficiency and increase organic dry matter accumulation, making it the main limiting factor for regional vegetation productivity. However, in local mountainous areas with higher altitudes and more abundant precipitation, photosynthesis becomes limited by temperature, strengthening the correlation between vegetation NPP and temperature and making the "warm and dry" climate in high-altitude areas more conducive to mountain vegetation growth. However, the decrease in soil water availability caused by low-temperature environments may limit or offset the positive effects of temperature increases on vegetation growth. Therefore, the relationship between warming rates and vegetation productivity variability in high-altitude areas requires further research. Meanwhile, studies can confirm that vegetation response to hydrothermal condition changes has a time-lag effect, although this was not discussed in detail in this paper.

The vertical zonal distribution of vegetation is another intuitive manifestation of altitudinal gradient differences. As altitude increases, Xinjiang vegetation types transition from desert grassland to grassland, forest, mountain meadow grassland, alpine meadow, or cushion vegetation. Different vegetation types have different water requirements, coverage areas, geographical distribution characteristics, organic matter accumulation efficiency, and response levels to climate change. Combined with different intensities of human activities at different altitudes and topographic diversity caused by slope and aspect, these factors will further aggravate the altitudinal differentiation of vegetation NPP, making more comprehensive and thorough research necessary.

7. Conclusions

Based on MODIS NPP data and meteorological observation data from 2000 to 2017, this study analyzed the horizontal and vertical spatial distribution characteristics and change patterns of regional vegetation productivity in Xinjiang, and for the first time explored the vertical differences in the correlation between vegetation dynamic changes and hydrothermal climate factors. The main conclusions are as follows:

(1) From 2000 to 2017, vegetation NPP in Xinjiang showed an insignificant increasing trend, with an average annual value of 145.96 g $C \cdot m^{-1}$ and a growth rate of 4.422 g $C \cdot m \cdot (10a)^{-1}$. Vegetation productivity exhibited a distribution pattern of being higher in northern Xinjiang than in southern Xinjiang, and greater in mountainous areas than in plains. The main distribution area of vegetation was below 1400 m altitude, with accumulated vegetation area of 26.40$×10^{6}$ hm^2. Vegetation productivity and vegetation coverage showed inconsistent vertical distribution characteristics, with the highest productivity levels occurring at altitudes of 1700–1800 m.

(2) Vegetation NPP was dominated by increasing trends in 58.2% of the region, with improvement trends mainly concentrated on the northern slope of the Tianshan Mountains, the southern margin of the Junggar Basin, and the northwestern margin of southern Xinjiang. The decline in productivity was more prominent in high-altitude mountainous areas such as the Tianshan Mountains and Altai Mountains.

(3) The influence degree of hydrothermal conditions on vegetation NPP changes in Xinjiang differed. Precipitation is the main limiting factor for regional vegetation productivity, being positively correlated (60.3%) or significantly positively correlated (6.6%) with NPP. Meanwhile, the relative contribution of temperature and precipitation changes to NPP is closely related to altitude, indicating that the vegetation-climate relationship in Xinjiang has vertical differences. The positive promoting effect of precipitation on vegetation NPP exists widely except in extremely low (<200 m) and extremely high (>3900 m) altitude areas. Temperature is mainly negatively correlated with vegetation, but some mid- and low-altitude areas are simultaneously controlled by both precipitation and temperature.

8. References

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