# Spatiotemporal Characteristics of Vegetation Carbon Use Efficiency and Its Sensitivity to Climate in the Shaanxi Yellow River Basin: Postprint

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## Abstract

Vegetation carbon use efficiency (Carbon Use Efficiency, CUE) can objectively reflect the efficiency of vegetation in fixing atmospheric carbon and the feedback of vegetation to climate change. Using MOD17, land use data, and meteorological data, and applying methods such as Hurst exponent, correlation analysis, and sensitivity analysis, this study explored the spatiotemporal variation of vegetation CUE and its sensitivity to climatic factors in the Yellow River Basin of Shaanxi from 2001 to 2021. The results show that: (1) From 2001 to 2021, vegetation gross primary productivity (Gross Primary Productivity, GPP), net primary productivity (Net Primary Productivity, NPP), and vegetation CUE in the Yellow River Basin of Shaanxi showed an upward trend, with a mean vegetation CUE of 0.51. (2) Only 14.21% of the study area showed a decreasing trend in vegetation CUE. High-value areas of vegetation CUE were mainly concentrated in the windbreak and sand fixation areas and the grain-for-green areas in northern Shaanxi. The area where vegetation CUE will show a decreasing trend in the future accounts for 59.96%, with most being a transition from increasing to decreasing trend. (3) Temperature and precipitation both showed an overall negative correlation with vegetation CUE, but the relationship with precipitation was more significant than that with temperature. Areas showing positive correlations with temperature and precipitation were distributed in the windbreak and sand fixation areas of northern Shaanxi. Sensitivity coefficient analysis of temperature and precipitation indicated that the thresholds for vegetation CUE with temperature and precipitation are 10 ℃ and 500 mm, respectively. When temperature $<$ 10 ℃ and precipitation $<$ 500 mm, vegetation CUE increases with increasing temperature and precipitation. The relationship between vegetation CUE and climatic factors was more significant and showed stronger sensitivity in arid areas such as the grain-for-green areas and windbreak

and sand fixation areas in northern Shaanxi.

## Full Text

# Spatiotemporal Characteristics of Vegetation Carbon Use Efficiency and Its Sensitivity to Climate in the Yellow River Basin of Shaanxi Province

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### Abstract

Vegetation carbon use efficiency (CUE) can objectively reflect the efficiency of vegetation in sequestering atmospheric carbon and the feedback response of vegetation to climate change. Using MOD17 data, land use data, and meteorological data, this study applied the Hurst exponent, correlation analysis, and sensitivity analysis to explore the spatiotemporal variability of vegetation CUE and its sensitivity to climate factors in the Shaanxi section of the Yellow River Basin from 2001 to 2021. The results showed that: (1) From 2001 to 2021, gross primary productivity (GPP), net primary productivity (NPP), and vegetation CUE in the Shaanxi Yellow River Basin exhibited an increasing trend, with a multi-year average CUE value of 0.51. (2) Only 14.21% of the study area showed a decreasing trend in vegetation CUE. High-value CUE areas were mainly concentrated in the windbreak and sand-fixation zones and the Grain-for-Green Project areas of northern Shaanxi. Areas where vegetation CUE will show a decreasing trend in the future accounted for 59.96% of the total, with most transitioning from increasing to decreasing trends. (3) Temperature and precipitation both showed overall negative correlations with vegetation CUE, but the relationship with precipitation was more significant than with temperature. Areas with positive correlations between CUE and temperature/precipitation were distributed in the windbreak and sand-fixation zones of northern Shaanxi. Sensitivity coefficient analysis of temperature and precipitation indicated threshold values of 10 °C and 500 mm, respectively. When temperature is below 10 °C and precipitation is below 500 mm, vegetation CUE increases with rising temperature and precipitation. The relationship between vegetation CUE and climate factors is

more pronounced and sensitive in arid regions such as the Grain-for-Green areas and windbreak and sand-fixation zones of northern Shaanxi.

**Keywords:** vegetation CUE; spatiotemporal characteristics; Hurst index; climate factors; sensitivity; Yellow River Basin

## Introduction

Vegetation is a key factor in regulating and promoting ecosystem carbon cycling processes. Through photosynthesis, respiration, and transpiration, it integrates soil, atmosphere, and water into a unified whole, permeating all important aspects of ecosystem energy flow and material cycling. Early studies considered vegetation carbon use efficiency (CUE) to be a stable constant independent of environmental variables and spatial scales, serving as an assumption in vegetation productivity models. However, further research has revealed that vegetation CUE is highly sensitive to environmental changes, with significant differences among vegetation types and across spatial scales. Therefore, CUE cannot be treated merely as a constant.

Remote sensing observations at global scales indicate that CUE varies considerably with climate, region, and vegetation type. Zhang et al. found that for global vegetation, when rainfall exceeds a certain threshold, CUE changes little, but below this threshold, CUE shows a negative correlation with rainfall. An et al. studied East Asian forests and grasslands and found significant differences in CUE among different vegetation types. Liu et al. demonstrated that across China, CUE is negatively correlated with temperature and positively correlated with precipitation as climate and vegetation types change. Chen found that increased annual precipitation was the main factor driving fluctuations and increases in vegetation CUE in Northeast China' s forest ecosystems. Zheng et al. showed that in the Three-River Headwaters region, CUE was positively correlated with temperature but negatively correlated with precipitation. Different vegetation types exhibit varying relationships with climate factors. For instance, Gang et al. found that grassland CUE is positively correlated with rainfall, while Luo et al. found that in the Guangdong-Hong Kong-Macao Greater Bay Area, different vegetation types showed varying CUE values but were all positively correlated with temperature and precipitation.

Due to large spatial scale differences in vegetation CUE and its high sensitivity to climate change, few studies have reported on CUE in the Shaanxi Yellow River Basin. Large-scale studies in China have only quantitatively analyzed the relationship between climate factors and CUE without deeply exploring the sensitivity of CUE to climate change and future trends. Therefore, it is necessary to strengthen future prediction and climate factor sensitivity analysis of vegetation CUE in this region.

The Shaanxi Yellow River Basin is located in the hilly and gully region of the Loess Plateau, characterized by low annual precipitation with uneven spatiotemporal distribution, severe soil erosion, fragile vegetation growth conditions, and high sensitivity to climate change and human activities. Since the implementation of the Grain-for-Green Project in 1999, vegetation cover has been rapidly restored and increased, making it the core region with the largest greening magnitude in China. Therefore, investigating the spatiotemporal characteristics of CUE and its response to climate in this region helps understand the mechanisms of CUE changes under climate change and reveals vegetation feedback to climate change. This study employs statistical methods such as the Hurst exponent and sensitivity index to investigate the spatiotemporal characteristics, future trends, and climate sensitivity of vegetation CUE in the Shaanxi Yellow River Basin, quantitatively analyzing the response of CUE to climate factors. This research aims to understand CUE changes under climate change, provide scientific basis for achieving carbon neutrality and peak carbon goals, and offer data support and practical significance for future studies on ecosystem carbon cycle changes in the study area.

### 1.1 Study Area Overview

The Shaanxi Yellow River Basin is located in the middle reaches of the entire Yellow River Basin, extending from Fugu County in Yulin City to Tongguan County in Weinan City. It is situated between 106.35°–111.31°E and 33.66°–39.54°N, with elevations ranging from 309 to 3546 m. The region has low annual precipitation with uneven spatiotemporal distribution, with an average annual precipitation of less than 500 mm. Soil erosion is severe, vegetation growth conditions are fragile, and the ecosystem is highly sensitive to climate change and human activities. Since the implementation of the Grain-for-Green Project in 1999, vegetation cover has been rapidly restored and increased, becoming the core region with the largest greening magnitude in China.

### 1.2 Data Sources

Vegetation productivity data (GPP and NPP) were obtained from the EOS/MODIS MOD17A3HGF and MOD17A2HGF product datasets, respectively. The data have a spatial resolution of 500 m × 500 m, a temporal resolution of 8 days, and are in GeoTIFF format. Data were downloaded from https://ladsweb.nasa.gov/data/search.html for the period 2001–2021. The data were processed using ArcGIS for projection transformation, image clipping, and removal of outliers. The 8-day GPP data were accumulated to obtain annual values, and CUE was calculated as the ratio of annual NPP to GPP. The reliability of the MODIS productivity dataset has been validated through measured data and applications in various regions worldwide.

Climate data, including daily temperature and precipitation from 2001 to 2021, were obtained from the Shaanxi Meteorological Information Center. Observations from 66 meteorological stations in the basin were interpolated using the standard Kriging method and resampled to 500 m × 500 m to match the vegetation data resolution.

Land use data were obtained from the GlobeLand30 all-element data product (V2020) from http://www.globallandcover.com/. The data include ten land cover types: cropland, forest, grassland, shrubland, wetland, water body, tundra, artificial surface, bare land, and glacier/permanent snow. The overall accuracy of the data is 85.72% with a Kappa coefficient of 0.82, meeting classification accuracy requirements. Wu et al. evaluated the accuracy of GlobeLand30 data in the Yellow River Basin, reporting an overall accuracy of 85.32% and Kappa coefficient of 0.81, which is higher than data at the hectometer scale and suitable for land use analysis in the Shaanxi Yellow River Basin.

### 1.3 Methods

**1.3.1 Vegetation CUE Estimation** Vegetation CUE represents the ability of vegetation to convert atmospheric carbon into biomass and can be expressed as the ratio of NPP to GPP. The calculation formula is as follows:

$$CUE = \frac{NPP}{GPP}$$

where CUE is vegetation carbon use efficiency, NPP is net primary productivity ($g\ C \cdot m^{-2}$), GPP is gross primary productivity ($g\ C \cdot m^{-2}$), and Ra is autotrophic respiration carbon consumption ($g\ C \cdot m^{-2}$).

**1.3.2 Change Trend Prediction** The Hurst exponent is widely used to predict future trends in time series data. The calculation method is as follows: For a time series L, it is divided into N continuous but non-overlapping subsequences of length b. The mean and cumulative deviation of each subsequence are calculated and denoted as Ab and Sb, respectively. The range and standard deviation of the squared deviations of each subsequence are then calculated and denoted as Rb and Db, respectively. Finally, the rescaled range is calculated using the following formula:

$$\frac{R_b}{D_b} = \frac{1}{N} \times \sum_{n=1}^{N} \frac{R_{b,n}}{D_{b,n}}$$

The process is repeated by continuously expanding b until it equals L. The Hurst exponent H is obtained as the regression coefficient from linear fitting of log(Rb/Db) versus log(b). When $H > 0.5$, the time series shows a persistent trend; when $H = 0.5$, it indicates a random sequence; and when $H < 0.5$, it shows an anti-persistent trend.

**1.3.3 Sensitivity Coefficient** The sensitivity coefficient was used to analyze the sensitivity of vegetation CUE to climate factors. The calculation formula is:

$$S = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(P_i - \bar{P})}{\sum_{i=1}^{n}(X_i - \bar{X})^2}$$

where S is the sensitivity coefficient of CUE to climate factors, indicating the change in CUE caused by climate factor changes; i represents the year in the time series; Xi represents meteorological elements; Pi represents vegetation CUE; and $\bar{X}$ and $\bar{P}$ are the average values of climate factors and vegetation CUE, respectively.

## Results

### 2.1 Interannual Variation Characteristics of Vegetation GPP, NPP and CUE

From 2001 to 2021, vegetation GPP in the Shaanxi Yellow River Basin showed a fluctuating increasing trend, ranging from 420 to 780 g $C \cdot m^{-2}$, with a multi-year average of 627.00 g $C \cdot m^{-2}$. Using moving average for trend simulation, GPP increased rapidly before 2015 and then remained at a high level with fluctuations. NPP showed a consistent fluctuating increasing trend, with a multi-year average of 363.60 g $C \cdot m^{-2}$ and an interannual change rate of 10.69 g $C \cdot m^{-2}$. Vegetation CUE ranged from 0.54 to 0.64, with an interannual change rate of 0.003–0.006, reaching its maximum value in 2015 and then fluctuating at a high level (Figure 2). Since 1999, the Shaanxi Yellow River Basin has fully implemented the Grain-for-Green Project and grazing prohibition policies, leading to rapid increases in vegetation cover and improved vegetation growth conditions. Li et al. found that vegetation cover in Shaanxi Province reached its maximum value in 2019 and subsequently fluctuated at a high level. Vegetation GPP and NPP increased with cover, both showing fluctuating upward trends, though CUE reached its peak slightly earlier than GPP and NPP.

### 2.2 Spatial Distribution of Vegetation CUE

The spatial distribution of multi-year average vegetation CUE is generally consistent with that of GPP and NPP (Figure 3). High-value areas are concentrated in the western part of the natural forest protection zone in southern Shaanxi and the northern part of the natural forest protection zone in northern Shaanxi, with values above 0.60. Low-value areas are mainly distributed in the windbreak and sand-fixation zone in northern Shaanxi, followed by most areas of the Grain-for-Green zone in northern Shaanxi, with values below 0.50. The standard deviation distribution shows that areas with large fluctuations (standard deviation $> 0.02$) are mainly in the southern part of the Grain-for-Green zone in northern Shaanxi and most of the natural forest protection zone, followed by most of the Grain-for-Green zone in northern Shaanxi with standard deviation above 0.015. Areas with small fluctuations (standard deviation $< 0.01$) are mainly scattered in the Guanzhong Plain and the western part of the natural forest protection zone in southern Shaanxi (Figure 4). Regions with large fluctuations experience significant environmental changes, where vegetation growth is easily affected by environmental conditions.

### 2.3 Change Trend of Vegetation CUE

As shown in Figure 5, only 14.21% of the area exhibited a decreasing trend, primarily distributed in the southern Guanzhong Plain and parts of the Grain-for-Green zone in southern Shaanxi, though most of these were non-significant decreases. The remaining areas showed increasing trends, with 13.40% being significant increases ($p < 0.05$), mainly in the natural forest protection zone of northern Shaanxi, the Taibai Mountain and northern Qinling area in Guanzhong, and parts of northwestern Yulin. In terms of change rate, increasing rates were generally 0.003–0.006, while decreasing rates were 0–0.003.

The average Hurst exponent for vegetation CUE in the Shaanxi Yellow River Basin was 0.51, indicating that future trends will maintain a certain degree of persistence but with anti-persistent effects. Therefore, vegetation CUE in the study area will show an overall decreasing trend in the future, accounting for 59.96% of the total area. Among these, 55.39% of the area will transition from increasing to decreasing trends, mainly concentrated in the natural forest protection zone, Grain-for-Green zone, and windbreak and sand-fixation zone in northern Shaanxi. Only 4.57% of the area will show a continuous decreasing trend. Areas with future increasing trends account for 40.04% of the total, with 30.44% showing continuous increases, mainly in the western parts of the Grain-for-Green and windbreak and sand-fixation zones in northern Shaanxi, as well as the Guanzhong Plain.

### 2.4 Relationship Between Vegetation CUE and Climate Factors

Vegetation CUE in the study area was predominantly negatively correlated with temperature, with negative correlation areas accounting for 62.55% of the region, mainly distributed in the eastern part of the natural forest protection zone in northern Shaanxi, the southern Guanzhong Plain, and the natural forest protection zone in southern Shaanxi. The proportion of significantly negative correlation areas was only 9.53%. Areas with higher positive correlations were mainly in the natural forest protection zone and the northern foothills of the Qinling Mountains, dominated by forest vegetation.

The overall relationship between CUE and precipitation was also negative (Figure 6), with negative correlation areas accounting for 69.38% of the region, though almost all were non-significant. The proportion of significantly positive correlation areas was 4.57%, distributed in the windbreak and sand-fixation zone and northeastern Grain-for-Green zone of northern Shaanxi. The relationship between CUE and sunshine hours showed positive correlation in 45.55% of the area and negative correlation in 54.45% of the area, with a polarized distribution but no significant correlations. Only 0.32% of the area showed significant positive correlation with sunshine hours. Therefore, the effects of temperature and precipitation on CUE in the Shaanxi Yellow River Basin are more significant than those of sunshine hours.

Further analysis of the sensitivity of vegetation CUE to climate factors revealed that positive sensitivity coefficients to temperature accounted for 37.45% of the area, concentrated in the Grain-for-Green and windbreak and sand-fixation zones of northern Shaanxi and most areas of the Guanzhong Plain. Negative sensitivity coefficients to precipitation accounted for 69.38% of the area, mainly in the Guanzhong Plain, natural forest protection zone, and Grain-for-Green zone in southern Shaanxi. Negative sensitivity coefficients to sunshine hours accounted for 54.45% of the area, mainly in most of the Guanzhong Plain, parts of the Grain-for-Green zone in southern Shaanxi, and the western Grain-for-Green zone in northern Shaanxi.

To further explore the sensitivity of CUE to temperature and precipitation, Table 1 shows that when annual average temperature is below 10 °C, the sensitivity coefficient of CUE to temperature is positive, and CUE increases with temperature, mainly distributed in the windbreak and sand-fixation zone and northwestern Grain-for-Green zone of northern Shaanxi. When temperature exceeds 10 °C, the sensitivity coefficient becomes negative and CUE decreases with increasing temperature. In areas with annual precipitation below 500 mm (mainly the windbreak and sand-fixation zone in northern Shaanxi), the sensitivity coefficient to precipitation is negative. In areas with precipitation between 500–650 mm, the sensitivity coefficient slowly decreases, and CUE fluctuates and decreases with increasing precipitation. When precipitation exceeds 650 mm, CUE shows a decreasing trend with increasing precipitation, and the negative sensitivity coefficient decreases.

## Discussion

The results indicate that vegetation CUE is overall negatively correlated with temperature, which differs from some previous studies. Under the combined effects of ecological restoration projects and climate change, vegetation has gradually grown and matured, increasing the total amount of organic matter absorbed and converted through photosynthesis. However, NPP represents the remaining organic matter after vegetation’ s growth and maintenance metabolism consumption. As vegetation matures, the organic matter required for maintenance metabolism increases, causing NPP to peak earlier than GPP. The multi-year average CUE in the Shaanxi Yellow River Basin is 0.51, higher than the national average (0.45) but lower than that in the Three-River Headwaters region (0.58) and Northeast China’ s forest ecosystems (0.55), indicating relatively high CUE levels in the study area.

Vegetation CUE also shows a predominantly negative correlation with precipitation. Liu et al. found that across China, CUE is negatively correlated with temperature and positively correlated with precipitation. Our study’ s negative correlation with temperature aligns with this conclusion, but the negative correlation with precipitation differs. CUE is extremely sensitive to research scale and climate change, and different scales and climate conditions yield varying characteristics and climate sensitivities. Therefore, analyzing CUE changes and their response to climate in the Shaanxi Yellow River Basin can accurately reflect regional ecosystem carbon cycle changes.

CUE measures the amount of carbon fixed by plants for growth and reproduction relative to the carbon absorbed from the atmosphere. Studies show that when annual average precipitation exceeds 500 mm, CUE decreases with increasing precipitation. In recent years, although regional precipitation has increased, the frequency of high-intensity precipitation events (e.g., heavy rain) has increased significantly, which has no significant positive effect on improving CUE and may even reduce it. Excessive precipitation intensity can cause soil surface compaction and erosion, leading to loss of soil moisture and nutrients, thereby limiting vegetation growth and photosynthetic efficiency and reducing CUE.

In areas with annual precipitation below 500 mm (the windbreak and sand-fixation zone in northern Shaanxi), CUE is positively correlated with precipitation. Research shows that vegetation in arid regions experiences increased photosynthetic stress when water is scarce, reducing nitrogen supply for growth hormones and consequently decreasing vegetation growth rates. Increased precipitation enhances photosynthesis, which to some extent reduces root respiration and decreases autotrophic respiration, thereby increasing CUE.

Vegetation CUE in the study area shows an increasing trend in most regions, with significant increases mainly in the Grain-for-Green and windbreak and sand-fixation zones of northern Shaanxi, consistent with NPP trends. The Hurst exponent analysis indicates that CUE will show an overall decreasing trend in the future, with 55.39% of the area transitioning from increasing to decreasing trends, mainly in the natural forest protection zone, Grain-for-Green zone, and windbreak and sand-fixation zone of northern Shaanxi. Considering only climate factors, warming and humidification have extended the vegetation growing season and increased photosynthesis time, raising GPP. However, enhanced vegetation autotrophic respiration slows NPP growth, causing CUE to show a decreasing trend.

The study identified thresholds of 10 °C for temperature and 500 mm for precipitation. In areas below these thresholds (the windbreak and sand-fixation zone of northern Shaanxi), CUE increases with rising temperature. This region has relatively low temperatures, and vegetation growth requires a certain temperature range. Temperature increases extend the growing season and improve photosynthetic efficiency, thereby increasing CUE. In arid regions, CUE increases with water availability. Increased water reduces vegetation investment in roots and decreases autotrophic respiration, improving ecosystem NPP/GPP ratio.

Changes in vegetation CUE in the Shaanxi Yellow River Basin are mainly concentrated in the Grain-for-Green and windbreak and sand-fixation zones of northern Shaanxi, fluctuating at high levels after peaking. Future trends indicate these areas will shift to decreasing trends. Climate factors significantly impact CUE, and it is recommended that future research further investigate ecosystem carbon cycling mechanisms and change causes under climate change in this region.

## Conclusion

Based on MOD17 data, land use data, and climate data, this study applied trend prediction and sensitivity coefficient methods to explore the spatiotemporal variability of vegetation CUE and its climate sensitivity in the Shaanxi Yellow River Basin from 2001 to 2021. The main conclusions are:

(1) From 2001 to 2021, vegetation GPP and NPP in the Shaanxi Yellow River Basin showed fluctuating increasing trends, with multi-year average values of 627.00 g $C \cdot m^{-2}$ and 363.60 g $C \cdot m^{-2}$, respectively. Vegetation CUE ranged from 0.54 to 0.64 with a multi-year average of 0.51, also showing a fluctuating increasing trend, though the growth rate slowed after 2015.

(2) High CUE values were mainly distributed in the windbreak and sand-fixation zones and Grain-for-Green zones of northern Shaanxi, with values above 0.55. Only 14.21% of the area showed decreasing CUE trends, mainly in the southern Guanzhong Plain and parts of the Grain-for-Green zone in southern Shaanxi, though most decreases were non-significant.

(3) The average Hurst exponent for vegetation CUE in the Shaanxi Yellow River Basin was 0.51, indicating an overall decreasing trend in the future, accounting for 59.96% of the study area. Among these, 55.39% of the area will transition from increasing to decreasing trends, mainly in the natural forest protection zone, Grain-for-Green zone, and windbreak and sand-fixation zone of northern Shaanxi.

(4) Vegetation CUE in most areas of the Shaanxi Yellow River Basin was negatively correlated with temperature and precipitation, with the relationship to precipitation being more significant. Areas with significant positive correlations with precipitation were mainly in the windbreak and sand-fixation zone of northern Shaanxi. Sensitivity coefficient analysis revealed thresholds of 10 °C for temperature and 500 mm for precipitation. Below these thresholds, vegetation CUE increases with rising temperature and precipitation. The relationship between CUE and climate factors is more significant and sensitive in arid regions such as the Grain-for-Green and windbreak and sand-fixation zones of northern Shaanxi.

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