Spatiotemporal Variation in Vegetation Net Primary Productivity and Driving Factors in the Shiyang River Basin (Postprint)

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Abstract

The CASA (Carnegie-Ames-Stanford Approach) model was utilized to simulate vegetation net primary productivity (NPP) in the Shiyang River Basin from 2000 to 2020, analyzing the spatiotemporal variation characteristics, stability, and future change trends of basin NPP, and exploring the influences on NPP changes from three aspects: climatic factors, topographic factors, and human activity factors. The results indicate: (1) The multi-year average vegetation NPP in the Shiyang River Basin from 2000 to 2020 was 291.01 g C • m-2 • a-1, exhibiting a non-significant increasing trend, with a spatial distribution pattern of high in the south and low in the north. (2) Areas where vegetation NPP exhibited an increasing trend since 2000 accounted for 86.4% of the total area, with areas of extremely significant increase and significant increase accounting for 6.7% and 10.1%, respectively. (3) The proportion of areas with NPP variation above moderate fluctuation (coefficient of variation Cv$ $0.25) was 50.4%. (4) From the perspective of future change trends, the sustainability of vegetation NPP recovery in the Shiyang River Basin is weak, with the proportion of areas showing increasing but anti-persistent trends reaching 57.1%. (5) Vegetation NPP changes in the basin are positively correlated with both temperature and precipitation, with a more sensitive response to temperature. NPP shows a trend of increasing then decreasing with increasing altitude and slope; in recent years, a series of measures implemented in the basin, such as artificial afforestation, conversion of cropland to forest and grassland, have significantly promoted the increase in vegetation NPP.

Full Text

Abstract

We estimated vegetation net primary productivity (NPP) in the Shiyang River Basin from 2000 to 2020 using the Carnegie-Ames-Stanford Approach (CASA) model to analyze the spatiotemporal variation characteristics, stability, and future trends of NPP, and to examine the impacts of climatic, topographic, and anthropogenic factors. The results revealed that: (1) The multi-year average NPP was 291.01 g $C \cdot m^{-1}$, showing an increasing trend, with a spatial distribution pattern of high values in the south and low values in the north. (2) Since 2000, vegetation NPP has increased across 86.4% of the basin area, with extremely significant and significant increases accounting for 6.7% and 10.1% of the total area, respectively. (3) From the perspective of future trends, the capacity for sustained vegetation improvement is weak; areas showing increasing but anti-persistent trends constitute 57.1% of the total area. (4) The coefficient of variation ($Cv \geq 0.25$) indicates that 50.4% of the basin experienced moderate or higher fluctuation in NPP. (5) Vegetation NPP was positively correlated with both temperature and precipitation, though the response to temperature was more sensitive. NPP initially increased then decreased with rising elevation and slope gradient. In recent years, a series of ecological engineering measures including artificial afforestation and the Grain-for-Green program have significantly promoted NPP increase.

Keywords: vegetation net primary productivity; spatiotemporal variation; driving factors; Shiyang River Basin

1. Introduction

Vegetation net primary productivity (NPP) represents the organic matter remaining after plant respiration is subtracted from the total organic matter produced through photosynthesis per unit time and area. NPP reflects the production capacity of vegetation under natural conditions and serves as an important indicator of terrestrial ecosystem quality, ecosystem function, and structural change. Current regional NPP estimation methods primarily include field measurements and model simulations, with the latter encompassing climate correlation statistical models (e.g., Miami, Thornthwaite, Chikugo), ecosystem process simulation models (e.g., BIOME), light use efficiency models (e.g., CASA), and ecological remote sensing coupling models. Numerous scholars have applied these models across different regions and temporal scales. For instance, Zhu et al. and Yang et al. used the Thornthwaite Memorial model to investigate NPP dynamics in Ningxia grasslands, Inner Mongolia grasslands, and the Loess Plateau, respectively, while Zhou et al. employed the CASA model to examine spatiotemporal patterns and influencing factors in Central Asian grasslands.

The Shiyang River Basin, located at the intersection of the Loess, Qinghai-Tibet, and Mongolian-Xinjiang plateaus, features a unique topography with diverse underlying surface types and significant geographic and climatic differences from south to north, forming a typical "desert-forest" ecosystem. Under the dual influence of regional climate change and human activities, the basin's ecological structure and function have undergone marked changes, including glacier retreat and snowline rise in the Qilian Mountains, declining water conservation capacity, reduced biodiversity, grassland degradation, and desertification. While previous studies have examined NPP dynamics in the Yangtze River Basin and Southwest China using MOD17A3 data, research on the Shiyang River Basin remains limited, particularly regarding the impacts of recent ecological restoration projects. This study employs the CASA model, which integrates multiple natural factors and utilizes large-scale remote sensing data, to analyze spatiotemporal NPP dynamics and their driving mechanisms. The findings provide a scientific basis for evaluating vegetation growth status, terrestrial ecosystem quality, and the effectiveness of ecological restoration efforts in this ecologically vulnerable region.

1.1 Study Area

The Shiyang River Basin is situated in the eastern Hexi Corridor of Gansu Province at the northern foothills of the Qilian Mountains, spanning 101°41 – 104°16 E and 36°29 –39°27 N. The terrain comprises three distinct zones: the southern Qilian Mountains, the central plain, and the northern desert region. The basin experiences a continental temperate arid climate characterized by strong solar radiation, abundant sunshine, short hot summers, long cold winters, large temperature variations, low precipitation, and strong evaporation. Meteorological data indicate that the basin has exhibited a warming and wetting trend since 1960, with notable increases in both temperature and evaporation. The basin can be broadly divided into three climatic zones from south to north: a high-cold semi-arid and semi-humid zone in the Qilian Mountains, a cool-arid zone in the central corridor plain, and a warm-arid zone in the north. Land use types include cropland, forest, grassland, shrubland, wetland, water bodies, snow cover, and bare land [Figure 1: see original paper].

1.2 Data Sources

Remote sensing data consisted of monthly MOD13A3 NDVI composite data at 1 km resolution, obtained from the National Qinghai-Tibet Plateau Scientific Data Center (http://data.tpdc.ac.cn/). Meteorological data including monthly temperature and precipitation from six stations (Minqin, Liangzhou, Tianzhu, Wushaoling, Gulang, Yongchang, Jinchang, and Sunan) were acquired from the China Integrated Meteorological Information Service System (CIMISS). These data were spatially interpolated using inverse distance weighting in ArcGIS to generate spatial distribution maps of meteorological factors. Data on ecological engineering projects were sourced from the *Wuwei Statistical Yearbook* and the Northwest Regional Climate Center.

1.3 Methods

1.3.1 CASA Model

We employed the light use efficiency-based CASA model to estimate monthly NPP in the Shiyang River Basin from 2000 to 2020, with annual NPP obtained through monthly accumulation. The model calculations followed established methodologies [2,25-26].

1.3.2 Trend Analysis

A univariate linear regression trend analysis was performed on a pixel-by-pixel basis to examine spatial changes in vegetation NPP across the basin. The least squares method was used to fit the slope of each pixel and calculate the change rate. The significance of trends was tested using F-tests.

1.3.3 Hurst Index

The Hurst index quantitatively describes the persistence characteristics of time series data. We used this index to analyze the persistence features of NPP in the study area. For a time series $\{NPP(t), t = 1, 2, ..., n\}$, the mean, cumulative deviation, range, and standard deviation were defined following standard procedures. The Hurst index ranges from 0 to 1, where $H > 0.5$ indicates persistence (future trends consistent with past trends, with stronger persistence as H approaches 1), $H = 0.5$ indicates randomness, and $H < 0.5$ indicates anti-persistence (future trends opposite to past trends, with stronger anti-persistence as H approaches 0).

1.3.4 Stability Analysis

The coefficient of variation (Cv) reflects the relative fluctuation degree of time series data. We used Cv to analyze the stability of NPP changes, where smaller Cv values indicate more concentrated data distribution and lower temporal fluctuation.

1.3.5 Partial Correlation Analysis

Partial correlation analysis was employed to examine the relationship between NPP and temperature/precipitation. Significance testing was conducted using t-tests.

2. Results

2.1 Temporal Variation Characteristics

From 2000 to 2020, the average annual vegetation NPP in the Shiyang River Basin was 291.01 $g\ C \cdot m^{-1}$, with a non-significant increasing trend of 2.2975 $g\ C \cdot m^{-1} \cdot yr^{-1}$. The minimum value (192.61 $g\ C \cdot m^{-1}$) occurred in 2000, while the maximum (421.47 g $\mathrm{C \cdot m^{-1}}$) occurred in 2019. Areas showing increasing trends accounted for 86.4% of the total basin area [Figure 2: see original paper].

2.2 Spatial Distribution and Changes

Vegetation NPP exhibited substantial spatial heterogeneity, with a clear pattern of high values in the south and low values in the north [Figure 3: see original paper]. Areas with NPP below 150 g $\mathrm{C \cdot m^{-1}}$, primarily distributed in the mid- and downstream desert regions and upstream snow-covered areas of the Qilian Mountains, accounted for 42.9% of the basin. These regions, characterized by desert and semi-desert landscapes with sparse or no vegetation cover, showed the lowest NPP values. Areas with NPP between 150–300 g $\mathrm{C \cdot m^{-1}}$, covering 13.5% of the basin, were mainly intermontane basins and low hilly regions dominated by bare land and grassland in western Yongchang and Gulang counties. NPP values of 300–450 g $\mathrm{C \cdot m^{-1}}$, representing 31.0% of the basin, included oasis farmland irrigation areas in southeastern Jinchang and central Minqin, as well as dryland areas at the mountain front in the upper reaches. Areas with NPP of 450–600 g $\mathrm{C \cdot m^{-1}}$ (13.9%) were primarily located in oasis farmland irrigation areas of Liangzhou District, while values above 600 g $\mathrm{C \cdot m^{-1}}$ (11.0%) were concentrated in the upstream Qilian Mountains region, including northern Tianzhu, southwestern Liangzhou, and Sunan County, where forest and grassland dominate [Figure 4: see original paper].

2.3 Stability Analysis

Based on the coefficient of variation, NPP stability was classified into five levels: low, relatively low, moderate, relatively high, and high fluctuation. Low ($\mathrm{Cv} < 0.20$) and relatively low ($0.20 \leq \mathrm{Cv} < 0.25$) fluctuation areas accounted for 43.0% and 11.8% of the basin, respectively, primarily distributed in the midstream and downstream regions of Liangzhou and Minqin. Moderate fluctuation ($0.25 \leq \mathrm{Cv} < 0.30$) covered 13.5% of the area, while relatively high ($0.30 \leq \mathrm{Cv} < 0.35$) and high ($\mathrm{Cv} \geq 0.35$) fluctuation areas accounted for 11.0% and 31.0%, respectively. These high-fluctuation regions were mainly distributed in Gulang County, Qingtu Lake in Minqin, the oasis-desert ecotone between Liangzhou and Minqin, and the upstream Qilian Mountains, where vegetation restoration has been particularly significant in recent years [Figure 5: see original paper].

2.4 Future Trend Changes

The Hurst index for vegetation NPP in the Shiyang River Basin ranged from 0.195 to 0.815, with an average of 0.515. Areas with $\mathrm{H} < 0.5$ (indicating anti-persistence) accounted for 64.5% of the basin, predominantly in the southern, eastern, and southwestern regions including Gulang, Tianzhu, Sunan, and eastern Minqin. Areas with $\mathrm{H} > 0.5$ (indicating persistence) constituted 35.5%, mainly distributed in the midstream and downstream regions of Liangzhou, Jinchang, and Minqin.

Integrating the Hurst index with NPP change trends revealed that areas showing increase and persistence accounted for 24.7% of the basin, primarily in western Gulang and central-western Minqin. Decrease and persistence areas comprised only 1.8%, sporadically distributed in downstream Minqin and Yongchang. Notably, increase and anti-persistence areas occupied 57.1% of the basin, indicating that while vegetation has improved, the sustainability of this improvement is weak. These areas were concentrated in Tianzhu, Sunan, and eastern Minqin in the upstream region. Decrease and anti-persistence areas accounted for 11.8%, distributed in Liangzhou and Minqin [Figure 6: see original paper].

2.5 Climate Factors

Vegetation is a crucial component of terrestrial ecosystems and responds significantly to climate change. Climate data show that both temperature and precipitation in the Shiyang River Basin increased during 2000–2020, consistent with NPP trends [Figure 7: see original paper]. The partial correlation coefficient between NPP and temperature ranged from -0.552 to 0.875 (mean: 0.421), with positive correlations covering 97.6% of the basin. Significant positive correlations ($P < 0.05$) were found in 73.0% of the area, particularly in the northern low hills and desert regions of Gulang, Liangzhou, and Minqin. Negative correlations were limited to 2.4% of the basin.

The partial correlation coefficient between NPP and precipitation ranged from -0.587 to 0.766 (mean: 0.215), with positive correlations in 89.6% of the basin. Significant positive correlations ($P < 0.05$) occurred in 34.1% of the area, mainly in upstream Gulang and desert regions of the midstream and downstream areas. Negative correlations occupied 10.4%, primarily in the southwestern upstream region including Sunan and the mountainous areas of Liangzhou and Tianzhu [Figure 8: see original paper].

2.6 Topographic Factors

Elevation primarily influences the distribution of temperature, humidity, and light. The Shiyang River Basin's terrain slopes from high in the south to low in the north, encompassing mountains, plains, hills, and deserts. NPP varied significantly across elevation zones, showing an initial increase followed by decrease with rising altitude. Below 1638 m, dominated by low hills and desert areas, mean NPP was only 179.67 $g\ C \cdot m^{-1}$. NPP gradually increased with elevation, reaching a maximum of 665.62 $g\ C \cdot m^{-1}$ at 3158–3538 m, where land cover is primarily forest and grassland. Above this elevation, land cover transitions to grassland, bare land, and snow, causing NPP to decline rapidly [Figure 9: see original paper].

Slope gradient affects water and nutrient absorption and influences temperature distribution from hilltops to bases. NPP generally increased with slope ($R^2 = 0.5974$), peaking at 507.88 $g\ C \cdot m^{-1}$ on 30°–35° slopes, then decreasing slightly on steeper slopes.

2.7 Human Activities

Recent ecological restoration efforts have significantly improved the Shiyang River Basin's environment. Through implementation of the "Ecological Barrier Action" and construction of a water-saving society, the basin has advanced comprehensive management focusing on water conservation in the south, oasis protection in the center, and sand control in the north. Key ecological projects include sand fixation, afforestation, and the Grain-for-Green program. Statistical data show that afforestation area [Figure 10a: see original paper], returning farmland to forest and grassland area [Figure 10b: see original paper], and closed hillside (sand) afforestation area [Figure 10c: see original paper] all positively correlated with annual NPP. Afforestation area showed a significant positive correlation with NPP ($R^2 = 0.45$, $P < 0.05$), demonstrating that policy measures have markedly improved the ecological environment.

3. Discussion

Our findings of significantly increasing NPP trends in the Shiyang River Basin since 2000 align with studies by Li et al. and Tong et al. The implementation of ecological projects such as water replenishment at Qingtu Lake has created over 100 km^2 of wetland in this arid region. Meanwhile, ecological migration and afforestation measures in Gulang County have established extensive forest-grassland areas in the southern mountains, protecting and restoring vegetation ecosystems. These results are consistent with Wang et al. and Xu et al., who found that returning farmland to forest and afforestation on barren hills significantly enhanced NPP in the Shiyang River Basin.

Both temperature and precipitation in the basin showed increasing trends. Michaletz et al. identified temperature and water availability as fundamental drivers of plant physiology and ecosystem metabolism at local scales, while other studies have shown that arid region vegetation is particularly sensitive to climate change. Our partial correlation analysis revealed positive relationships between NPP and temperature/precipitation across 97.6% and 89.6% of the basin, respectively. The warming and wetting trend since 1960, documented in multiple studies, has provided sufficient water and heat conditions to promote vegetation growth and biomass accumulation. However, NPP showed stronger correlation with temperature than precipitation, with some negative correlations in the southwestern Qilian Mountains. This differs from studies identifying precipitation as the primary factor controlling NPP in northern China's arid regions, likely due to differences in spatiotemporal scales and underlying surface types. In the Shiyang River Basin, midstream and downstream agriculture relies on irrigated farmland where crop growth is guaranteed even during precipitation deficits, resulting in non-significant positive correlations between NPP and precipitation in oasis areas. In the precipitation-rich southwestern Qilian Mountains (annual precipitation >400 mm), abundant rainfall means more cloudy days, reduced solar radiation, and insufficient light-heat conditions that can inhibit photosynthesis and vegetation growth.

The spatial pattern of high NPP in the south and low NPP in the north, with NPP first increasing then decreasing with elevation, matches Cao's findings for the Hexi Corridor. The southern mountains have abundant precipitation, forest-grassland cover, and minimal human disturbance. As elevation decreases toward the central and northern regions, land use transitions to cropland and construction land, with increasing anthropogenic interference. Northern areas are dominated by desert land cover. This combination of topography, vegetation type, precipitation, and human activity shapes the observed spatial pattern.

Future trend analysis indicates that a large proportion (57.1%) of the basin shows increasing but anti-persistent NPP trends, similar to Zhang's findings for Northwest China. This suggests the basin's ecological environment remains fragile. Despite recent improvements through ecological projects, sustainability is weak due to the harsh natural environment, extensive desertification, water resource scarcity, and frequent disasters such as sandstorms and droughts. While management measures have improved the situation, fundamental pressures on ecological protection persist, and the transition from key management to comprehensive management remains challenging.

Land use change significantly affects NPP, and future research should analyze vegetation responses to various factors at finer scales. More targeted measures in ecological project implementation, combined with systematic, comprehensive, and source-based management, will enhance ecosystem stability and provide scientific support for ecological restoration and protection in the Shiyang River Basin.

4. Conclusions

(1) The multi-year average vegetation NPP in the Shiyang River Basin from 2000 to 2020 was 291.01 g $\mathrm{C \cdot m^{-1}}$, showing an increasing trend. Influenced by climate, human activities, and topography, NPP exhibited a spatial pattern of high values in the south and low values in the north, exceeding 600 g $\mathrm{C \cdot m^{-1}}$ in the southern mountains and falling below 150 g $\mathrm{C \cdot m^{-1}}$ in the northern desert region.

(2) Since 2000, NPP has increased across 86.4% of the basin area, with extremely significant and significant increases accounting for 6.7% and 10.1%, respectively. Comprehensive management measures have substantially enhanced NPP, with afforestation area, returning farmland to forest and grassland area, and closed hillside (sand) afforestation area all showing positive correlations with annual NPP.

(3) Stability analysis indicated that 50.4% of the basin experienced moderate or higher fluctuation ($\mathrm{Cv} \geq 0.25$). The average Hurst index was 0.515, with 64.5% of the basin showing anti-persistent trends opposite to past changes. Areas with increasing but anti-persistent trends accounted for 57.1%, indicating that the overall ecological environment remains fragile.

(4) Vegetation NPP was positively correlated with both temperature and precipitation, with average correlation coefficients of 0.421 and 0.215, respectively. NPP initially increased then decreased with rising elevation and slope gradient.

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